Dysphagia 19:192–206 (2004)
DOI: 10.1007/s00455-004-0006-5

Dysphagia

Influence of Bolus Consistency on Lingual Behaviors in Sequential Swallowing

Catriona M. Steele, PhD, SLP(C), CCC-SLP, Reg. CASLPO,[1,2] and Pascal H.H.M. Van Lieshout, PhD[2]

[1]Toronto Rehabilitation Institute, Toronto, Ontario; and [2]Oral Dynamics Laboratory, Graduate Department of Speech–Language Pathology, University of Toronto, Toronto, Ontario, Canada

Abstract. Thickened liquids are a commonly recommended intervention for dysphagia. Previous research has documented differences in temporal aspects of bolus transit for paste versus liquid consistencies; however, the influence of liquid viscosity on tongue movements during swallowing remains unstudied. We report an analysis of the influence of bolus consistency on lingual kinematics during swallowing. Electromagnetic midsagittal articulography was used to trace tongue body and dorsum movement during sequential swallows of three bolus consistencies: *thin*, *nectar*-thick, and *honey*-thick liquids. Rheological profiling was conducted to characterize viscosity and density differences among six liquids (two of each consistency). Eight healthy volunteers participated; four were in a younger age cohort (under age 30) and four were over the age of 50. The primary difference observed across the liquids of interest was a previously unreported phenomenon of sip-mass modulation; both flavor and density appeared to influence sip-sizing behaviors. Additionally, significantly greater variability in lingual movement patterns was observed in the older subject group. Systematic variations in lingual kinematics related to bolus consistency were restricted to the variability of downward tongue dorsum movement. Otherwise, the present analysis failed to find empirical evidence of significant modulations in tongue behaviors across the thin to honey-thick consistency range.

Key words: Swallowing — Kinematics — Bolus consistency — Rheology — Electromagnetic midsagittal articulography — Deglutition — Deglutition disorders.

Restriction of diet consistency is a common recommendation for individuals with oropharyngeal dysphagia. Clinicians prescribe such modifications for patients on an individual basis, depending on particular physiological impairments observed during assessment [1]. Thickened liquids are selected for the purpose of retarding the flow of liquids as they enter the pharynx. This strategy may reduce the risk of aspiration in patients with delayed swallow initiation [2,3]. Conversely, mechanical soft or pureed textures are prescribed to facilitate safe and efficient bolus transfer for patients who have difficulty manipulating solid or particulate food textures [4,5]. Nonetheless, little empirical evidence exists to support or guide the use of texture modifications as an intervention for dysphagia [6]. A recent initiative, launched by a working group of the American Dietetic Association, has proposed the adoption of standard terminology and rheological boundaries for four classes of liquid consistency: thin, nectar-thick, honey-thick, and spoon-thick [7].

Several reports suggest that the basic neurophysiology of swallowing is fine-tuned in response to both peripheral feedback and central afferent inputs associated with variations in bolus volume and consistency [8,9]. Trigeminal touch and pressure receptors in the oral cavity provide information on the shape, consistency, and stereoscopic aspects of the bolus [10]. In addition, mucosal chemoreceptors and thermoreceptors are likely to play a role in modifying swallowing behaviors, together with input from the tongue papillae and olfactory nerve with respect to the perception of taste (e.g., see [11,12]). Young adults of both

---

Correspondence to: Catriona M. Steele, PhD, SLP(C), CCC-SLP, Reg. CASLPO; 550 University Avenue, Room 801, Toronto, Ontario, Canada, M5G 2A2. Telephone: (416) 597-3422 x 3895, Fax: (416) 597-3031, E-mail: catriona.steele@utoronto.ca

genders can reliably detect viscosity differences for stimuli held in the oral cavity, but sensory discrimination deteriorates as viscosity increases [13].

Rheological and Material Properties of the Bolus

Clinicians commonly use the term viscosity to refer to the clinically relevant property of liquids used for dysphagia management. More correctly, viscosity is a measure of the intrinsic ability of a fluid to resist flow under force and is quantified as the ratio of shear-stress (the force applied) to shear-rate (i.e., rate of fluid material deformation) [14,15]. The units of viscosity measurement are centipoise (cP) or millipascal seconds (mPa s). Water has viscosity of 1 cP at 20°C. Viscosity is also known to vary as a function of temperature and the concentration and molecular weight of suspended particles [14]. Familiar examples of temperature-dependent fluctuations in viscosity include ice cream, which melts to a thin liquid at higher temperatures, and flour or cornstarch based sauces, which thicken when heated. Flow characteristics may be further classified as Newtonian (i.e., a linear relationship between shear-stress and shear-rate is observed) or non-Newtonian (nonlinear and shear-rate-dependent) [14]. For non-Newtonian liquids, viscosity cannot be accurately represented as a single value, but must be reported as viscosity at a specific shear-rate. The majority of ingestible liquids are non-Newtonian [14]. To date, estimates of lingual shear-rates for swallowing have been proposed on the basis of perceptual viscosity discrimination studies [16–18], and there is little consensus, with estimates ranging from 5 to 1000 s^{-1}.

Research investigating the impact of bolus consistency manipulations on oropharyngeal swallowing physiology provides evidence of both temporal and spatial influences. Swallows of high-viscosity (paste) barium have been reported to show longer durations than swallows of low-viscosity liquid barium in oral and pharyngeal bolus transit, submental muscle contraction, tongue-base to posterior pharyngeal wall contact, pharyngeal peristaltic waves, and pharyngo-esophageal (P–E) segment opening. Others have observed increases in the diameter of P–E segment opening with paste compared to liquid boluses [19–22]. Opinion differs regarding the influence of bolus viscosity on the magnitude of vertical and horizontal hyoid displacement [23,24]; review of this literature suggests that bolus consistency–related changes in hyoid movement are not observed within the thin-to-honey-thick consistency range, but emerge with spoon-thick items. However, the cited studies focus largely on pharyngeal physiology, and little is known about the influence of bolus consistency on precursor events in the oral cavity. Furthermore, it must be noted that the reported consistency manipulations are somewhat crude. With few exceptions, researchers have failed to adequately describe the rheological properties of the items used. In particular, most prior studies have failed to use instruments that accurately measure flow in non-Newtonian fluids [25].

Although viscosity has been embraced in the clinical world as a salient bolus property for dysphagia management, it is only one of several bolus characteristics that have the potential to serve as a clinically important property for swallowing [25,26]. Some non-Newtonian liquids exhibit yield-stress-dependent flow (i.e., flow does not occur until the applied shear-stress force exceeds a threshold). Ketchup is a commonly cited example [27] that requires a minimum level of stress to begin flow from the bottle. Bolus density (i.e., mass per unit volume) has also been reported to contribute to observed differences in the magnitude of anterior hyoid displacement [28], but has not been systematically controlled in other studies of swallowing across different consistencies. Future investigations of the influence of bolus characteristics on swallowing physiology must be careful not to restrict their analyses to the domain of viscosity. Other potentially confounding influences must also be considered.

The Present Investigation

This article describes the results of research designed to identify and measure systematic variations in lingual kinematics during continuous drinking (sequential swallowing), associated with manipulations of liquid bolus consistency. Electromagnetic midsagittal articulography (EMMA) was used to transduce movements of the tongue with high spatiotemporal precision. Stability in swallowing kinematics across sessions has previously been demonstrated using this technique [29]. It has previously been reported that swallowing-related movements of the tongue body and dorsum are larger in amplitude than those of the tongue blade and mandible [4]. Consequently, we decided that bolus consistency influences on swallowing would be most easily recognized in the movement patterns of these two tongue segments. Therefore, the current investigation is restricted to data for the tongue body and dorsum.

The current analysis was restricted to sequential swallowing data in order to eliminate any

Table 1. Rheological and material properties of six liquids used to study the impact of bolus consistency on swallowing kinematics[a]

Consistency class	Item	Density (g/cc)	Yield stress (Pa)	Viscosity $6–15s^{-1}$	(cP) $16–25s^{-1}$	for shear–rate $26–35s^{-1}$	Ranges of: $36–45s^{-1}$
Thin	Apple juice[b]	1.007	0.029	8	6	5	5
	Water	0.993	0.000	18	15	13	12
Nectar-thick	Chocolate milk[c]	1.053	0.052	695	470	376	324
	Apple juice[d]	1.067	0.264	667	466	381	325
Honey-thick	milk[e]	1.04	0.000	1182	867	n/a	n/a
	Apple juice[f]	1.073	1.424	1774	1140	1023	785

n/a: Data not available. Maximum stress input ranges failed to induced shear rates in this range during rheological testing.
[a] Steele et al. [30].
[b] President's Choice®Cox's Orange Pippin Apple Juice from Concentrate. Sunfresh Limited, Toronto, ON.
[c] Sealtest* 1% M.F. Chocolate Milk (partly skimmed), Natrel inc., Don Mills, ON.
[d] Resource® Thickened Apple Juice from Concentrate: nectar consistency. Foodservice, Novartis Nutrition, Minneapolis, MN.
[e] Resource® Original Dairy Thick® Honey Consistency, made with 2% reduced fat milk, vitamins A and D and zinc added. Foodservice, Novartis Nutrition, Minneapolis, MN.
[f] Resource® Thickened Apple Juice from Concentrate: honey consistency. foodservice, Novartis Nutrition, Minneapolis, MN.

confounding influences related to cup positioning and removal between swallows. Liquids of different consistencies were selected for inclusion in the present study based on the criterion that their viscosity was low enough to permit continuous sipping from a cup (see Table 1). This criterion of sippability allowed subjects to perform the experimental task with maximum normalcy and to preserve their habitual bolus-sizing habits.

Research Questions and Hypotheses

Bolus Size

During swallowing, the size of a bolus can be measured in terms of either its volume (in cubic centimeters) or its mass (in grams). Previous studies of the influence of bolus characteristics on discrete swallowing behaviors have employed strict control of bolus size through syringe or spoon delivery of calibrated volumes [24,31]. Only one study [28] has considered the possibility that bolus density (i.e., mass per unit volume) might influence swallowing physiology, either instead of or in combination with bolus viscosity. Controlling bolus volume via syringe administration not only precludes the possibility of collecting data during series of self-paced sequential swallows, but it also eliminates natural behaviors of possible importance involved in acceptance/extraction of the bolus from the cup. In this study, sip size was not controlled; rather, measurements of average sip mass were computed. Since volumetric measures can be easily extrapolated from mass, assuming that the density of a liquid is known, mass was selected as the primary variable of interest. No specific hypotheses regarding sip-sizing behaviors were formulated prior to the study, but it was of interest to observe and describe any patterns of sip-mass variation that occurred across the liquids studied.

Swallow Frequency

In clinical settings liquid viscosity is assumed to affect the speed of bolus flow at the time of transfer into the pharynx; thicker liquids are believed to have a lower probability of reaching and invading the laryngeal inlet prior to initiation of the pharyngeal phase of the swallow. It was hypothesized that thicker liquids would take longer to reach the pharyngoesophageal junction, thereby reducing the frequency (swallows per second) with which repeated sequential swallows could be generated.

Spatiotemporal Variability

The spatiotemporal variability of cyclic tongue movement during speech or swallowing can be captured using a variable known as the cyclic Spatio-Temporal Index (cSTI) [32]. In order to calculate the cSTI, individual movement cycles are first amplitude- and time-normalized and aligned with each other. The data are then divided into segments, each representing successive 2% intervals in relative time. The standard deviation of normalized amplitude is then calculated for each 2% segment. The cSTI is defined as the sum of these standard deviations; higher cSTI values reflect greater spatiotemporal pattern variability across individual movement cycles.

Table 2. Subject demographics and transducer coil positions

			Session number		Tongue blade (mm posterior to anatomical tongue tip)	Tongue body (mm posterior tongue blade coil)				Tongue dorsum (mm posterior to tongue blade coil)			
Gender	Subject	Age	Session A	Session B		Session A	Session B	Mean	SD	Sesssion A	Session B	Mean	SD
Females	2	28	3	4	10.00	17.31	21.28	19.30	2.81	36.59	39.54	38.07	2.09
	4	28	1	2	10.00	22.46	29.72	26.09	5.13	41.72	38.39	40.06	2.35
	3	59	2	3	10.00	21.27	27.59	24.43	4.47	32.57	35.47	34.02	2.05
	8	56	2	3	10.00	21.80	20.83	21.32	0.69	31.60	38.87	35.24	5.14
							Group:	22.78	3.27		Group:	36.84	2.91
Males	1	27	2	4	10.00	28.95	16.95	22.95	8.49	34.78	21.28	28.03	9.55
	5	23	2	3	10.00	21.87	26.68	24.28	3.40	36.02	36.99	36.51	0.69
	6	66	1	3	10.00	26.11	26.22	26.17	0.08	35.65	33.49	34.57	1.53
	7	56	1	2	10.00	23.63	32.31	27.97	6.14	47.04	54.26	50.65	5.11
							Group:	25.34	4.53		Group:	37.44	4.22

Coil positions are shown for two data collection sessions, selected for analysis from a series of three or more repeated data collection sessions per subject. Subjects 1 and 2 each attended a total of four data collection sessions. All other subjects attended three data collection sessions. The tongue blade coil position was always 10 mm posterior to the anatomical tongue tip.

Lingual Effort

In the speech science literature, the tongue has been modeled as a simple, nonlinear mass–spring system [33]; within this model, peak velocity is used as a relative measure of physical effort in performing skilled movements [34]. Previous swallowing researchers have observed increases in the amplitude of lingual force used to propel boluses of higher viscosity [35–37]. In line with these observations, it was proposed that boluses with greater resistance to flow (i.e., higher viscosity) would demand longer and greater propulsive effort by the oral tongue. We therefore hypothesized that increases in the amplitude, peak velocity, and duration of tongue movement would be observed across increases in bolus viscosity.

Age Effects

Reduced tongue strength has been reported with advancing age [36] and has been posited as a reason why multipeaked swallowing gestures are observed in the tongue and hyoid in elderly subjects [36,38], Accordingly, we predicted that age effects would be observed in the current analysis. Specifically, older subjects were expected to exhibit slower swallowing frequencies (swallows per second) than younger subjects and to show signs of increased lingual effort in swallowing, characterized by a higher number of movement cycles per swallow. Consistent with previous findings [26,39], it was further predicted that the older-subject cohort would show higher spatiotemporal variability, as measured by cSTI, as well as prolongation and greater within-trial variability of movement durations.

Methods

Subjects

Eight adults with no history or complaints of neurological impairment or swallowing difficulty volunteered for participation in the study. Four of these subjects were under 30 years of age, and four were over 50 years of age. Gender distribution was balanced within each age cohort to avoid a potential bias and to be in line with Canadian ethical guidelines [40]. Demographic characteristics of the subjects are summarized in Table 2. Data from these same subjects for other swallowing tasks have been reported elsewhere [26,29]. All subjects provided informed consent to participate and completed a brief medical history questionnaire. The first author, a certified speech–language pathologist, performed an oral mechanism and motor speech examination to screen each subject for signs of speech motor or swallowing abnormalities prior to acceptance into the study.

Instrumentation

An electromagnetic midsagittal articulograph (Carstens Medizin-Elektronik AG-100) was used to trace the position of very small transducer coils (2.4 mm in

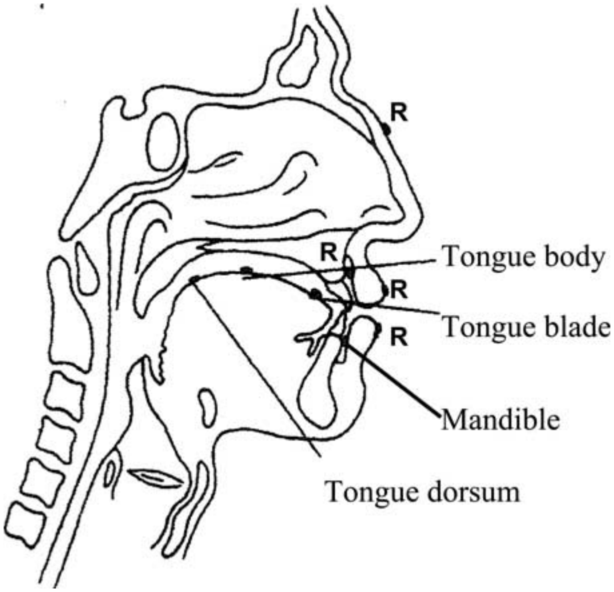

Fig. 1. EMMA transducer coil positions. During electromagnetic midsagittal articulography studies of swallowing, transducer coils are attached in midline to the fleshpoint positions shown in the diagram. Reference coils are denoted by the letter **R**.

diameter) that were attached in midline to the oral articulators, as shown in Figure 1. EMMA, like other methods of fleshpoint parameterization (e.g., electropalatography, X-ray microbeam) does not allow concurrent visualization of tongue fleshpoint position and bolus size, shape, or location. Consequently, the resulting tongue movement data cannot be mapped onto the oral preparatory, oral propulsive, and pharyngeal stages of bolus movement, traditionally identified during videofluoroscopy swallowing assessments [2]. However, EMMA offers some advantages over videofluoroscopy because it permits extended and repeated data collection sessions for individual subjects without risk of significant biohazard [41]. Finally, EMMA does not require the use of radiopaque contrast media and, therefore, allows the study of bolus influences on swallowing behaviors without altering the flavor, density, and viscosity of the chosen liquid stimuli [28,42].

Procedure

For the present investigation, three transducer coils were attached in midline to the surface of the tongue using a combination of surgical methacrylate resin (Cyanodent, Ellman International Mfg.) and zinc polycarboxylate dental cement (Durelon, Espe Dental AG). With the tongue extended outside the mouth, these coils were positioned on tongue blade and tongue body (10 mm and 30 mm posterior to the tongue tip, respectively) and the tongue dorsum (as far back as tolerated by the subject). Coil locations on the nonextended tongue were calculated (in mm posterior to the tongue tip) from the EMMA data, with the tongue held at rest inside the closed mouth, and are tabulated for each subject in Table 2. A fourth coil was attached to the mandibular incisors using a custom thermoplastic dental impression; this allowed for measurement of jaw movement and corrections of the tongue coil data for jaw contributions. Four additional transducer coils were attached in midline to the nose, the vermilion borders of the upper and lower lip, and the gums of the upper central incisors to provide reference data.

The subject was then seated comfortably in a dental chair, with his or her head positioned inside a large plastic helmet (62 cm) that was suspended from the ceiling. Three transmitters attached to this helmet create an alternating magnetic field within the helmet. When a transducer coil is placed inside this field, an alternating voltage is induced in the transducer. The distance between the transmitter and the transducer is directly related to the amplitude of the signal induced in that transducer [43], allowing precise determination of the location of each coil (spatial error ≤ 0.35 mm). A specially designed inner helmet was tightly connected to the subject's head and to the larger outer helmet, so that head movements were closely followed by the entire structure.

Temporal resolution of the EMMA system is limited only by the memory and processing capacity of the computer used to store the data. For the present study, coil-position data were acquired at 400 Hz. Time-locked measurements of the acoustics of swallowing (see Fig. 2) were collected for the purposes of indexing the number of swallows in each EMMA recording window. The number of swallows was calculated using the acoustic swallow peaks which previously were reported to coincide with bolus passage through the pharyngoesophageal segment [44–46].

Subjects were required to perform sets (henceforth called trial-sets) of repeated sequential swallows (8 swallows per trial-set). The data set comprises two trial-sets per subject with each of 6 liquids, for a total of 96 swallows per subject. A single trial-set was easily completed within a 40-s EMMA recording window. Trial-set order was randomized across data collection sessions.

Liquid Selection and Rheological Profiling

Six different liquids were selected for study, including two liquids in each of three consistency classes: thin, nectar-thick, and honey-thick. Rheological profiling

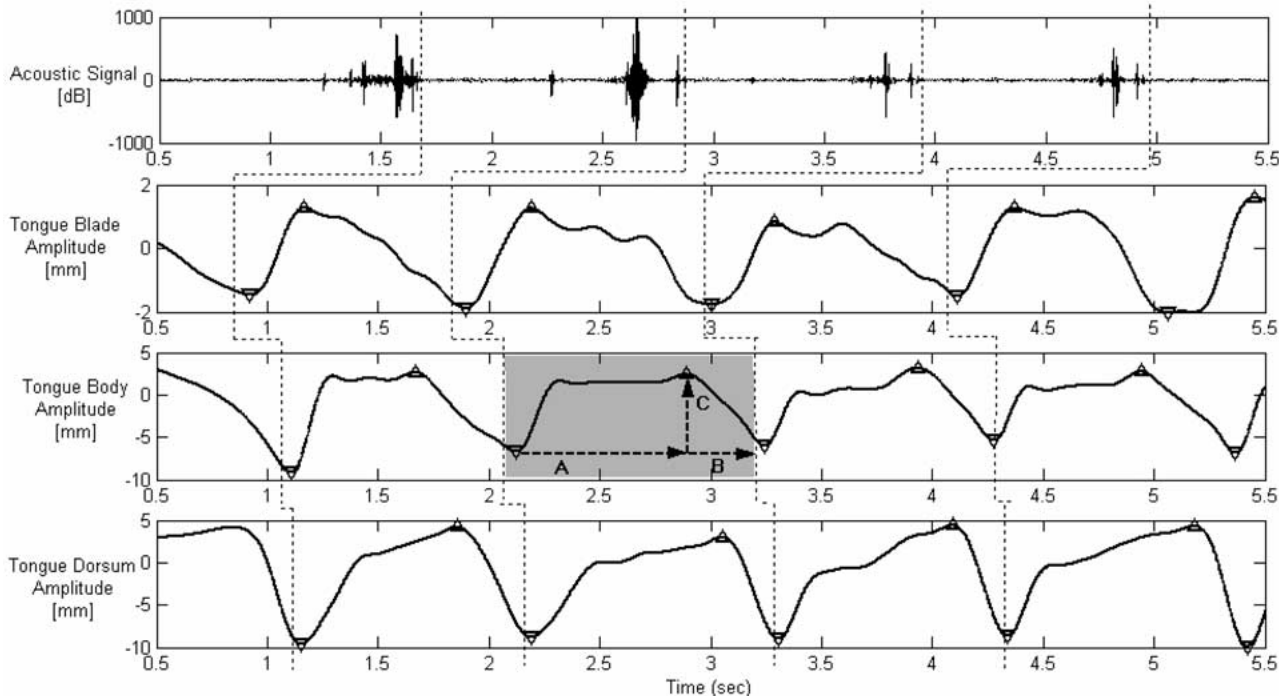

Fig. 2. Example of EMMA data showing positional peaks and valleys for vertical tongue movements in a series of four sequential water swallows. Data are shown for Subject 4. At the top of the figure, the acoustic signal shows a series of four peaks, representing bolus flow through the pharyngoesophageal segment. Dashed vertical lines are used to demarcate events preceding each acoustic swallow peak in the vertical movement histories for each transducer coil. The tongue blade leads the movement sequence, displaying a single cycle of rising and descending movements prior to each acoustic swallow peak. This pattern is followed by upward and downward deflections in the tongue body and tongue dorsum. Positional peaks and valleys detected by an automated algorithm based on the Cyclic Spatio-Temporal Index are identified by upward- and downward-facing triangles in each movement signal. A single movement cycle is identified by the gray-shaded box in the tongue body trace. The arrow labeled "A" corresponds to the duration of upward movement (in seconds). The arrow labeled "B" shows the duration of downward movement. The arrow labeled "C" shows the amplitude of the position change (in mm) between position minimum and maximum.

was conducted on all the liquid stimuli with assistance from the Department of Food Science at the University of Guelph; a detailed description of these procedures was reported previously [26]. Density measurements (g/cc) were derived from mass measurements for 15-cc volumes of each liquid at room temperature (22°C), measured on a digital scale, accurate to a level of 0.1 g (Mars Scale Industries, Toronto, ON, Canada). Viscosity and yield-stress measurements for each item were obtained at 22 ± 0.1°C using cone-and-plate geometry on a Carri-Med Controlled Stress CSL Rheometer (Carri-Med Ltd., Dorking, England).

Data Collection Protocol

Prior to the collection of swallowing movement data, 10 speech and nonspeech oral movement tasks were performed for the purposes of collecting baseline static and dynamic position measurements. These included an occlusal plane measurement, which was taken from two transducer coils mounted with 3-cm separation on a plastic bite plate [47]. Data collection for swallowing was conducted in the following manner: The subject was given a container of liquid and instructed to perform 8 swallows in a continuous series (a sequential trial-set), without lowering the cup from the lips between sips. A research assistant announced the ordinal value (1 through 8) for each swallow as it occurred and reminded the subjects to stop drinking as soon as the eighth swallow was completed; thus, subjects were not required to mentally track the number of swallows performed and were free to swallow in as natural a manner as possible, given the experimental setup.

Data Reduction

EMMA studies of swallowing face a particular challenge, in comparison to studies of speech production, in that the transducer coils can become dislodged or break under the shearing forces of bolus propulsion during swallowing. In anticipation of this situation, an *a priori* decision was made to complete at least three data collection sessions (spaced at least one week apart) with each subject and, subsequently, to discard data from the session in which the highest rate of coil breakage or displacement was encountered. In fact, breakage of a single coil was encountered in only 3 of 26 data collection sessions; when this did not occur, data from the first data collection session was discarded by convention. As shown in Table 2, both subjects 1 and 2 completed an additional data collection session for a total of four sessions each; consequently, data reduction for these two individuals required the exclusion of data from two sessions.

Data Processing

Data processing followed the same principles described for previous speech studies [48]. Movement data were smoothed using an 11-point triangular filter (effective low-pass frequency = 27.5 Hz) before data processing. Position-reference information from the subject's occlusal plane measurement was then used to rotate the data and align them with the horizontal axis of the EMMA measurement field. In this manner, a uniform coordinate reference frame was established for all subjects [47]. All movement data were then imported into MATLAB (Version 6.0.0.42a, Release 12, The Mathworks, Inc.), and bandpass-filtered between 0.1 Hz (removing slow varying drifts) and 6 Hz using a seventh-order Hamming window Butterworth filter. Tongue coil signals were corrected for jaw contribution using an estimate of jaw rotation based on the principal component of the mandible transducer coil trajectory for each trial [49,50].

Event Indexing

An automated peak-picking algorithm was used to detect the onset and offset (peaks and valleys) of directional changes in the position [32]. This algorithm reiteratively computed the cSTI (described above), using different relative amplitude and relative time criteria for data segmentation. This procedure identified those relative amplitude and relative time criteria that generated the lowest cSTI (i.e., identifying movement cycles that are the most similar in terms of their spatiotemporal pattern); these optimal criteria were then used to identify the temporal and positional boundaries for each movement cycle in both the vertical and horizontal dimensions (where a cycle is defined as the interval between two successive positional valleys, with a single intervening position peak). It is important to realize that a single movement cycle does not necessarily coincide with a single swallow; the transportation of a bolus as part of a single swallow event may require multiple opening and closing movements (i.e., multiple cycles) in any or all of the tongue transducer coils. Figure 2 shows the peaks and valleys identified by the cSTI algorithm in movement signals of the three tongue transducer coils during a 4-s segment of sequential water swallows collected from subject 4.

Analysis

Statistical Procedures

The statistical analysis was performed using NCSS 2000 (Number Cruncher Statistical System) software (NCSS, Kaysville, UT). Repeated-measures ANOVA with a between-subject factor of COHORT (2: < age 30; > age 50) and a within-subject factor of ITEM (6: water; apple juice; chocolate milk; nectar-thick apple juice; honey-thick milk; honey-thick apple juice) were used. The alpha level for statistical significance was set at $\alpha = 0.05$. When multiple comparisons were performed across the two transducer coils within each plane of movement, a Bonferroni corrected at alpha criterion of 0.05/4 = 0.013 was applied. Similarly, for multiple comparisons performed across the two transducer coils and four movement directions, a corrected alpha criterion of 0.05/8 = 0.006 was used [17]. In recognition of the possibility that the Bonferroni correction might be overly conservative [51], trends with statistical significance at $\alpha = 0.01$ are also reported. Power estimates are reported for all significant statistical comparisons.

Variables

Sip Mass

Average sip mass was calculated by dividing the pre-to-post trial-set difference in cup mass (in grams), and dividing this value by the number of swallows (8) in the trial-set. The data set comprised a single average value for each trial-set; thus, variation across successive swallows within the trial-set was not captured.

Swallow Frequency

In order to calculate the average swallow frequency for any single trial-set, durational boundaries for each trial-set were defined respectively as the onset of the first upward oral articulatory movement in the trial-set and the offset of the last downward movement of the dorsum transducer coil. These events respectively represented the beginning of the first swallow and the end of the last swallow in the trial-set. The sequence of oral movements for swallowing was most commonly led by the mandible (63% of the time) or the tongue blade (26% of the time). In the remaining 11% of the data trial-sets, upward tongue body movement led the sequence. Downward movement of the tongue dorsum was always the final event in the sequence. Since the variable of swallowing frequency is a global measure rather than one specific to lingual movement, the onset boundary of this variable was determined on a trial-specific basis by the onset of movement in the leading transducer coil. Total trial-set duration was measured between these boundary points and divided by the number of swallows in the trial-set (8); the reciprocal of the resulting average swallow duration value provided an estimate of average swallow frequency (in swallows per second). Durational variations between swallows within the trial-set were not captured.

Average Number of Movement Cycles per Swallow

The average number of movement cycles per swallow (in either the vertical or horizontal plane) was calculated as the total number of movement cycles in the trial-set divided by the number of swallows in the trial-set (8).

Cyclic Spatio-Temporal Index (cSTI)

The cSTI was calculated for vertical and horizontal movements of each transducer coil, as previously described. Once again, each data point represented the average value for a trial-set.

Direction-Specific Kinematic Parameters

Three kinematic variables were studied at the level of the individual movement cycle: amplitude, peak velocity, and duration. Using Figure 2 as a reference to illustrate these variables, amplitude would be defined as the magnitude of position change between any contiguous pair of peaks and valleys; a single example is shown in the shaded box for vertical movement of the tongue body (arrow C). Peak velocity would represent the maximum velocity (mm/s) measured within each position change. Movement duration would be measured as the difference (in milliseconds) between onset and offset of the position change; the shaded box in Figure 2 shows and examples for upward and downward movement of the tongue body (arrows A and B, respectively). These variables reflect basic characteristics of individual fleshpoint movement and have previously been used in both kinematic studies of speech and X-ray microbeam studies of swallowing [4], The kinematic analyses were performed separately for each transducer coil (i.e., tongue body and dorsum) and movement direction (i.e., up, down, forward, backward). For each trial-set, a single direction-specific mean value was calculated for each kinematic variable across the individual movement cycles in the trial-set. Additionally, for each kinematic variable, the direction-specific standard deviation for each trial-set was calculated as a measure of within-trial-set variation.

Results

Sip Mass

Descriptive statistics for sip mass are tabulated by item (i.e., liquid) and age cohort in Table 3. As shown in Table 3, the COHORT effect failed to reach statistical significance [$F(1, 6) = 0.01$, $p > 0.05$], and there were no significant interactions. A significant main effect was observed for ITEM [$F(5, 30) = 15.22$, $p = 0.000$, power = 1.0]. *Post-hoc* Tukey–Kramer subtests identified two subgroups of sip mass by item. Significantly smaller sip masses ($M = 5.37 \pm 2.92$ g) were observed for the the three apple-flavored products (thin, nectar-thick, and honey-thick liquid), while larger and more variable sip masses ($M = 10.03 \pm 5.82$ g) were observed for water, chocolate milk, and honey-thick milk products. Although, sip mass was smaller for honey-thick items than for thin-consistency liquids in both the apple-flavored and non-apple-flavored subgroups, this difference failed to achieve statistical significance. Further *post-hoc* analyses were performed on the sip-sizing data to explore differences in sip volume (in cc) across both consistencies and flavor groups. Since the previous analyses had not identified any differences between the nectar- and honey-thick items, these were pooled into a thickened-liquids category for comparison with the thin liquids. This procedure revealed significantly smaller volumes for both the apple-flavored items ($p < 0.001$) and the thickened liquids within each flavor category (honey-thick and nectar-thick combined: $M = 5.16 \pm 2.9$ cc; thin: $M = 9.78 \pm 5.7$ cc; $p < 0.05$).

Table 3. Average sip mass (g), shown by item and age cohort

	Younger Cohort		Older Cohort	
Item	Mean	SD	Mean	SD
Nectar-thick apple juice	5.35	1.81	3.47	1.44
Honey-thick apple juice	5.88	2.30	3.40	1.62
Apple juice	7.53	3.53	6.59	3.97
Honey-thick milk	8.65	5.51	8.97	6.82
Water	9.22	2.85	11.97	7.65
Chocolate Milk	10.20	4.17	11.35	7.75
ANOVA table				
Source term	*df*	*F*-ratio	*P*	Power ($\alpha = 0.05$)
COHORT	1,6	0.01	0.916	0.05
Item[a]	5,30	15.22	0.000*	1.00
Cohort × Item	5,30	1.88	0.127	0.56

[a] Post hoc analyses revealed smaller and less variable sip mass for the three apple-flavored items than for the non-apple-flavored liquids.

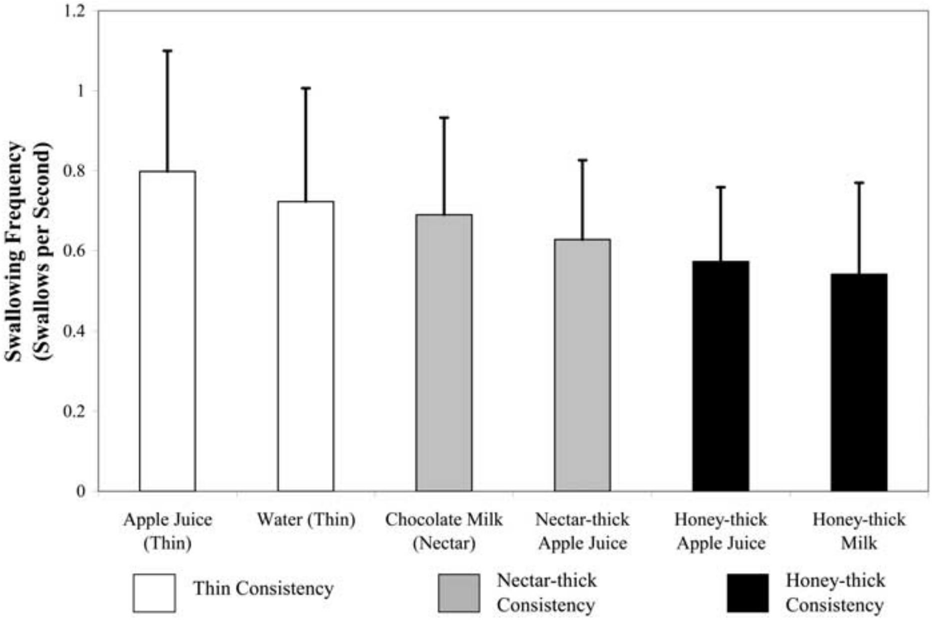

Fig. 3. Means and standard deviations (error bars) for sequential swallowing frequency (swallows per second) by liquid consistency, shown in order of descending frequency.

Swallow Frequency

Significant main effects were observed for both COHORT [$F(1, 7) = 25.83$, $p = 0.001$, power = 0.99], and ITEM [$F(5, 30) = 7.52$, $p < 0.000$, power = 1.0] with respect to swallow frequency. There were no significant COHORT by ITEM interactions. Post-hoc Tukey–kramer comparisons showed that the older subjects had lower swallowing frequencies ($M = 0.48 \pm 0.16$ swallows per second) than the younger subjects ($M = 0.84 \pm 0.19$ swallows per second). Swallowing frequency was also observed to decrease as the liquids became thicker in consistency, as shown in Figure 3. No significant correlations were observed between sip mass and swallowing frequency in either cohort.

Movement Cycles per Swallow

As shown in Figure 4, the older subjects produced a higher number of movement cycles per swallow in the vertical dimension and showed greater variability than the younger subjects in this measure across the six different liquids. The COHORT difference was statistically significant for vertical movements of the body [$F(1, 6) = 17.00$, $p = 0.006$, power = 0.93], but not for vertical movements of the tongue dorsum ($p > 0.01$). In the horizontal plane of movement, this COHORT effect failed to reach the criterion for statistical significance for either transducer coil. Similarly, the analyses failed to identify any notable ITEM effects ($p < 0.01$) for either transducer coil in either orientation, and there were no significant COHORT by ITEM interactions.

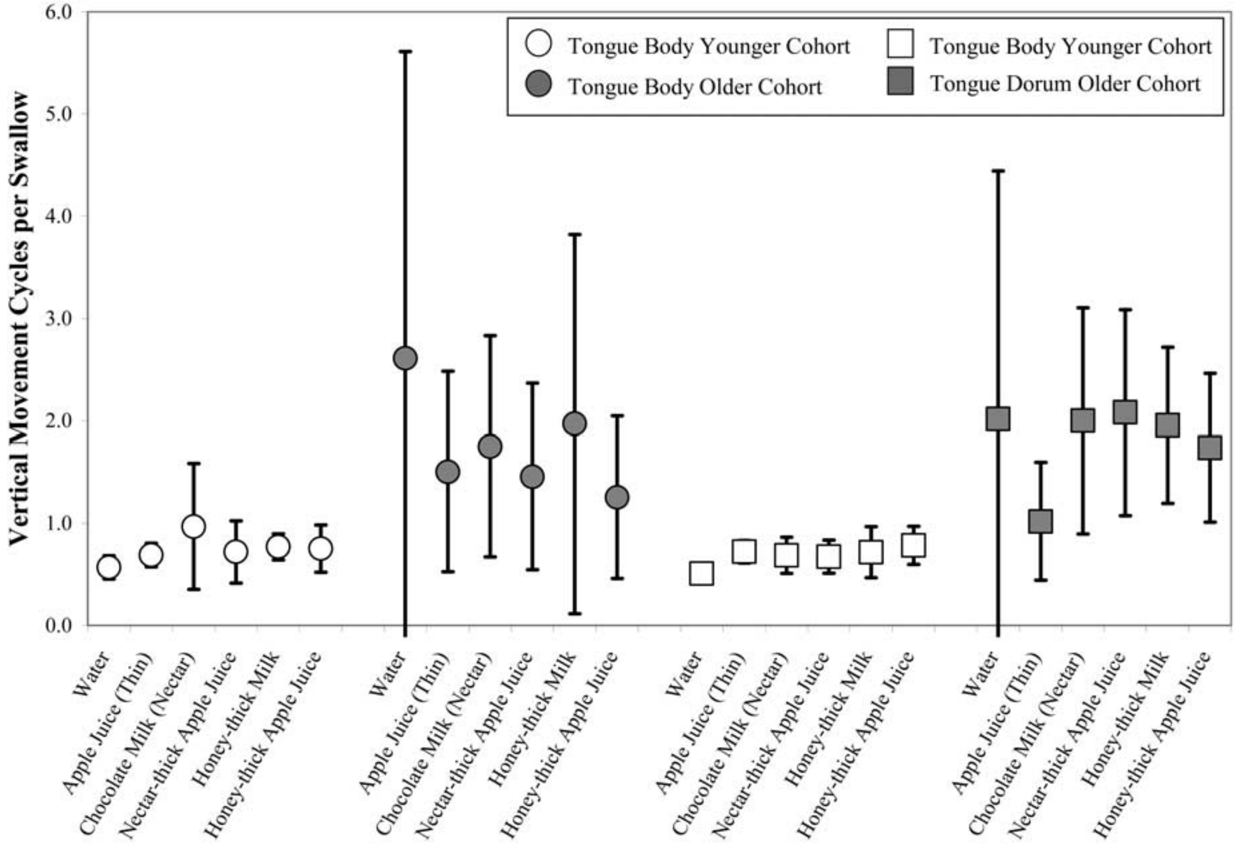

Fig. 4. Means and standard deviations for the number of vertical movement cycles per swallow, for the tongue body and dorsum, during sequential swallows of six different liquids.

Cyclic Spatio-Temporal Index (cSTI)

Significant COHORT effects were found for vertical cSTI of the tongue dorsum [$F(1,6) = 20.11$, $p = 0.004$, power = 0.32]; significantly higher cSTI values for vertical tongue dorsum movement were found in the older cohort ($M = 24.81$) than in the younger cohort ($M = 10.06$). A single significant main effect for ITEM was found for horizontal cSTI in the tongue body [$F(5, 30) = 5.38$, $p = 0.001$, power = 0.65]. *Post-hoc* Tukey–Kramer pairwise comparisons identified significantly higher horizontal tongue body cSTI values for the honey-thick milk ($M = 27.85$) than for the chocolate milk ($M = 16.88$), with values for the other liquids falling between these two points. COHORT by ITEM interactions were not statistically significant.

Kinematics

Tongue Body

The analyses failed to find any notable main effects ($p < 0.01$) of COHORT or ITEM, or any COHORT by ITEM interactions on trial-set mean values of amplitude, peak velocity, or duration of tongue body movement in any direction. The analysis of within-trial variability (SDs) in these parameters revealed a single COHORT trend for the variability of upward movement duration [$F(1, 6) = 18.01$, $p = 0.005$, power = 0.43]. Greater variability in upward tongue body movement durations was seen in the older subjects ($M = 0.306$ s) compared to the younger group ($M = 0.131$ s). The analysis failed to identify any differences in within-trial variability across ITEMs, and there were no COHORT by ITEM interactions.

Tongue Dorsum

Main effects of COHORT failed to reach either the Bonferroni-corrected alpha level of 0.006 or the relaxed criterion of 0.01 with respect to tongue dorsum movement. The analyses also failed to identify statistically significant main effects of ITEM at an alpha level of $p < 0.003$. However, ITEM trends were observed in the domain of within-trial-set variation in downward movement amplitudes [$F(5,$

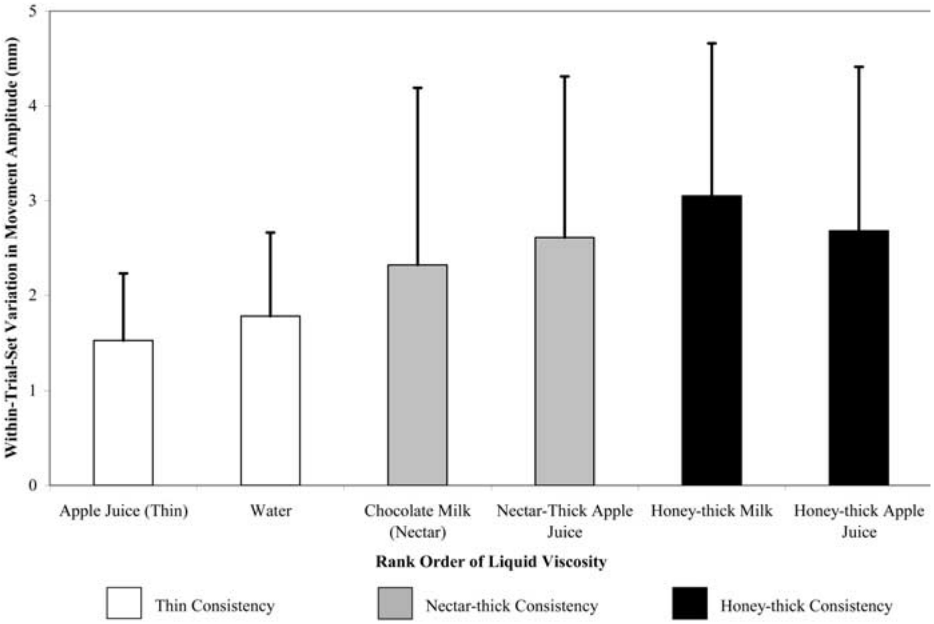

Fig. 5. Means and standard deviations of within-trial-set variation in downward tongue dorsum movement amplitude, shown by liquid in order of ascending viscosity rank.

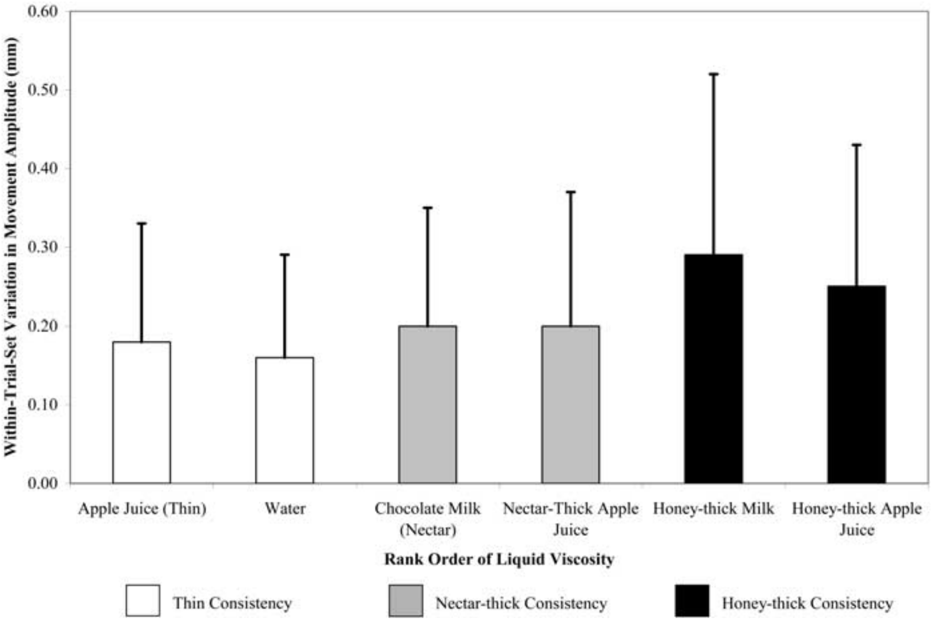

Fig. 6. Means and standard deviations of within-trial-set variation in downward tongue dorsum movement duration, shown by liquid in order of ascending viscosity rank.

30) = 3.72, $p = 0.009$, power = 0.50], and durations [$F(5, 30) = 4.07$, $p = 0.006$, power = 0.56], *Post-hoc* Tukey–Kramer analyses failed to identify significant differences between specific items. Nonetheless, in both instances, the least variability within a trial-set was observed with the thin-liquid items (either water or apple juice) and the greatest variability was observed with the honey-thick items (honey-thick apple juice and honey-thick milk). Thus, the pattern of increasing variability in these parameters corresponds closely to the ascending order of their viscosity, as illustrated in Figures 5 and 6.

Discussion

The present study is the first to provide a detailed analysis of the influence of bolus consistency on lingual kinematics in swallowing. A number of differences were found in swallowing behaviors across the six liquids studied. Specifically, subjects were observed to modulate their sip size during natural, continuous drinking, taking significantly smaller volumes per sip for the apple-flavored liquids, and also for thicker and heavier liquids within both the apple-flavored and the non-apple-flavored liquid subgroups. Second, the frequency of sequential swallowing (swallows per second) decreased with increasing bolus viscosity; this suggests that the more viscous consistencies required more time for the completion of the oropharyngeal transit sequence. Third, a nonsignificant trend toward increased variability in the amplitude and duration of downward tongue dorsum movement was observed with boluses of thicker consistency. Finally, a number of age-related differences were observed in the current analysis. Specifically, older subjects showed a reduced frequency of sequential swallowing (swallows per second) and produced a higher number of vertical tongue movement cycles per swallow. Variability was greater in the older cohort, reflected in both the CSTI and the measures of within-trial-set variability for movement amplitudes and durations.

Evidence of statistically significant bolus consistency influences on kinematic characteristics of tongue movement was limited in the present study. In particular, the predicted effect of an increase in movement duration for boluses with greater flow resistance (i.e., viscosity) was not observed despite the fact that the lower swallowing frequencies observed with these liquids suggested that the overall time required for a liquid to flow from the mouth through the pharynx to the esophagus increased with thicker consistencies. Furthermore, the observed trend toward increased variability in downward tongue dorsum movement with boluses of thicker consistency runs counter to Tasko's proposal that tongue movement variability might decrease with heightened bolus sensory input [52]. Indeed, the present data suggest the possibility that bolus-tailored modulation of swallowing behavior may occur at relatively later points (i.e., during the pharyngeal rather than the oral phase) in the swallow process, despite the traditional classification of pharyngeal events as reflexive. To date, the literature does not help us understand the importance of tongue movement variability in assisting or hindering swallowing efficiency and integrity. This deserves further study both in healthy and disordered subjects, across the lifespan.

The current protocol explored a clinically meaningful range of liquids, spanning the spectrum from thin to honey-thick sippable liquids. In clinical settings, texture modifications within this range are frequently recommended to reduce aspiration risk. The comparative benefits of finer-scale texture modifications (i.e., comparisons between nectar- and honey-thick liquids) are currently the subject of a major clinical trial in the United States. The lack of concrete, quantifiable evidence of bolus consistency–related variations in normal lingual kinematics in the present investigation is in agreement with previous data on hyoid movement [24] and provides justification for further, careful study and scrutiny of the benefits of texture modification in clinical practice.

Sip-Sizing Behaviors

An important difference between the methodology of this study and those of previous investigations was the decision to allow subjects to sip naturally from a cup and self-select their sip size. The eight healthy subjects in this study showed statistically significant downscaling in sip size (both mass and volume) for apple-flavored items compared with the three non-apple-flavored items. Notably, within both the apple-flavored and the non-apple-flavored subgroups, sip volume was lower for the honey-thick-consistency than for the thin-consistency liquids. Thus, it appears that the subjects may have been modifying sip size across liquids of different densities to achieve a preferred and uniform range of bolus mass within flavor groups. Sip-size modulation appears, in and of itself, to be an important characteristic of normal, healthy swallowing.

Aging

The older cohort for this research comprised four healthy individuals, ranging in age from 56 to 66. None of these individuals reported any symptoms of swallowing difficulty, and all were judged to have normal oral motor and swallowing function in a clinical examination. These subjects were considerably younger than the elderly subjects studied by others [53–55]. Recent literature suggests that age-related changes in tongue muscle mass and composition may contribute to reduced functional motor capacity for swallowing [35,56]. The present data are consistent with this suggestion but imply that the senescent changes may be visible in swallowing behaviors as early as the sixth decade of life. Future studies with much larger sample sizes are needed to substantiate this impression. The clinical relevance of the generally increased motor variability observed in the swallowing of the older (yet healthy) subjects in this study remains unclear. It is unknown, for example, whether greater variability emerges naturally as a compensatory feature of swallowing, as lingual pressure-generating capacity decreases with age. Similarly, it is unknown whether changes in swallowing motor variability reflect peripheral or central changes in swallowing neurophysiology. Changes in oral sensory function have also been reported in normal aging [57]; therefore, reductions in oral sensitivity to gradations of bolus consistency may also have contributed to the increased variability of oral swallowing behaviors observed in the older cohort in this research.

Disordered Versus Normal Swallowing

In the present study, subjects were observed to exhibit the least variable lingual behaviors with thin liquids. A reasonable hypothesis resulting from this finding would be that dysphagic individuals who have difficulty managing thin liquids exhibit significantly greater lingual movement variability and are unable to execute patterned lingual movements with the stability of patterning required for safe swallowing of thin liquids. Alternatively, given that greater variability was characteristic of the lingual movements produced by our subjects with thicker consistencies, it might be that individuals who benefit from a restricted variety of diet textures exhibit much less variable and more rigid lingual movement patterning and are therefore unable to make fine-scale modifications of tongue movements to accommodate variations in dietary consistency. In considering potential explanations for the lack of strong findings with respect to bolus consistency influences on healthy oral motor behaviors in swallowing in the present study, one must also entertain the possibility that such influences become evident only in the presence of impaired physiology. Although the healthy, normal subjects in this study failed to show a decrease in the variability of tongue behavior for swallowing with thicker consistencies, it remains unknown whether this finding would be typical of dysphagic individuals.

Limitations

The main limitations of EMMA are that it provides a restricted two-dimensional midsagittal representation of tongue movements and can sample only discrete positions (in this case, 3) on the tongue. As previously mentioned, bolus position cannot be visualized in the EMMA data. Previous authors have concluded that tongue movements for bolus accommodation and propulsion occur primarily along the midsagittal groove of the tongue [58–60]. The EMMA technique, therefore, is considered a suitable method for describing the swallowing movements of the tongue and jaw. Importantly, a previous study has shown that the use of pellet markers (similar to EMMA coils) causes no consistent interference with tongue motions [61].

In this research, measurements of the relative size of the oral articulators and craniofacial structures were not taken across subjects. Thus, it is not possible to comment on possible correlations between the magnitude of oral articulatory movement and skeletal or morphological variations. However, a recently reported analysis of size scaling of oral movement in speech production failed to find significant evidence of a size-amplitude scaling relationship [62]. This evidence suggests that normal variations in craniofacial and oral articulatory size do not pose major concerns for interpretation of the present data.

It is important to remember that the bolus consistency manipulations explored in this article were restricted to an apparent viscosity range of 6–1140 cP at a shear rate of 25 s^{-1}; similarly, a restricted range of densities was studied: 0.99–1.073 g/cc. This restriction was necessary to facilitate a single, natural method of bolus delivery (i.e., continuous sipping from a cup) across all liquid stimuli. However, the range of viscosities studied was narrower than the liquid–paste comparisons reported by others. Nonetheless, the current protocol did include two examples each of thin, nectar-thick, and honey-thick liquids, classified in a manner consistent with the rheological definitions proposed by the American Dietetic Association. These different classes of bolus consistency are broadly assumed to have clinical relevance in the management of swallowing difficulties [63].

Videofluoroscopic swallowing examinations usually involve a broader sampling of bolus consistency than that explored in the current research, (e.g., from thin through nectar- and honey-thick liquids to spoon-thick consistencies and chewable solids). Radiopaque contrast media must be mixed into all assessment items to facilitate visualization under fluoroscopy. It may be that the addition of barium sulfate powders sufficiently alters the rheological values of consistency-class boundaries to yield visible changes in bolus flow on X-ray that are not associated with measurable changes in lingual kinematics.

Summary

In conclusion, this study provides evidence that bolus characteristics have the potential to influence tongue movement amplitudes, durations, and variability during normal, sequential swallowing. However, significant differences in lingual behaviors were not observed among traditional clinical classifications of bolus consistency (e.g., thin, nectar-thick, and honey-thick) [7]. Instead, the observed influence of bolus viscosity and density was limited to the overall duration of oropharyngeal transit (measured here as swallowing frequency) and movement variability in the tongue dorsum. These findings raise questions regarding the prescription of texture modifications according to consistency class for the clinical management of dysphagia. In particular, no evidence was found to support the hypothesis that normal tongue movements become enhanced, either in their spatial or temporal swallowing characteristics, as bolus viscosity surpasses the rheological boundaries proposed to differentiate classes of bolus consistency [7]. Further research is necessary to determine whether individuals with specific physiological profiles of swallowing impairment fail similarly to exhibit measurable differences in tongue behaviors across these proposed consistency boundaries.

References

1. Jones B, Donner MW: Interpreting the study (Chapter 4). In: Jones B, Donner MW (eds.): *Normal and abnormal swallowing: Imaging in diagnosis and therapy*. Springer-Verlag, New York, 1991
2. Logemann JA: *Evaluation and treatment of swallowing disorders*. College Hill Press, Inc, San Diego, CA, 1983
3. Curran J, Groher ME: Development and dissemination of an aspiration risk reduction diet. *Dysphagia 5(1)*:6–12, 1990
4. Martin RE: *A comparison of lingual movement in swallowing and speech production*. Doctoral dissertation, University of Wisconsin–Madison, 1991
5. Pardoe EM: Development of a multistage diet for dysphagia. *J Am Diet Assoc 93(568)*:571.
6. Robbins J, Nicosia MA, Hind JA, Gill GD, Blanco R, Logemann JA: Defining physical properties of fluids for dysphagia evaluation and treatment. Perspectives on Swallowing and Swallowing Disorders (Dysphagia). *Am Speech Lang Hear Assoc Special Interest Div 13 Newslett 11*:16–19, 2002
7. National Dysphagia Diet Task Force: *National Dysphagia Diet: Standardization for Optimal Care*. American Dietetic Association, Chicago IL, 2002
8. Martin RE, Murray GM, Kemppainen P, Masuda Y, Sessle BJ: Functional properties of neurons in the primate tongue primary motor cortex during swallowing. *J Neurophysiol 78(3)*:1516–1530, 1997
9. Jean A: Brain stem control of swallowing: neuronal network and cellular mechanisms. *Physiol Rev 81(2)*:929–969, 2001
10. Sawczuk A, Mosier KM: Neural control of tongue movement with respect to respiration. *Swallowing and Crit Rev Oral Biol Med 12(1)*:18–37, 2001
11. Logemann JA, Pauloski BR, Colangelo L, Lazarus C, Fujiu M, Kahrilas PJ: Effects of a sour bolus on oropharyngeal swallowing measures in patients with neurogenic dysphagia. *J Speech Hear Res 38(3)*:556–563, 1995
12. Pelletier CA, Lawless HT: Effect of citric acid and citric acid–sucrose mixture on swallowing. *Dysphagia 18(4)*:231–241, 2003
13. Smith CH, Logemann JA, Burghardt WR, Carrell TD, Zecker SG: Oral sensory discrimination of fluid viscosity. *Dysphagia 12(2)*:68–73, 1997
14. Bourne MC: Viscosity and consistency. In: Bourne MC (eds.): *Food texture and viscosity: Concept and measurement*. Academic Press, New York, 199–246, 1982
15. Tung MA, Paulson AT: Rheoiogical concepts for probing ingredient interactions in food systems. In: Gaonkar AG (ed.): *Ingredient interactions: Effects on food quality*. New York, Marcel Dekker, Inc., 45–84, 1995
16. Shama F, Sherman P: Identification of stimuli controlling the sensory evaluation of viscosity. *J Texture Stud 4*:111–118, 1973
17. Stevens SS, Guirao M: Scaling of apparent viscosity. *Science* 1157–1158, 1964
18. Wood FW: Psychophysical studies on the consistency of liquid foods In: Wood Fw (eds.): *Society of chemical industry monograph no. 27: Rheology and texture of foodstuffs*. Kent Staples Printers Ltd., Rochester, 40–49, 1968
19. Lazarus C, Logemann JA, Rademaker AW, Kahrilas PJ, Pajak R, Lazar R, Halper A: Effects of bolus volume, viscosity, and repeated swallows in nonstroke subjects and stroke patients. *Arch Phys Med Rehabil 74(10)*:1066–1070, 1993
20. Bisch EM, Logemann JA, Rademaker AW, Kahrilas PJ, Lazarus CL: Pharyngeal effects of bolus volume, viscosity, and temperature in patients with dysphagia resulting from neurologic impairment and in normal subjects. *J Speech Hear Res 37(5)*:1041–1059, 1994
21. Dantas RO, Dodds WJ: Effect of bolus volume and consistency on swallow-induced submental and infrahyoid electromyographic activity. *Braz J Med Biol Res 23(1)*:37–44, 1990
22. Dantas RO, Kern MK, Massey BT, Dodds WJ, Kahrilas PJ, Brasseur JG, Cook IJ, Land IM: Effects of swallowed bolus variables on oral and pharyngeal phases of swallowing. *Am J Physiol 258(5, Pt 1)*:G675–G681, 1990
23. Perlman AL, Vandaele DJ, Otterbacher MS: Quantitative assessment of hyoid bone displacement from video images during swallowing. *J Speech Hear Res 38(3)*:579–585, 1995
24. Chi–Fishman G, Sonies BC: Effects of systematic bolus viscosity and volume changes on hyoid movement kinematics. *Dysphagia 17(4)*:278–287, 2002
25. Cichero JAY, Hay G, Murdoch BE, Halley PJ: Videofluoroscopy fluids versus mealtime fluids: Differences in viscosity and density made clear. *J Med Speech Lang Pathol. 5*:203–215, 1997
26. Steele CM: Kinematics and coordinative dynamics of normal human swallowing. Doctoral dissertation, University of Toronto, 2003
27. Borwankar RP: Food texture and rheology: a tutorial review. *J Food Eng 16*:1–6, 1992
28. Dantas RO, Dodds WJ, Massey BT, Kern MK: The effect of high- vs low-density barium preparations on the quantitative features of swallowing. *AJR Am J Roentgenol 153(6)*:1191–1195, 1989
29. Steele CM, Van Lieshout PHHM: Use of electromagnetic midsagittal articulography in the study of swallowing. *J Speech Lang Hear Res 47*:342–352, 2004
30. Steele CM, Van Lieshout PHHM, Goff HD: The rheology of liquids: A comparison of clinicians' subjective impressions and objective measurement. *Dysphagia 18*:182–195, 2003

31. Reimers–Neils L, Logemann J, Larson C: Viscosity effects on EMG activity in normal swallow. *Dysphagia 9(2):*101–106, 1994
32. Van Lieshout PHHM, Rutjens CAW, Spauwen PHM: The dynamics of interlip coupling in speakers with a repaired unilateral cleft lip history. *J Speech Lang Hear Res 45:*5–19, 2002
33. Nelson WL: Physical principles for economies of skilled movements. *Biol Cybernet 46(2):*135–147, 1983
34. Perkell JS, Zandipour M: Economy of effort in different speaking conditions II. Kinematic performance spaces for cyclical and speech movements. *J Acoust Soc Am 112(4):*1642–1651, 2002
35. Miller JL, Watkin KL: The influence of bolus volume and viscosity on anterior lingual force during the oral stage of swallowing. *Dysphagia 11(2):*117–124, 1996
36. Nicosia MA, Hind JA, Roecker EB, Carnes M, Doyle J, Dengel GA, Robbins J: Age effects on the temporal evolution of isometric and swallowing pressure. *J Gerontol Ser A Biol Sci Med Sci 55 (11):*M634–M640, 2000
37. Pouderoux P, Kahrilas PJ: Deglutitive tongue force modulation by volition, volume, and viscosity in humans. *Gastroenterology 108(5):*1418–1426, 1995
38. Sonies BC, Parent LJ, Morrish K, Baum BJ: Durational aspects of the oral–pharyngeal phase of swallow in normal adults. *Dysphagia 3(1):*1–10, 1988
39. Lof GL, Robbins J: Test–retest variability in normal swallowing. *Dysphagia 4:*236–242, 1990
40. Medical Research Council of Canada, NSERCC, Social Sciences and Humanities Research Council of Canada. *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans*. Ottawa, ON, 1998
41. Hasegawa–Johnson M: Electromagnetic exposure safety of the Carstens articulograph AG100. *J Acoust Soc Am 104:*2529–2532, 1998
42. Li M, Brasseur JG, Kern MK, Dodds WJ: Viscosity measurements of barium sulfate mixtures for use in motility studies of the pharynx and esophagus. *Dysphagia 7(1):*17–30, 1992
43. Schönle PW, Gräbe K, Wenig P, Höhne J, Schrader J, Conrad B: Electromagnetic articulography: Use of alternating magnetic fields for tracking movements of multiple points inside and outside the vocal tract. *Brain Lang (31):*26–35, 1987
44. Hamlet SL, Nelson RJ, Patterson RL: Interpreting the sounds of swallowing: fluid flow through the cricopharyngeus. *Ann Otol Rhinol Larynsol 99(9 Pt 1):*749–752, 1990
45. Perlman AL, Ettema SL, Barkmeier J: Respiratory and acoustic signals associated with bolus passage during swallowing. *Dysphagia 15:*89–94, 2000
46. Cichero JA, Murdoch BE: The physiologic cause of swallowing sounds: answers from heart sounds and vocal tract acoustics. *Dysphagia 13(1):*39–52, 1998
47. Westbury JR: On coordinate systems and the representation of articulatory movements. *J Acoust Sco Am 95:*2271–2273, 1994
48. Van Lieshout PHHM, Moussa W: The assessment of speech motor behaviors using electromagnetic articulography. *Phonetician 81(1):*9–22, 2000
49. Westbury JR: Mandible and hyoid bone movements during speech. *J Speech Hear Res 31:*405–416, 1998
50. Westbury JR, Lindstrom MJ, McClean MD: Tongues and lips without jaws: a comparison of methods for decoupling speech movements. *J Speech Language Hear Res 45:*651–662, 2002
51. Feise RJ: Do multiple outcome measure require p-value adjustment?. *BMC Med Res Methodol 2:*8, 2002
52. Tasko SM, Kent RD, Westbury JR: Variability in tongue movement kinematics during normal liquid swallowing. *Dysphagia 17(2):*126–138, 2002
53. Robbins J, Hamilton JW, Lof GL, Kempster GB: Oropharyngeal swallowing in normal adults of different ages. *Gastroenterology 103(3):*823–829, 1992
54. Rademaker AW, Pauloski BR, Colangelo LA, Logemann JA: Age and volume effects on liquid swallowing function in normal women. *J Speech Lang Hear Res 41(2):*275–284, 1998
55. Logemann JA, Pauloski BR, Rademaker AW, Colangelo LA, Kahrilas PJ, Smith CH: Temporal and biomechanical characteristics of oropharyngeal swallow in younger and older men. *J Speech Lang Hear Res 43(5):*1264–1274, 2000
56. Hind JA, Nicosia MA, Roecker EB, Carnes ML, Robbins J: Comparison of effortful and noneffortful swallows in healthy middle- aged and older adults. *Arch Phys Med Rehabil 82(12):*1661–1665, 2001
57. Chavez EM, Ship JA: Sensory and motor deficits in the elderly: impact on oral health. *J Public Health Dent 60(4):*297–303, 2000
58. Kahrilas PJ, Lin S, Logemann JA, Ergun GA, Facchini F: Deglutitive tongue action: volume accommodation and bolus propulsion. *Gastroenterology 104(1):*152–162, 1993
59. Hamlet SL: Dynamic aspects of lingual propulsive activity in swallowing. *Dysphagia 4(3):*136–145, 1989
60. Hamlet SL, Stone M, Shawker TH: Posterior tongue grooving in deglutition and speech: preliminary observations. *Dysphagia 3(2):*65–68, 1988
61. Weismer G, Bunton K: Influences of pellet markers on speech production behavior: acoustical and perceptual measures. *J Acoust Soc Am 105(5):*2882–2894, 1999
62. Riely RR, Smith A: Speech movements do not scale by orofacial structure size. *J Appl Physiol 94(6):*2119–2126, 2003
63. Hiss SG, Dikeman KJ, Green J, Inman A, Kelchner L, Lazarus C, Miller C, Hasselkus A, Johnson A: *Knowledge and skills needed by speech–language pathologists performing videofluoroscopic swallowing examinations.* (draft). Rockville, MD: American Speech–Language Hearing Association (ASHA) Special Interest Division 13, Swallowing and Swallowing Disorders, 2003