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## Tongue Movements During Water Swallowing in Healthy Young and Older Adults

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**Purpose:** The purpose of this study was to explore the nature and extent of variability in tongue movement during healthy swallowing as a function of aging and gender. In addition, changes were quantified in healthy tongue movements in response to specific differences in the nature of the swallowing task (discrete vs. sequential swallows).

**Method:** Electromagnetic midsagittal articulography (EMMA) was used to study the swallowing-related movements of markers located in midline on the anterior (blade), middle (body), and posterior (dorsum) tongue in a sample of 34 healthy adults in 2 age groups (under vs. over 50 years of age). Participants performed a series of reiterated water swallows, in either a discrete or a sequential manner.

**Results:** This study shows that age-related changes in tongue movements during swallowing are restricted to the domain of movement duration. The authors confirm that different tongue regions can be selectively modulated during swallowing tasks and that both functional and anatomical constraints influence the manner in which tongue movement modulation occurs. Sequential swallowing, in comparison to discrete swallowing, elicits simplification or down-scaling of several kinematic parameters.

**Conclusion:** The data illustrate task-specific stereotyped patterns of tongue movement in swallowing, which are robust to the effects of healthy aging in all aspects other than movement duration.

**KEY WORDS:** tongue, swallowing, kinematics, electromagnetic articulography, aging, dysphagia

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**T**he tongue plays a critical role in swallowing, creating a channel in which the bolus can flow and then generating a rostro-caudal pressure pattern that effectively transports the bolus through the oropharynx and into the esophagus. Questions remain regarding the exact manner in which the tongue moves to achieve this pressure pattern. The tongue is thought to have hydrostatic properties and to be deformable (K. K. Smith & Kier, 1989). The extrinsic muscles of the tongue are thought to govern the position of the tongue within the oropharyngeal cavity, whereas a complex network of intrinsic muscles (oriented in longitudinal, vertical, and transverse directions) supports changes in the shape of the tongue (Napadow, Chen, Wedeen, & Gilbert, 1999; Perrier, Ostry, & Laboissière, 1996; Sanguineti, Laboissière, & Payan, 1997). It is unconfirmed whether and how many functional segments might exist within the tongue with the capacity to act independently in swallowing, although previous data confirm that regional variations in tongue movement exist in swallowing (Steele & Van Lieshout, 2008; Tasko, Kent, &

Westbury, 2002; Wilson & Green, 2006) as well as in speech (Alfonso & Baer, 1982; Honda, 1996; Perrier et al., 1996).

Recent literature suggests that the tongue musculature undergoes morphologic changes with age and that maximum isometric force capacity declines with age in both genders (Bassler, 1987; McComas, 1998; Mortimore, Fiddes, Stephens, & Douglas, 1999). How such changes impact tongue movements, and the extent to which they contribute to functional changes in swallowing, remains unquantified. It is important to characterize tongue movements and their variation in both young and older healthy individuals so that disease-related changes in oropharyngeal swallowing physiology may be properly recognized. Additionally, it is important to determine whether particular swallowing tasks represent relatively greater challenges for the tongue so that age-related differences become more clearly apparent in those circumstances. Although oral motor behaviors in swallowing have traditionally been studied using single *discrete* swallows (Chi-Fishman, Stone, & McCall, 1998; Dodds, Stewart, & Logemann, 1990; Kennedy & Kent, 1988; Miller & Watkin, 1996), Chi-Fishman et al. (1998) have pointed out that natural eating behaviors include both discrete and continuous (or *sequential*) patterns of swallowing (as in cup drinking). Chi-Fishman et al. have proposed that sequential swallowing involves increased motor control demands (for movement sequencing, coordination, and rate accommodation). In the present study, we undertook to perform a detailed analysis of movement for three segments of the tongue (blade, body, dorsum) during water swallows in a sample of 34 healthy adults. We were specifically interested in identifying differences in tongue movement that emerged as a function of participant age, both in discrete water swallowing and under the increased motor control demands of a sequential water swallowing task.

Common instrumental methods for imaging swallowing (i.e., videofluoroscopy or nasoendoscopy) do not allow for the precise tracking of tongue movement. Historically, tongue movement has been traced in one of two ways: either with videofluoroscopy incorporating pellet markers, whose position is then traced on the basis of the recorded sequence of images (Gay, Rendell, & Spiro, 1994; Hiimae & Palmer, 1999, 2003) or with the x-ray microbeam system, which also involves tracking pellets, but at a much higher sampling rate using a computer-guided narrow beam of short-wave radiation (Green & Wang, 2003; Martin, 1991; Tasko et al., 2002; Wilson & Green, 2006). Electropalatography has been used to document contact patterns between the dorsal surface of the tongue and the hard palate (Chi-Fishman & Stone, 1996), but this technique does not allow one to identify the specific portion(s) of the tongue that come into contact with the palate, nor does it capture tongue movements prior to or following palate contact. Ultrasound

has also been used to image the air-tissue contrast that exists along the dorsal surface of the tongue (Peng, Jost-Brinkmann, Miethke, & Lin, 2000; Shawker & Sonies, 1984; Söder & Miller, 2002; Stone & Shawker, 1986) and can, therefore, represent both static and dynamic (up to 30 Hz) representations of overall tongue shape and position, but it has limitations with respect to capturing the finer details of movement, especially of the tongue tip.

In this study, we used electromagnetic midsagittal articulography (EMMA) to trace the position of markers (transducer coils) attached to the midline of the tongue. Advantages of this method include the ability to collect a large amount of data without the biohazards of radiation and without the need for radio-opaque stimuli, and the excellent resolution (both spatial and temporal) of the measurement system (Hasegawa-Johnson, 1998; Tuller, Shao, & Kelso, 1990). Disadvantages of the EMMA method (some of which are shared with other methods) include the inability to view the bolus or movements of structures such as the larynx or hyoid. In the present study, we build on previous work in our lab, where we collected data on swallowing-related tongue movement patterns (body and dorsum) in 8 healthy participants swallowing water and five other stimuli of differing consistency (Steele & Van Lieshout, 2004a, 2004b, 2005, 2008). These preliminary reports suggested that tongue movements may exhibit age-related changes in healthy individuals as young as 50 years.

In order to confidently describe differences in tongue movements for swallowing (e.g., between participants of different ages), it is first necessary to quantify the variation that exists in the healthy population at large. Researchers have suggested in previous studies that there may be considerable variability in both the spatial and temporal characteristics of tongue movement during swallowing (Gay et al., 1994; Tasko et al., 2002). With respect to spatial measures, Gay and colleagues (1994) reported observations of within-participant variability, both in the stability of the starting and ending positions and in the actual trajectories of radiographically traced tongue pellet movement in a sample of 10 healthy young adults. Larger tongue movements (distance) were reported for males compared with females. Tongue marker positions were translated relative to a single fixed midline point on the maxillary central incisors. However, Westbury (1994) argued that artifacts can be introduced into the representation of tongue pellet position (and the resulting measurements of movement trajectory and distance) unless a standardized definition of the *x-y* axis is used, based on the locations of at least two reference markers (one on the maxillary central incisors and one on the maxillary molar teeth), taken during a stable bite posture.

An x-ray microbeam study of 12 healthy adult participants (Tasko et al., 2002), in which the data were rotated and translated according to the procedures recommended

by Westbury (1994), also concluded that considerable variation in pellet movement exists during swallowing (this time across participants), based on an analysis of the position-history of markers during the major palatal approach movement of the tongue. In that study, the standard deviations (*SDs*) of the magnitude (distance) of pellet movement on 10 mL water swallows were in the range of 4 mm. As in the Gay et al. (1994) study, significantly larger movement distances were reported in males compared with females. Such variability in kinematic parameters both within- and across participants is not limited to swallowing, as shown in a study of tongue movements in speech (Alfonso & van Lieshout, 1997). However, more recent studies by Wilson and Green (2006) and those conducted in our lab (Steele & Van Lieshout, 2008) show that variables that pertain to coordinative aspects of tongue control in swallowing may reveal more consistency across participants when compared with individual movement data.

Durational measures of tongue movement were not reported in Gay and colleagues' (1994) study; however, *SDs* in the range of 198 ms (six video frames) were reported in the relative timing of tongue pellet position maxima compared with the onset of hyoid excursion. Whether this observation supports the interpretation that temporal variability exists in tongue movements themselves is questionable. Mendell and Logemann (2007) have recently argued for using upper esophageal sphincter (UES) opening as the preferred temporal reference point in swallowing (rather than hyoid movement onset). Using a relatively large sample of 100 individuals, they reported less variation in event timing than did Gay et al. (1994), with the anticipatory onset of base-of-tongue retraction ranging from 6 ms to 39 ms before UES opening. One possible reason for the reduced temporal variability observed by Mendell and Logemann may be that they used a command-swallow paradigm (Daniels, Schroeder, DeGeorge, Corey, & Rosenbek, 2007). In Tasko et al.'s (2002) x-ray microbeam study, a command-swallow paradigm was also used. The duration (sampled at 80 Hz) of the palatal approach movement of tongue pellets averaged 140 ms–190 ms (depending on the marker location and participant gender), with *SDs* ranging from 22 ms to 60 ms. Male participants were reported to have significantly longer tongue movement durations than females, but this could be directly related to the larger amplitudes of movement observed in male participants in that study.

Questions remain regarding the extent of variability across participants in tongue movement during healthy swallowing and the degree to which systematic modulations can be expected in healthy tongue movements in response to specific manipulations. In particular, the influences of age and gender must be studied in a sample that is sufficiently large to support the detection of

groupwise trends. Task differences must be similarly explored so that we can identify the principle factors governing tongue movement modulation for swallowing. In order to study tongue movement modulation, one must first recognize that tongue movements can be measured and described in different planes or coordinate systems and that the choice of perspective may influence the resulting representation of behavior. It is possible, for example, to examine changes in the position of tongue segments in a two-dimensional space, relative to their starting position (i.e., upward, downward, forward, or backward). However, prior studies suggest that the trajectory of tongue movement in swallowing begins with a rostrally directed movement (i.e., a movement that takes the shape of both upward and forward changes in position, approaching the palate and the front of the mouth; Martin, 1991; Tasko et al., 2002). The degree to which upward or forward position changes dominate this trajectory may differ depending on the tongue segment in question. Similarly, the subsequent caudally directed vector of tongue movements in swallowing has both backward and downward components. It is reasonable to posit that the anatomical configuration of the vocal tract might influence tongue movements in swallowing, such that the dominant axis of modulation for different tongue segments will occur parallel to the axis of movement upon which the anatomy places the least restriction. Similar biomechanical influences have previously been observed on jaw movement variability in speech (Shiller, Laboissière, & Ostry, 2002). The effect of this hypothesized anatomical/biomechanical constraint would be a pattern of tongue movement modulation in which the anterior regions of the tongue display greater movement modulation in the horizontal plane; conversely, the more posterior regions of the tongue (whose starting position is relatively lower, i.e., in the upper pharynx) would display greater movement modulation in the vertical plane.

Flexible motor systems are capable of adjusting to changing task demands (Moore, Smith, & Ringel, 1988; Van Lieshout, 2004) and achieve faster rates of movement through simplification of the motor pattern, and principles of motor economy. In speech, increased rate has been associated with fusing, overlapping, or dropping of motor components (Browman & Goldstein, 1990; Lindblom, 1983; Stetson, 1951). Many authors have reported modifications of movement amplitudes and velocities in the context of increased speaking rate (e.g., Abbs, 1973; Munhall, 1985; Ostry, Cooke, & Munhall, 1987; Ostry & Flanagan, 1989; Perkell & Zandipour, 2002; Perkell, Zandipour, Matthies, & Lane, 2002). The comparative study of motor behaviors for swallowing under different rate conditions is suggested as one means for exposing underlying mechanisms of swallowing motor control. Chi-Fishman and colleagues (1998) observed shortened durations of propulsive tongue movement in

sequential swallowing, with associated reductions in the durations of oropharyngeal bolus transit and hyoid movement. Interestingly, forward peak velocities of the hyoid remained unchanged, suggesting that faster swallowing rates are achieved through a strategy of amplitude down-scaling (Chi-Fishman & Sonies, 2000, 2002; Chi-Fishman et al., 1998). Rate-based differences in the spatial characteristics of tongue movement have not been described.

## The Present Investigation

The present investigation was undertaken to address the various gaps in researchers' understanding of tongue movement and its modulation in swallowing. We studied swallowing-related movements of markers located in midline on the anterior (blade), middle (body), and dorsum (dorsum) of the tongue in healthy participants. We were specifically interested in identifying group-wise differences in tongue movement as a function of participant age and gender and in quantifying task-based modulation in a comparison of discrete-to-sequential water swallows. The primary difference between younger and older participants was expected to take the form of differences in tongue movement variability, based on our previous studies with a much smaller sample (Steele & Van Lieshout, 2004b, 2006). We also expected possible gender differences in tongue movement amplitudes and durations (both longer for males) on the basis of previous data reported by Tasko et al. (2002) and by Gay et al. (1994).

Modulation of tongue movements was expected as a function of swallowing task (i.e., discrete vs. sequential swallowing). Specifically, we expected to see a simplification of the overall movement pattern during sequential swallowing, exhibited in the form of movement amplitude down-scaling, as described previously by Chi-Fishman and Sonies (2000). We hypothesized that tongue movement modulations would be concentrated either in the vertical or in the horizontal plane of movement (parallel with the axis of least anatomical constraint), with anterior tongue segments (blade and body) showing a preference for modulation in the horizontal plane and the tongue dorsum exhibiting modulation primarily in the vertical plane. We expected to see larger movement amplitudes, higher peak velocities, and longer movement durations for horizontally oriented movements of the tongue blade and body and the opposite effect (i.e., vertically oriented movements) for the tongue dorsum.

## Method

### Participants

Data are reported for a sample of 34 healthy adults—15 over the age of 50 (6 men, 9 women) and 19 under the

age of 50 (10 men, 9 women). Fifty years was used as the separation boundary because previous work from our laboratory suggested that aging effects may already be observable at this age (Steele & van Lieshout, 2004a, 2004b, 2005, 2008). A health history questionnaire and brief interview confirmed that none of the participants had a history of speech, swallowing, neurological, or gastrointestinal abnormalities. A clinical swallowing assessment incorporating an oral mechanism examination and swallowing trials with water (Martino, Pron, & Diamant, 2000) confirmed that there were no clinical signs of swallowing difficulty in any of the participants. The research study was approved by the local institutional research ethics board.

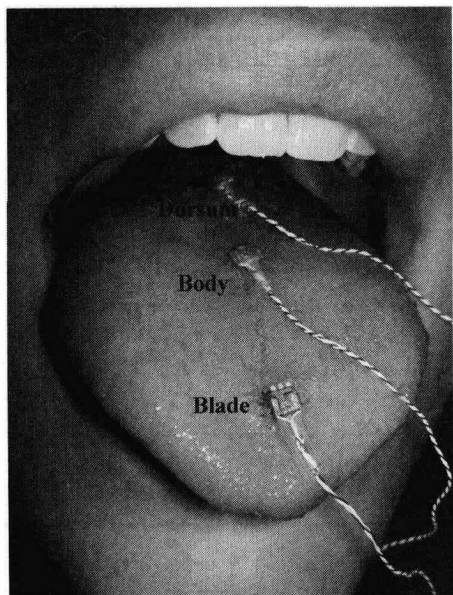
### Procedure

Participants completed a number of swallowing tasks with different stimuli. In the present study, an analysis of water swallows, which is considered to be an appropriate reference point for comparison on other tasks, is reported. Participants were asked to take a cup of water and take six sips at a comfortable rate. This sequence of 6 sips was called a *trial*. Trials were performed in one of two manners: discrete and sequential. Task order was randomized across participants. Results for two trials each of discrete and sequential swallows are reported, representing 24 water swallows per participant. Volume was not controlled but was measured by cup weights before and after each trial; the results showed an average sip volume of 6.5 ml, consistent with our previous reports (Bennett, Van Lieshout, Pelletier, & Steele, 2009).

### Instrumentation and Signal Processing

Tongue movements were measured using a Carstens AG-100 Electromagnetic Midsagittal Articulograph (Carstens Medizintechnik GmbH, Lengler, Germany). In this method, three magnets (located in a helmet suspended around the participant's head) induce a signal in the transducer coils on the tongue, allowing the investigator to trace the location of each tongue coil in a two-dimensional space (Engelke, Engelke, & Schweska, 1990; Schönle et al., 1987). Transducer coils were affixed with surgical methacrylate resin (Cyanodent, Ellman International Mfg.) to three positions (anterior: *blade*, mid: *body*, and posterior: *dorsum*) at approximately 10 mm, 30 mm, and 50 mm behind the tongue tip along the midsagittal groove of the tongue, as in our previous research (see Figure 1; Steele & Van Lieshout, 2004b). According to standardized procedures used in our lab (Van Lieshout & Moussa, 2000), movement signals were band-pass filtered between 0.1 Hz and 6 Hz with a seventh-order Hamming-windowed Butterworth filter. This procedure removes DC drift and higher frequency noise but preserves the main motion components. Next,

**Figure 1.** Transducer coil location. This photo shows the location of three transducer coils along the midsagittal groove of the tongue, representing, respectively, the tongue blade, body, and dorsum.



the data were rotated to reflect movements in a two-dimensional coordinate system aligned with the occlusal plane (determined at the start of each session using a custom-made bite-plane device; Van Lieshout & Moussa, 2000; Westbury, 1991, 1994). Tongue movements were corrected for jaw influences using an estimate of jaw rotation based on the principal component of the mandible coil trajectory (Westbury, Lindstrom, & McClean, 2002). Compared with a simple subtraction method, which ignores jaw rotation, this method reduces positional and speed errors by approximately 65%–70%.

**Dependent variables.** Prior to analysis, the tongue coil movement signals were divided into movement cycles and further subdivided into direction-specific movement segments (Y-plane: upward, downward; X-plane: forward, backward) using an automated algorithm that identifies candidate movement cycle boundaries on the basis of the detection of changes in movement direction in the coil position waveforms. This procedure has been used previously in studies of both speech and swallowing kinematics (Steele & Van Lieshout, 2004a, 2004b; Van Lieshout, Rutjens, & Spauwen, 2002) and uses a measure of cyclic movement consistency known as the *cyclic spatio-temporal index* (cSTI; A. Smith & Goffman, 1998; A. Smith, Goffman, Zelaznik, Ying, & McGillem, 1995; Van Lieshout & Moussa, 2000). To calculate cSTI for the purpose of signal segmentation, candidate movement cycles, defined by positional peaks and valleys in each signal, are amplitude- and time-normalized and aligned with each other. The algorithm then calculates *SDs* across the

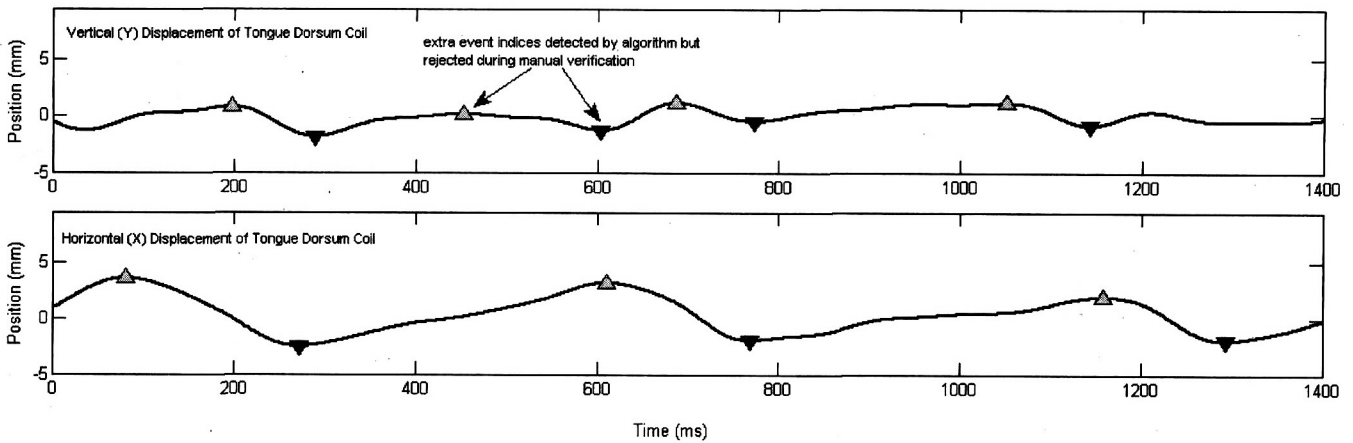
candidate waveform segments at successive 2% intervals in the normalized time window to indicate differences in amplitude between overlapping parts of the normalized candidate cycles. cSTI is then defined as the sum of these *SDs*. This procedure is performed reiteratively across different candidate boundaries, and the solution yielding the smallest cSTI value is selected as the preferred segmentation solution. The event indices proposed by the algorithm were inspected and verified by two trained research assistants (see Figure 2; Van Lieshout & Moussa, 2000). The verification stage allowed the rejection of algorithm-proposed indices that were judged to be inappropriate and also allowed for the insertion of additional index events that were felt to have been omitted by the algorithm.

Following event-index verification, measures of interest were calculated both at the direction-specific movement level (amplitude, peak velocity, and duration) and at the movement cycle level (movement variability, measured using the cSTI, described previously). The cSTI was used as a measure of the stability of motor execution, reflecting consistency in cyclic movement. All computed measures were averaged across the six swallows in each trial prior to statistical analysis.

Interrater agreement for the event-indexing process was assessed in the following way: Ten percent of the trials verified by each of the two raters were reverified by the other rater. The duplicate data set was then compared with matched data from the original data set using a univariate repeated measures analysis of variance (ANOVA) for each of the derived measures (amplitude, peak velocity, duration, and cSTI). This process failed to identify any statistically significant differences between the two data sets (original and duplicate) in the derived measures ( $p = .19$  or higher for all comparisons).

**Statistical analysis.** Mixed design repeated measures ANOVAs were performed on the trial mean value data with between-participant factors of age group (under/over 50) and gender (man/woman) and within-participant factors of coil position (tongue blade, tongue body, tongue dorsum); movement plane (X vs. Y); movement trajectory (rostral, representing forward movements in the X-plane and upward movements in the Y-plane vs. caudal, representing backward movements in the X-plane and downward movements in the Y-plane); task (discrete, sequential); and set (two trials per task). Figure 3 provides a schematic representation of these planes and trajectories of movement, superimposed on a still x-ray image taken in lateral view. In order to adjust for Type I error attributable to multiple comparisons across the four dependent variables, a Bonferroni correction was applied to the alpha-level criterion for statistical significance ( $\alpha = .05/4 = .013$ ; Feise, 2002; Stevens, 2002). Effect sizes are reported using the Cohen's *d* statistic; values of 0.2 or less can be considered to show weak effect size, values

**Figure 2.** Event indexing. In this figure, a vertical position trace of a transducer coil positioned in midline on the tongue dorsum is shown over an 8-s time window. This segment contains four movement cycles associated with four sequential water swallows. Candidate movement peaks selected by an automated segmentation algorithm are shown by upward-pointing, gray-shaded triangles. Similarly, candidate movement valleys selected by the algorithm are shown by downward-pointing, black-shaded triangles. The stars indicate position maxima and minima that were detected by the automated segmentation algorithm as candidate boundaries for a movement cycle but that were rejected through subsequent manual verification.



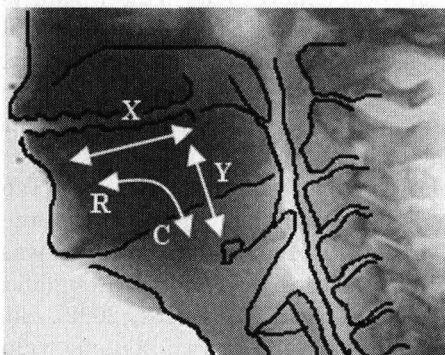
0.3–0.5 are considered moderate, whereas values of 0.6 or greater constitute strong effect (Kotrlík & Williams, 2003). There were no significant main effects or interactions for set; set was therefore removed from the model.

## Results

### Descriptive Statistics and Coil-Position Differences

Table 1 provides descriptive statistics for kinematics of tongue coil movement in discrete water swallows,

**Figure 3.** Schematic representation of coil movement planes and trajectories. In this schematic image, superimposed on a lateral plane static x-ray view of the head and neck, the horizontal and vertical movement planes (X and Y) are shown, rotated according to the occlusal plane. The arrow marked R-C illustrates rostral and caudal trajectories of movement, respectively.



summarized by coil position, movement trajectory, (rostral-caudal), and movement plane (X–Y) for the younger and older participants. Movement amplitudes were smallest for the tongue blade coil (4 mm–7 mm) and largest for the tongue dorsum coil (7 mm–11 mm), with movements of the tongue body coil falling in between (7 mm–9 mm), as illustrated in Figure 4. We observed a significant main effect of coil position,  $F(2, 63) = 46.238, p = .000$ , with the tongue dorsum showing significantly larger amplitudes than tongue body ( $d = 0.45$ ) and blade ( $d = 0.92$ ), and tongue body showing significantly larger amplitudes than tongue blade ( $d = 0.47$ ). This main effect was further qualified by a statistically significant two-way Coil Position  $\times$  Plane interaction,  $F(2, 63) = 46.238, p = .000$ , with horizontal movements of the tongue blade being of larger amplitude than vertically oriented movements of the same coil ( $d = 0.52$ ), but with the opposite pattern seen for the tongue dorsum coil ( $d = 0.38$ ). Movements of the tongue body coil were of approximately equivalent amplitude in both the vertical and horizontal movement planes. These findings are consistent with our hypothesis regarding the constraints that anatomy might impose on the principal axis of movement modulation for the different segments of the tongue.

Peak velocities were scaled similarly to movement amplitudes across the three transducer coil positions, with the highest values seen for the tongue dorsum, lowest values for the tongue blade, and intermediate values for the tongue body,  $F(2, 63) = 61.365, p = .000, d = 0.46$ – $0.52$ , for adjacent pairwise comparisons.

Movement durations also differed significantly across the three coils,  $F(2, 63) = 15.054, p = .000$ , with the longest



Table 1. Descriptive statistics.

Age group	Movement trajectory	Movement plane	Coil position	Amplitude (mm)		Peak velocity (mm/s)		Duration (s)	
				M	SD	M	SD	M	SD
Younger	Caudal	X	Blade	7.04	2.78	24.06	10.51	1.58	0.67
			Body	8.17	4.20	25.34	9.02	1.52	0.59
			Dorsum	9.66	4.65	38.15	17.57	1.27	0.44
	Caudal	Y	Blade	4.97	2.20	18.76	6.73	1.18	0.43
			Body	8.49	3.51	31.67	16.06	1.27	0.64
			Dorsum	11.33	3.97	42.47	15.73	1.25	0.44
	Rostral	X	Blade	7.05	2.92	25.17	10.86	1.35	0.49
			Body	5.08	2.06	20.33	8.76	1.28	0.50
			Dorsum	8.73	4.54	29.99	15.31	1.11	0.56
	Rostral	Y	Blade	8.41	3.62	36.01	19.02	1.04	0.36
			Body	9.84	4.32	34.29	14.37	1.16	0.49
			Dorsum	11.32	4.03	53.02	24.49	1.07	0.43
Older	Caudal	X	Blade	6.95	3.70	25.87	14.09	1.56	0.43
			Body	8.20	3.42	25.20	12.42	1.65	0.56
			Dorsum	8.78	4.50	26.05	12.49	1.40	0.41
	Caudal	Y	Blade	5.54	2.40	18.36	7.72	1.34	0.57
			Body	8.29	2.38	32.34	10.57	1.42	0.60
			Dorsum	10.71	4.31	40.25	18.29	1.27	0.51
	Rostral	X	Blade	6.92	3.67	26.06	12.99	1.26	0.54
			Body	5.45	2.46	20.75	10.19	1.71	0.68
			Dorsum	8.49	3.92	26.62	10.94	1.18	0.43
	Rostral	Y	Blade	8.25	2.46	33.61	13.65	1.49	0.54
			Body	8.71	4.53	30.83	18.55	1.34	0.54
			Dorsum	10.37	4.63	40.76	19.29	1.27	0.46

durations recorded for the tongue blade ( $M = 1.26$  s), followed by the tongue body ( $M = 1.15$  s;  $d = 0.20$  vs. tongue blade), and yet shorter durations for the tongue dorsum ( $M = 1.09$  s;  $d = 0.32$  and  $0.11$  vs. tongue blade and body, respectively). These coil differences were further qualified by a significant three-way Coil  $\times$  Trajectory  $\times$  Plane interaction,  $F(2, 63) = 6.323$ ,  $p = .003$ , whereby forward and downward movements of the tongue blade were longer in duration than upward ( $d = 0.27$ ) or backward ( $d = 0.47$ ) movements, whereas caudally oriented movements (i.e., backward and downward) had longer durations than rostrally oriented movements for both the tongue body ( $d = 0.43$ ) and the tongue dorsum coils ( $d = 0.21$ ).

We report descriptive statistics in Table 2 for tongue movement variability, as measured by the cSTI, by coil position and participant age group for discrete water swallows. No statistically significant differences were noted across coils or as a function of movement trajectory or plane.

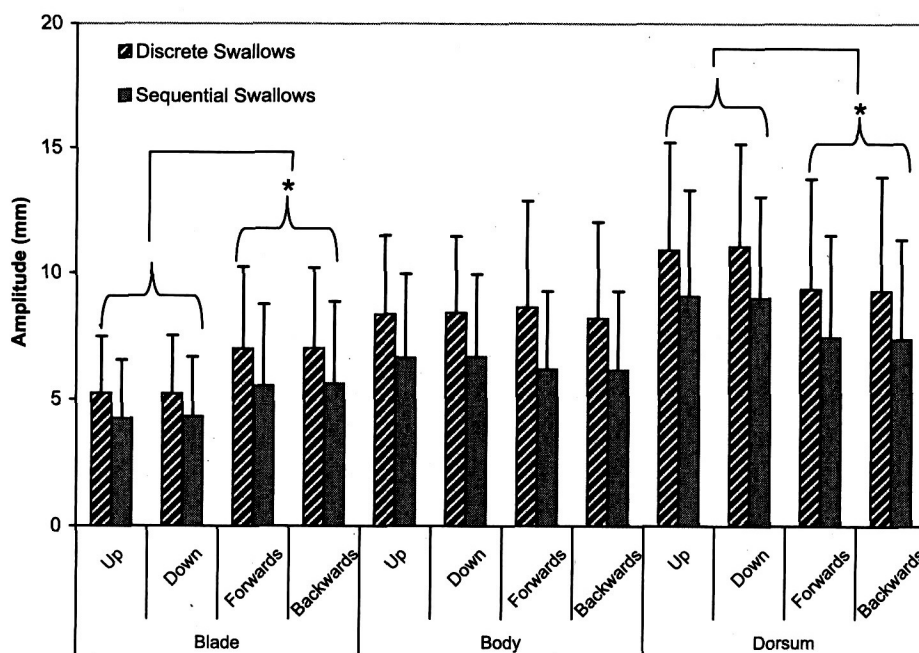
### Age and Gender Effects

Statistically significant main effects of age group were restricted to measures of movement duration, with longer durations observed in the older participants. Movement amplitudes were not influenced by participant age group,

$F(1, 64) = 0.224$ ,  $p = .637$ , or gender,  $F(1, 64) = 0.794$ ,  $p = .376$ . For peak velocity, we observed a statistically significant four-way Coil Position  $\times$  Plane  $\times$  Trajectory  $\times$  Age Group interaction,  $F(2, 63) = 10.998$ ,  $p = .000$ , such that peak velocities were generally higher for rostrally oriented movements than for caudal movements ( $d = 0.15$ ), peak velocity differences between the coil positions were greater in the vertical movement plane ( $d = 0.24$ ), and younger participants had higher peak velocities in general than older participants ( $d = 0.21$ ; see Table 1). Contrary to our predictions, there was no main effect of age group in the cSTI data (reflecting tongue movement variability). Furthermore, unlike the data reported by Tasko et al. (2002), our data failed to exhibit any statistically significant differences between male and female participants for any variable.

In view of the fact that the division of participants into two broad age groups (defined by a single boundary at 50 years of age) had the potential to mask age-related differences at the more extreme ends of the age distribution, we performed a post hoc analysis, comparing the 10 participants with the youngest ages (ranging from 19 to 25 years of age;  $M = 20.8$ ) with the 10 participants who were of the oldest ages in the sample (ranging from 56 to 73 years of age;  $M = 63.8$ ). Once again, we performed repeated measures ANOVAs, with the same within- and

**Figure 4.** Movement amplitudes for transducer coils located on the tongue blade, body, and dorsum during water swallowing. This figure shows mean values (plus standard deviation error bars) for movement amplitude for each transducer coil by direction, pooled across the entire participant sample. Significantly larger movement amplitudes are shown for horizontally oriented movements (compared with vertically oriented movements) of the tongue blade, highlighted by the bracketed comparison on the left-hand side of the graph. The opposite pattern of significantly larger movements in the vertical plane is seen for the tongue dorsum (highlighted by the bracket on the right-hand side of the graph). A consistent pattern of movement amplitude downscaling is noticed for all transducer coils in the sequential swallowing condition compared with discrete swallows. \*Statistical significance at  $p \leq .013$ .



between-participant factors used in the main analysis. However, given that the new subsamples were not perfectly gender balanced, we omitted gender from the model. The post hoc analysis failed to identify any statistically significant main effects or interactions involving the age group factor (youngest 10 vs. oldest 10) for movement amplitude, peak velocity, or variability (cSTI) of the three tongue coil positions. As with the main analysis, the post hoc analysis identified statistically significant differences as a function of age group in movement duration,  $F(1, 36) = 13.240, p = .001$ . Once again, this took the form

of longer movement durations in the older participants ( $d = 0.39$ ).

The hypothesis that a strategy of movement amplitude down-scaling would be observed in the sequential swallowing condition compared with discrete swallowing was confirmed,  $F(1, 64) = 42.785, p = .000, d = 0.43$ . Additionally, however, significant main effects of task were seen in both peak velocity,  $F(1, 64) = 18.505, p = .000, d = 0.22$ , and movement duration,  $F(1, 64) = 109.163, p = .000, d = 0.62$ , with higher peak velocities and longer movement durations seen in the discrete-swallowing condition. Furthermore, movement variability, as captured by the cSTI, was significantly greater in the discrete condition than in sequential swallowing and displayed a significant three-way Plane  $\times$  Task  $\times$  Age Group interaction,  $F(1, 64) = 9.677, p = .003$ , with greater reductions in movement variability during sequential swallowing ( $d = 0.28$ ) concentrated in the vertical plane for younger participants ( $d = 0.45$ ) and in the horizontal plane for the older participants ( $d = 0.09$ ).

Movement durations showed a statistically significant three-way Coil Position  $\times$  Trajectory  $\times$  Plane interaction,  $F(2, 63) = 6.323, p = .003$ , as well as a significant

**Table 2.** Descriptive statistics for the cyclic spatio-temporal Index (cSTI).

Coil position	Age group	M	SD
Blade	Younger	23.10	9.51
	Older	24.94	8.31
Body	Younger	27.18	7.41
	Older	24.41	8.42
Dorsum	Younger	26.21	7.86
	Older	24.52	8.14



three-way Plane  $\times$  Task  $\times$  Age Group interaction,  $F(1, 64) = 10.477$ ,  $p = .002$ . These influences took the pattern of longer movement durations in discrete swallows than sequential swallows ( $d = 0.62$ ), longer movement durations in older participants compared with younger participants ( $d = 0.28$ ), and longer horizontal movement durations for caudal versus rostral movements of the anterior tongue segments in the discrete-swallowing condition ( $d = 0.48$  for the tongue blade;  $d = 0.82$  for the tongue body). In the sequential condition, the older participants continued to exhibit prolonged durations of horizontal movement for caudally directed movements of the anterior tongue, whereas this modulation disappeared in the younger participants.

## Discussion

These data constitute the largest database to date regarding tongue movements in healthy swallowing across different age groups. Although it cannot be determined with certainty how many functional segments might exist within the tongue, the findings support the notion of functional specification for different regions of the tongue, including selective modulation during swallowing tasks (see also Tasko et al., 2002; Wilson & Green, 2006). The regional anatomy appears to place constraints on the manner in which tongue movement amplitude modulation occurs, such that more anterior portions of the tongue have a tendency to vary horizontal movement distance preferentially, whereas differences in posterior tongue movement are primarily appreciated in the vertical plane. Modulation of peak velocity was governed both by anatomy and by the functional direction or trajectory of tongue movement, with higher peak velocities observed for rostrally oriented movements than for caudal movements. Similarly, a combination of both anatomical and functional (trajectory) influences was seen on tongue movement durations.

One purpose of this study was to determine how tongue movements vary between healthy younger and older participants (under vs. over 50 years of age). The data do provide evidence of changes in tongue movements for swallowing between these two age groups; however, such differences were restricted to the domain of movement duration, with slower movements observed in the older participants. This finding was echoed in the lower peak velocities found in the older participant group. This phenomenon is entirely consistent with similar reports in the aging literature, regarding changes in temporal aspects of motor execution (Morgan et al., 1994), and the speech literature, in which durational changes in older participants have been associated with a speed-accuracy trade-off (Goozee, Stephenson, Murdoch, Darnell, & Lapointe, 2005; Parnell & Amerman, 1996). What is

perhaps more important about the present data set is that it identifies an absence of age-related changes in tongue movement amplitudes and variability in healthy individuals. Similarly, the influence of age group differences on peak velocity was only observed in the context of a four-way interaction. It must, of course, be recognized that the upper age limit explored in this study was 73 years of age, and the results do not preclude the possibility that additional changes may emerge with further advances in age in healthy seniors. However, the post hoc analysis did not find evidence to suggest that the age group boundary of 50 used in the main analysis was obscuring age-related differences between participants at the more extreme ends of the age continuum in this sample.

Tongue movements show considerable modulation between discrete and sequential swallowing, with evidence of simplification or down-scaling in several parameters (amplitude, peak velocity, duration, and variability) as swallowing frequency becomes faster. This phenomenon is consistent with previous reports of frequency-based changes in motor control both in the swallowing literature (Chi-Fishman & Sonies, 2000, 2002) and in the broader literature on human motor control (Adams, Weismer, & Kent, 1993; Kelso, 1977; Latash, Scholz, & Schöner, 2002).

Previous authors have been impressed by the degree of variability observed across participants in tongue and oral articulatory movements during swallowing tasks collected as single tokens (Gay et al., 1994; Tasko et al., 2002). Our data, collected from a larger participant pool and using an experimental paradigm involving reiterated swallows, provides evidence that tongue movements in swallowing can, in fact, adhere closely to a stereotypical pattern. The cSTI is a good measure for demonstrating this fact because it reflects consistency across repeated movement cycles, which should be a hallmark characteristic of stereotypical movement patterns. Spatio-temporal index values for lip kinematics across productions of the complete speech phrase "Buy Bobby a Puppy" at a normal speech rate have previously been reported to range from 13 to 21 (A. Smith et al., 1995). Lower values (i.e., less variable movements) of 8–11 have been reported for cSTI of upper and lower lip movement cycles in the reiterated speech tasks "api" and "ipa" (Steele & Van Lieshout, 2002; Van Lieshout et al., 2002). A recent study on tongue and lip movement data in 6 control speakers (males and females) for three different speech tasks (ipa, api, pataka) reported cSTI values ranging between 6 and 12 for tongue body movements, comparable to the lip data for the same tasks (Van Lieshout, Bose, Square, & Steele, 2007). Normative values for the cSTI have not previously been reported for tongue movements in swallowing. In the present study, cSTI values for tongue movements in swallowing fell in the range of 21–26. This

suggests that tongue movements in swallowing are more variable than lip and tongue movements during speech. Of importance is that we observed a reduction in tongue movement variability as measured by the cSTI in the sequential swallowing task compared with the discrete task, which suggests that this measure may indeed be a useful index of motor control for future swallowing research. In the present data set, cSTI was not sensitive to the influence of healthy aging, and it remains to be determined whether patients with disease-related changes in swallowing display differences in tongue movement variability as measured by the cSTI. Recent data from our lab comparing water swallows and speech tasks also failed to show significant differences between healthy older and younger participants with respect to tongue movement variability in either speech or sequential swallows (Bennett, van Lieshout, & Steele, 2007). This confirms that both types of tasks are fairly robust against changes induced by aging at the muscular and neurological levels of motor control (Bennett et al., 2007; Caruso, Mueller, & Shadden, 1995).

Our data also fail to show any differences between male and female participants, in contrast to the study by Tasko et al. (2002). The reason for this discrepancy is unknown, but it questions the idea put forward by Tasko et al. that gender differences may be related to differences in vocal tract size and/or facial morphology in general. Our male and female participants most certainly would have differed in this respect, too, but this was not reflected in kinematic effects. It is possible that procedural differences may play a role, as Tasko et al. used a paradigm in which participants had to hold the bolus until they were told to swallow, whereas in our study, participants used a more natural drinking mode. Perhaps in the context of a command-swallow paradigm, as used by Tasko and colleagues, female participants behave differently than male participants, but there is no obvious reason why this would be the case. It is also possible that their gender effects were based on idiosyncratic differences given their smaller sample size.

Future studies will have to provide more clarity on these issues.

The present study does have important limitations that need to be recognized. First, the EMMA technology cannot directly relate tongue movements to bolus control, as the bolus is invisible. It is possible to infer from our movement data that the pattern that is shown makes sense in the way tongue motion propels the bolus from the front cavity to the pharyngeal cavity using differential contributions of ventral and dorsal parts of the tongue. For example, it can be speculated that horizontal tongue motions in the front may provide an effective squeezing force, whereas vertical motions of the dorsal parts may facilitate a vacuum or a negative pressure zone downstream from the bolus, such as that described in infant nutritive sucking (see, e.g., Geddes, Kent, Mitoulas, & Hartmann, 2008; Tamura, Horikawa, & Yoshida, 1996). However, further studies using combined technologies (to the extent that this is possible) will be needed to confirm the relationship between tongue movement events and bolus transport or pharyngeal swallowing events.

A second limitation is in the restriction on water swallows, as tongue control is influenced by physical characteristics of the bolus (e.g., Steele & van Lieshout, 2004a, 2005). This issue will be addressed in future articles. Finally, like other studies in this area in which point-tracking devices like EMMA or microbeam are used (Tasko et al., 2002; Wilson & Green, 2006), our data are limited to tongue positions anterior to the tongue root. Other technologies such as ultrasound (Peng et al., 2000; Shawker & Sonies, 1984; Stone & Shawker, 1986) would be more suitable to monitor movements in that area.

Table 3 summarizes the statistically significant patterns of task- and age group differences observed across the different manipulations in this study, which is the most comprehensive description to date of systematic modulations in movement of the tongue blade, body, and dorsum during swallowing in both young and older adults of both genders. Contrary to previous reports, in which

**Table 3.** Sensitivity of tongue movements to different influences during swallowing.

Movement	Articulator (blade vs. body vs. dorsum)	Dimension (vertical vs. horizontal)	Direction (rostral vs. caudal)	Age group (under 50 vs. over 50)	Task (discrete vs. sequential)
Amplitude	✓				✓
Peak velocity	✓	✓	✓		✓
Movement duration	✓		✓	✓	✓
Movement variability (cSTI)					✓

Note. The check marks indicate where statistically significant patterns of variation in tongue movement parameters (rows) were observed according to the factors explored in the study (columns). Empty cells represent situations in which no statistically significant variations in tongue movement parameters were observed as a function of the factors shown.

small sample sizes have limited the extent to which group trends can be appreciated, the present data illustrate highly stereotyped patterns of tongue movement during swallowing, which are robust to the effects of aging in healthy individuals in all aspects other than movement duration. Gender differences were not identified, in contrast to previous studies. These data can serve as reference data for the future study of the effects of disease on tongue function in swallowing, and data provide a basis upon which suspicion of changes attributable to disease could be made with greater confidence. Future studies in different populations will serve to confirm the sensitivity of kinematic tongue movement parameters to disease-related changes.

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