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Dysphagia

Coordinative Organization of Lingual Propulsion during the Normal Adult Swallow

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Abstract. Lingual propulsion during swallowing is characterized by the sequential elevation of the anterior, middle, and dorsal regions of the tongue. Although lingual discoordination underlies many swallowing disorders, the coordinative organization of lingual propulsion during the typical and disordered swallow is poorly understood. The purpose of this investigation was to quantitatively describe the coordinative organization of lingual propulsion during the normal adult swallow. Tongue movement data were obtained from the X-Ray Microbeam Database at the University of Wisconsin. Movement of four pellets placed on specific tongue regions were tracked in 36 healthy adult participants while they swallowed 10 cc of water across five discrete trials. The propulsive action of the tongue during bolus transport was quantified using a cross-correlation analysis. Lingual transit time (LTT), which was defined as the interval (lag time) between the movements of the anterior- and posterior-most tongue regions, was determined to be approximately 168 ms. The average time interval (lag) between the movements of the posterior tongue regions was significantly shorter than the intervals between more anterior tongue regions. The results also suggest that during bolus transport movement patterns of the anterior tongue regions are distinct from those of the posterior tongue regions. Future work is needed to determine if the absence of the observed coordinative organization of lingual propulsion is indicative of oral stage dysphagia.

Key words: Tongue — Swallowing — Coordination — Kinematics — Dysphagia — Deglutition — Deglutition disorders.

Although lingual discoordination underlies many swallowing disorders, lingual coordination during the typical and disordered swallow is poorly understood. Because a majority of the existing empirical investigations on swallowing have studied more global aspects of swallowing performance, such as the time course of bolus transport, there is a paucity of data describing the action of the tongue during bolus transport. Several examples of the timing variables used to characterize swallowing performance are summarized in Table 1 [1–7]. Comprehensive quantitative descriptions of the coordinative organization of lingual propulsion in neurologically intact individuals are needed for (1) understanding tongue behavior for lingual propulsion and for (2) identifying and gauging the degree of deficit in neuromotor impairments of swallowing.

The development of quantitative measures of tongue performance during swallowing has been challenged by the inaccessibility of the tongue and the complexity of its architecture and function. The tongue exhibits a remarkable degree of behavioral flexibility during swallowing. The absence of a skeletal structure makes the tongue highly deformable. Shape changes are achieved by displacing the tongue's incompressible volume through contractions of a highly defined intrinsic muscular network [8]. Kier and Smith [9] classify this type of a movement system as a muscular hydrostat.

During the normal adult swallow, food is masticated and formed into a cohesive bolus. The

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Table 1. Examples of various timing variables used to characterize swallowing performance

Author and Method	Definition
Cleall (1965) Cinefluorography	*Subjects:* 28 adolescents (14 female, 14 male) with an average age of 15.6 years *Timing Measure:* the average swallow timing from "tongue-tip elevation" (p. 569) (stage 2) to "dorsum movement reaching junction of hard and soft palates" (p. 569) (stage 3) *Consistency:* "saliva-clearance swallows" (p. 568) ***Average Timing:*** *230 ms*
Shawker et al. (1984) Ultrasound	*Subjects:* 10 typical subjects (6 female, 4 male) with an average age of 24.8 years *Timing Measure:* several stages of swallow event timing. Below is the average timing for the duration between Event 1 (bolus begins to move from anterior tongue) and Event 2 (bolus reaches posterior tongue and moves into pharynx) *Consistency:* 5 cc H_2O bolus ***Average Timing:*** *370 ± 180 ms*
Stone and Shawker (1986) Single Point Parameterization Ultrasound	*Subjects:* 6 female subjects ranging in age from 20 to 40 years *Timing Measure:* four distinct stages of tongue movement during swallowing *Consistency:* 20 cc of H_2O ***Average Timing:*** *1. forward stage ranged from approximately 200–300 ms* *2. upward stage ranged from approximately 100–250 ms* *3. steady stage ranged from approximately 400–1000 ms* *4. downward stage ranged from approximately 100–250 ms*
Shaker et al. (1988) Oral Manometry and Videoradiography	*Subjects:* 5 male subjects with an average age of 30 years (range: 20–37 years) *Timing Measure:* the duration of tongue pressure during swallowing from tongue tip (T1) to tongue dorsum (T2) across 6 consistencies ***Average Timing across consistencies:*** Dry (0 ml): *230 ± 30 ms;* 2 ml H_2O: *210 ± 30 ms;* 5 ml H_2O: *230 ± 40 ms* 10 ml H_2O: *250 ± 30 ms;* 20 ml H_2O: *230 ± 30 ms;* Semisolid (5 ml): *330 ± 30 ms*
Martin (1991) X-Ray Microbeam System	*Subjects:* 6 subjects (5 females, 1 male) ranging in age from 19 to 31 years *Timing Measure:* four distinct "legs" of tongue movement during swallowing. Listed below are the average durations of tongue dorsum movement for each leg. *Consistencies:* 2 cc of H_2O; 10 cc of H_2O ***Average Timing:*** *2 cc* *10cc* Leg 1: *409.97 ms* *446.65 ms* Leg 2: *308.20 ms* *440.32 ms* Leg 3: *214.22 ms* *197.33 ms* Leg 4: *393.83 ms* *380.72 ms*
Chi-Fishman and Stone (1996) Electropalatography (EPG)	*Subjects:* 5 subjects (3 females, 2 males) ranging in age from 23 to 47 years *Timing Measure:* four distinct stages of tongue movement during swallowing *Consistencies:* 5 ml of H_2O; 30 ml of H_2O; 5 ml of gelatin; 30 ml of gelatin; dry swallow ***Average Timing:*** *I (Prepropulsion Stage): 251 ± 209 ms* *II (Propulsion Stage): 320 ± 159 ms* *III (Full contact Stage): 585 ± 258 ms* *IV (Withdrawal Stage): 289 ± 151 ms*
Klahn and Perlman (1999) Respirodeglutometer	*Subjects:* 12 college students (6 females, 6 males) *Timing Measure:* the swallow respiration cycle which was defined as the period of time from the "onset of the respiratory phase immediately preceding the swallow" to the "offset of the respiratory phase following the swallow" (p. 132) *Consistencies:* 5 ml of applesauce and 5 ml H_2O ***Average Timing:*** *3610 ± 710 ms*

propulsive action of the tongue subsequently drives the bolus posteriorly into the pharynx [10, 11]. Lingual propulsion requires a significant degree of coordination and functional independence among biomechanically coupled regions of the tongue and is characterized by the sequential elevation of the anterior, middle, and dorsal regions of the tongue, respectively [12, 13, p. 27]. Several investigators have divided the tongue into functionally distinct regions based on observations of lingual movement patterns during speech and swallowing [14]. One important step toward understanding the coordinative organization of lingual propulsion will be to determine the spatial and temporal requirements of different tongue regions for effective bolus transport.

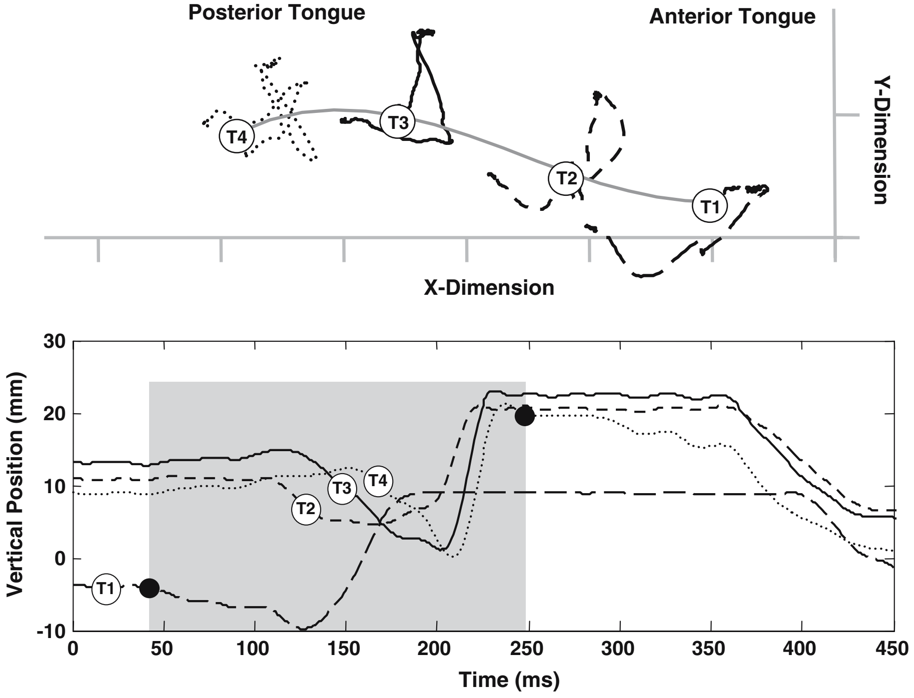

Fig. 1. (Top Panel) Example of the tongue pellet movement trajectories during a single swallow trial plotted in a two-dimensional coordinate system. (*Note*: only vertical movement data were analyzed in this investigation.) **(Bottom Panel)** Extracted vertical time histories for each pellet during a single swallow trial. The movement peak for each pellet indicates the timing at the point of maximum constriction when the tongue approximates the palate. Zero crossings in the velocity trace associated with the onset of T1 movement and offset of T4 movement are denoted as filled circles. All pellet movement data between the zero-crossings markers (shaded region) were analyzed for each swallow trial. The vertical position is referenced relative the maxillary occlusal plane as described in the Methods section.

In the present investigation, a time-series analysis was used to derive two indexes of coordination among the tongue tip, blade, and dorsum during lingual propulsion; one index provided a measure of the similarity among movement traces from these regions and the other an estimate of the timing between their movements. The results of these analyses will provide quantitative information about the spatial and temporal coordinative organization of lingual propulsion during the normal adult swallow.

Subjects and Methods

Tongue movement data were obtained from the X-Ray Microbeam Speech Production Database (XRMB-SPD) [15]. Thirty-six of the 57 participants in the database were included in this investigation. Subjects were excluded if they did not perform the swallowing tasks or if their data contained significant pellet mistracking during swallowing. The subject pool consisted of 19 females and 17 males with a mean age of 22 years 4 months. All subjects reported negative histories of neuromotor disorders or other health concerns.

Procedure

Four gold pellets (2–3 mm in diameter) were attached to the midsagittal portion of the subject's tongue using a dental adhesive (Ketac-Bond). To prevent the subjects from inadvertently swallowing a pellet, each pellet was attached to a string that was adhered to the face. The most anterior pellet (T1) was placed approximately 10 mm from the tongue tip. The most posterior pellet (T4) was placed on the tongue dorsum (approximately 60 mm from the tongue tip). Pellets T2 and T3 were placed on the tongue blade both equidistant from each other and pellets T1 and T4 [15].

Swallowing Task

Participants were asked to complete five discrete swallows each consisting of a 10-cc water bolus. Before each trial, the participants were administered the water bolus through a syringe and instructed to hold the water in their mouth until a tone was provided signaling them to swallow. The XRMB system then tracked the movement of the lingual pellets in the midsagittal plane during each discrete swallow.

Data Acquisition and Processing

X-Ray Microbeam System (XRMB)

The XRMB system is unique to the University of Wisconsin-Madison. For a detailed description of the system see Westbury [15]. Briefly, a power supply produces an electron beam, which is concentrated on a tungsten target to generate X-rays. The narrow X-ray beam (0.4 mm) is focused through a pinhole opening. A computer-guided positioning system continuously tracks the predicted position of the pellets as the participant swallows 10 cc of water for five trials. The resultant tongue movement trajectories (tracings) are represented as a time series in a two-dimensional coordinate system that is referenced to the maxillary occlusal plane (Fig. 1). The XRMB system results in low doses of radiation compared to traditional X-ray measures.

Sampling Rate and Filtering

Tongue pellet movement was initially sampled at 160 Hz for pellet T1 and 80 Hz for pellets T2, T3, and T4. For ease of analysis, the movements of T2, T3, and T4 were upsampled to 160 Hz so that all pellets had a uniform sampling rate. Before analysis, all signals were low-pass filtered (f_{lp} = 10 Hz) using a zero-phase forward and reverse digital filter.

Percentage of Missing Data

Mistracking occurred when the pellet adhesive did not bind to the surface of the tongue causing a pellet to loosen; when two or more pellet trajectories were overlapping; or when shadows occurred. Shadows were caused by "tissues, bones, teeth, and/or fillings" [15, p. 66] which prevented the computer from tracking the predicted location of the pellets. Each of the 36 subjects completed five discrete swallowing trials. Data from all five trials were analyzed in 26 (72.2%) of the subjects. Because of pellet mistracking, four swallowing trials were analyzed in five (13.9%) of the participants, three trials in four (11.1%) of the participants, and two trials in one participant (2.8%). A total of 164 swallowing trials across 36 participants were analyzed in this investigation.

Correction for Jaw Movement

The positional data of the tongue pellets were expressed relative to the maxillary occlusal plane [15]. Translatory and rotary components of mandibular movements were computed based on the motion of two mandibular pellets and were used to re-express the tongue positions in a mandibular-based coordinate system. This procedure allowed tongue movements to be represented independently of jaw movements [16].

Measurements and Analyses

The vertical tongue movements associated with lingual propulsion, which were along the y dimension of the occlusal plane coordinate system, were identified on each movement trace. The analysis was restricted to the vertical dimension because movements along this axis were expected to capture the pattern of sequential elevation that characterizes tongue movement during lingual propulsion [12, 13, *p.* 27]. The onset and offset of each propulsive event were estimated using the pellet's velocity trace (first-order derivative of the movement signal). The movement signal and its velocity trace were displayed simultaneously on a computer monitor. For each swallow, zero-crossings in the velocity trace associated with the onset of T1 movement and offset of T4 movement were identified algorithmically but required user input for verification (Fig. 1, bottom panel).

Procedure for Quantifying Lingual Coordination During the Swallow

A cross-correlation analysis, as described previously by Green et al. [17], was used to quantify the spatiotemporal characteristics of lingual propulsion during swallowing. Peak coefficients (negative or positive) and their associated lags were derived from each cross-correlation function, which were computed between the treated displacement traces of the following tongue pellet pairs: T1×T2, T2×T3, T3×T4, T1×T3, T2×T4, and T1×T4. The peak correlation coefficient quantified the similarity between movement traces of each pellet pair and the lag value quantified the time interval between the movements of each pellet pair. Before analysis, all displacement trajectories (T1, T2, T3, and T4) for each discrete swallow were centered about their mean (panel A in Fig. 2a and b). Panel B of Figure 2a shows a single cross-correlation function computed on the displacement traces of T3 and T4, which are displayed in panel A. From each cross-correlation function, the most prominent peak (positive or negative) within an approximately 500-ms window centered on zero lag was identified. If the cross-correlation function did not contain a prominent peak within the 500-ms window, the coefficient and lag for that pellet pair were omitted from the final data corpus. Long lags tended to occur when one or two of the tongue pellets moved very little during the trial. The lags of such poorly defined movement traces are uninterpretable and have the potential to skew the results. Approximately 5.6% of the pellet-pair data points exceeded the 500-ms criterion. Before analysis, all lag data were represented using absolute values.

The peak correlation coefficient (r) of each cross-correlation function indicated the extent to which different tongue regions move similarly toward the palate during lingual propulsion. During the normal adult swallow, we expected the movement patterns of different tongue regions to be similar with all regions elevating toward the palate forcing the bolus back into the pharynx. Peak coefficient values approaching one represented a high degree of movement pattern similarity (Fig. 2a) and correlation values decrease as movement patterns become less similar (Fig. 2b). This correlation-based measure is insensitive to variations in movement amplitude due to, for example, across-subject differences in the shape of the palate or anatomic size.

To quantify temporal aspects of lingual propulsion, the lag times between all possible lingual pairs were obtained directly from each cross-correlation function. The lag was the time point at which the peak coefficient occurred (Panel B of Fig. 2a and b). This measure represented the relative timing between the movements of lingual pellet pairs. As illustrated in Figure 3, the lag between pellets T2 and T4 was used to estimate the duration of lingual propulsion or lingual transit time (LTT). The movement of pellet T1 was not used to identify the onset of LTT because before the initiation of the swallow, the anterior tongue was typically braced against the palate to prevent water from leaking from the mouth.

Statistical Analysis

Coefficient values were converted to Fisher's z scores before statistical analysis. Data were averaged across trials for each subject and pellet pair. Analyses of variance (ANOVAs) were followed by multiple pairwise comparisons using the Bonferroni procedure (α = 0.05) to test for significant differences in peak coefficient and lag values across pellet pairs. If a violation of the assumption of homogeneity of variance was detected, the Games-Howell approach (α = 0.05) was used to test for significant differences.

Results

Spatial Similarity of Movement Traces Across Different Lingual Pellets

The average peak coefficients between the tongue pellets computed across trials and subjects are displayed in Figure 4. In general, the correlations were

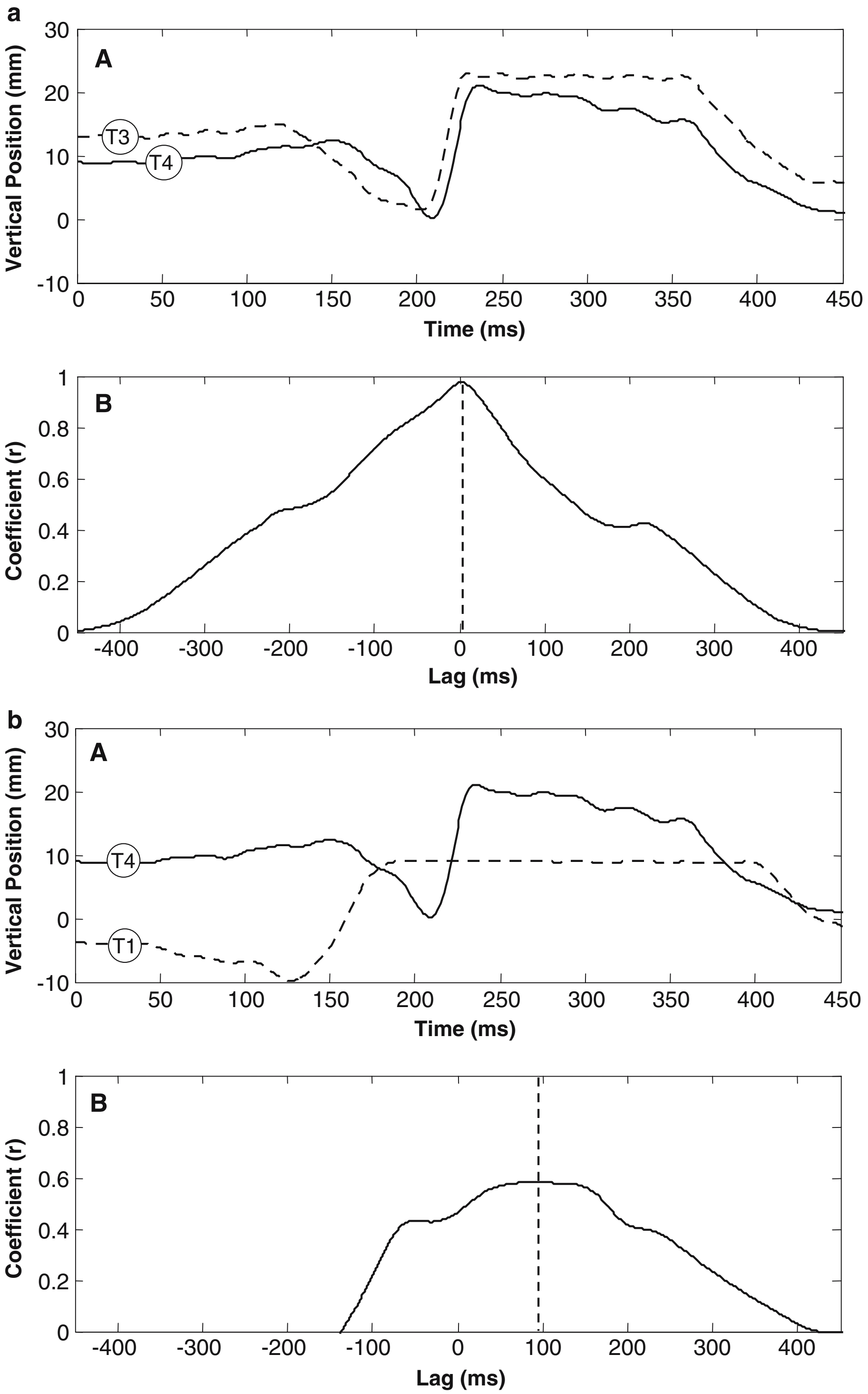

Fig. 2a. (Top Panel - A) Vertical displacement trajectories for T3 and T4 pellets during a discrete swallow trial. Note the shape similarity of the movement traces and the small time interval (lag) between the peak displacement of T3 and T4. The vertical position is referenced relative the maxillary occlusal plane as described in the Methods section. **(Bottom Panel - B)** The cross-correlation functions for signals T3 and T4. The peak coefficient and lag value were extracted from each cross-correlation function. The corresponding peak correlation coefficient is represented in the vertical axis. Note the high degree of movement similarity that was visually observed in panel A is represented as a coefficient value (vertical axis). The resultant lag value, represented on the horizontal axis, is also derived from the cross-correlation function. **Fig. 2b. (Top Panel - A)** Vertical displacement trajectories for T1 and T4 pellets during a discrete swallow trial. Note how the movement traces are relatively distinct, that is, their shape is less similar. Note also the relatively large time interval (lag) between the peak displacement of T1 and T4 in comparison to the lag of T3 + T4 as displayed in Fig. **2a**. The vertical position is referenced relative the maxillary occlusal plane as described in the Methods section. **(Bottom Panel - B)** The cross-correlation functions for signals T1 and T4. The peak coefficient and lag values were extracted from each cross-correlation. Note how the relatively low degree of spatial similarity (vertical axis) and the corresponding lag value (horizontal axis) are in contrast to the example in **2a** which resulted in a much higher degree of spatial similarity and shorter lag time.

stronger between posterior tongue regions than between anterior tongue regions (Table 2). That is, movement traces of posterior pairs were more similar than were those of more anterior pairs. Nonadjacent pairs were less similar (lower peak coefficient) than the adjacent pairs ($p \leq 0.01$). In particular, nonadjacent pellet pairs associated with T1 (T1×T3 and T1×T4) were less similar (lower peak coefficient) than were adjacent pairs associated with T1. The nonadjacent posterior pair (T2×T4) also appeared less similar than the adjacent posterior pairs (T2×T3 and T3×T4). Across-subject variability is denoted by the

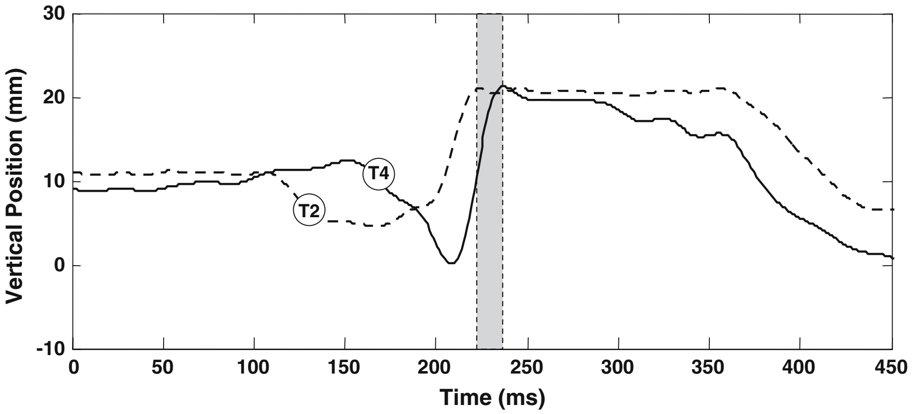

Fig. 3. Lingual transit time as defined by the interval (lag) between the motions of T2 and T4. The vertical position is referenced relative the maxillary occlusal plane as described in the Methods section.

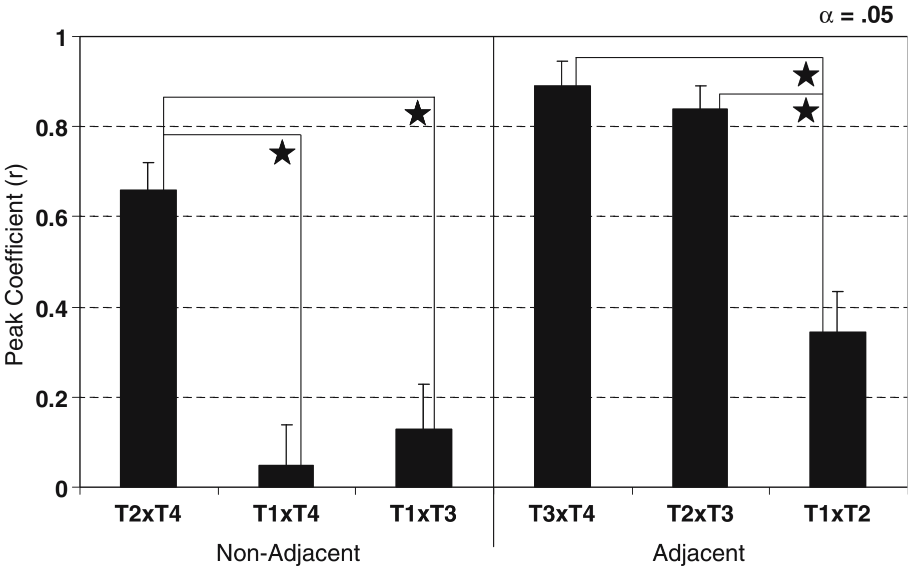

Fig. 4. Average peak coefficient for all pellet pairs across all subjects. All data were transformed into Fisher's *z* values and statistically analyzed. The values were then transformed using the inverse of Fisher's *z* function and are reported in the figure. *Note*: Standard error of the mean bars [average SD/√*n*] represent across-subject variation.

Table 2. Statistical results for pellet pair comparisons in average peak coefficient values

Comparisons		*p* value
Adjacent[a]		
T1×T2	T2×T3	≤ 0.01
T1×T2	T3×T4	≤ 0.01
T2×T3	T3×T4	= 0.21
Nonadjacent[b]		
T1×T3	T2×T4	≤ 0.01
T1×T3	T1×T4	= 1.00
T1×T4	T2×T4	≤ 0.01

[a] Multiple comparisons were made within the adjacent group using the Games-Howell approach because Levene's Test of Equality of Error Variances was significant [*F*(2,102) = 6.23, *p* = 0.003] indicating a violation of the assumption of homogeneity of variance.

[b] Bonferroni procedure was used to test comparisons because Levene's Test of Equality of Error Variances was not significant [*F*(2,101) = 1.63, *p* = 0.201].

standard error of the mean bars in Figure 4. An estimate of within-subject variability (i.e., standard deviation across trials) in peak coefficients values is given in Table 3.

Lag Time Between the Movements of Lingual Pellets

The average lag times for all pellet pairs across all subjects and trials are displayed in Figure 5. Lag times between pellet motions decreased as the bolus was propelled toward the pharynx. There was a significant difference between the lag times for all adjacent (T1×T2, T2×T3, T3×T4) pellet pairs. Specifically, the average lag time for T3×T4 was significantly shorter than that of T2×T3 and T1×T2 (see statistical findings listed in Table 4). As would be expected, the nonadjacent pairs had longer lag times than did the adjacent pairs ($p \leq 0.01$). Across-subject variability is denoted by the standard error of the mean bars in

Table 3. The average standard deviation for each pellet pair across both parameters (peak coefficient and lag time)

Pellet pairs	SD (peak coefficient)	SD (lag time)
Adjacent		
T1×T2	0.50	102.09
T2×T3	0.30	52.58
T3×T4	0.30	27.85
Nonadjacent		
T1×T3	0.52	105.40
T2×T4	0.34	77.32
T1×T4	0.49	102.13

Figure 5. The average standard deviations (within-subject variability across trials) for each pellet pair are reported in Table 3.

As indicated in Figure 5 (see T2×T4), the average lingual transit time for the 36 subjects was approximately 168 ms. Moreover, lag times appeared to decrease systematically between adjacent pellet pairs by approximately 50 ms between T1×T2, T2×T3, and T3×T4. The timings between tongue pellets, relative to T1, during the propulsive wave are displayed in Figure 6. The lag time systematically decreased as the bolus was forced back into the pharynx. That is, the average lag between the onset of T2 movement was approximately three times as long as the lag between the onset of T3 and the onset of T3 was approximately twice as long as the lag between the onset of T4 pellet movement.

Discussion

The primary purpose of this investigation was to characterize the temporal organization of lingual propulsion during the normal adult swallow. Several consistent patterns of coordinative organization were observed across individuals, which were consistent with prior clinical descriptions of tongue performance during swallowing. Future work is needed to determine if the features of tongue coordination identified in this study can serve as performance expectations for gauging the degree of impairment in individuals with oral stage dysphagia secondary to lingual discoordination.

Similarity of Movement Traces Among Distinct Tongue Regions

A large range of peak correlation coefficients was obtained across pellet pairs. In general, movement trace similarity was much greater for posterior tongue regions than it was for anterior regions. These regional differences in similarity may be attributable to differences in how the tongue tip and blade are used for bolus transport. Typically, the tongue tip and blade brace against the palate to prevent the bolus from escaping the mouth and to stabilize the tongue so that the more posterior regions can complete the propulsive wave [3, 6, 12, 18]. In the present study, the weak correlations between T1 and the other three pellets may be because T1 often remained elevated during the entire swallowing trial (Fig. 7).

The strong similarity observed between the movement traces of the posterior tongue regions may be due to the biomechanical properties of the tongue. For example, the movements of posterior tongue regions may be similarly influenced by extrinsic muscle activity and, therefore, more highly coupled. Extrinsic muscles are primarily responsible for changing the position of the tongue, in contrast to intrinsic muscles, which alter the tongue's shape [19]. The consistently strong similarity between movement traces of the posterior regions may also occur because these regions are bound to the pharynx by the extrinsic musculature and connective tissue and, therefore, restricted in their movement. In contrast, the dissimilarity observed between the movement traces of the anterior tongue regions and those of the other regions may be because the anterior tongue has a higher degree of mobility than does the posterior regions.

Temporal Features of Lingual Propulsion

Lingual transit time and the reported lag values among adjacent tongue regions may supplement previously established clinical measures of swallow timing. Lingual transit time was 168 ms on average. Moreover, lag times between adjacent pellets decreased systematically from anterior to posterior by approximately 50 ms (Fig. 5). Extrapolation of our findings to previous ones is difficult because the definition of oral transit time has varied considerably across studies. For example, Tracy et al. [20] used bolus movement to define the timing of oral transit, whereas Logemann [13, p. 77] used the initiation of tongue movement to define oral transit time.

Performance Variability

Because of anatomic and morphologic differences among our participants, we anticipated a high degree of across-subject variability in tongue movements.

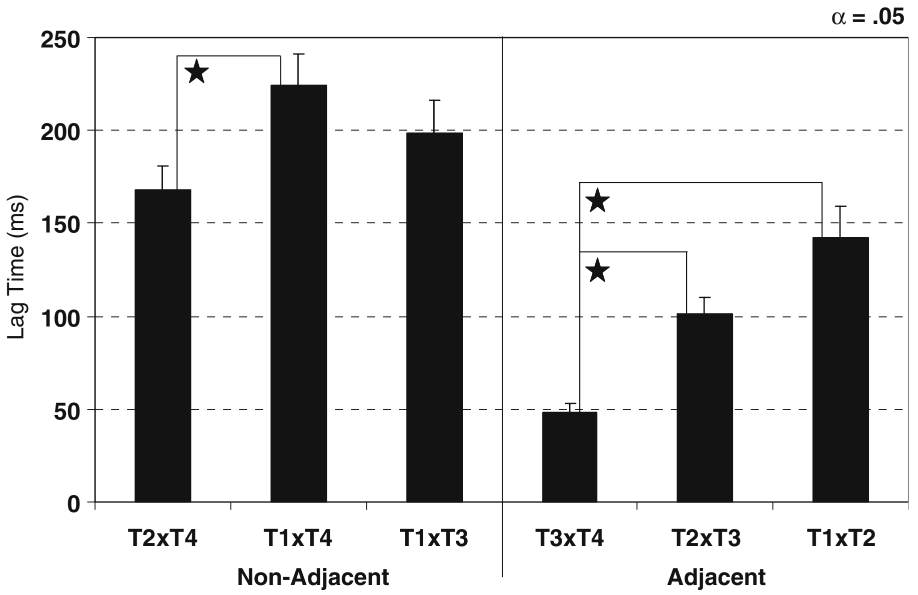

Fig. 5. Average lag value for all pellet pairs across all subjects. *Note*: Standard error of the mean bars [average SD/$\sqrt{n}$] represent across-subject variation.

Table 4. Statistical results for pellet-pair comparisons in average absolute lag values

Comparisons		*p* value
Adjacent[a]		
T1×T2	T2×T3	= 0.13
T1×T2	T3×T4	≤ 0.01
T2×T3	T3×T4	≤ 0.01
Nonadjacent[b]		
T1×T3	T2×T4	= 0.43
T1×T3	T1×T4	= 0.64
T2×T4	T1×T4	≤ 0.02

[a] Multiple comparisons were made within the adjacent group using the Games-Howell approach because Levene's Test of Equality of Error Variances was significant [$F(2,102) = 7.03$, $p = 0.001$], indicating a violation of the assumption of homogeneity of variance.

[b] Bonferroni procedure was used to test comparisons because Levene's Test of Equality of Error Variances was not significant [$F(2,101) = 2.18$, $p = 0.119$].

Conclusions have differed considerably across prior investigations in their valuation of whether subjects in their studies exhibited significant differences in tongue performance during swallowing (Table 1). Using ultrasound, Shawker et al. [21], suggested that "considerable variation exists among normals" (p. 489). In contrast, using electropalatography (EPG), Chi-Fishman and Stone [6] described the variability seen in their investigation as "trivial" (p. 243). Of course, the degree of variability observed in this and previous investigations is dependent on the chosen level of analysis. For example, descriptions of tongue performance based on EPG data might be expected to yield less intra- and intersubject variability than those based on lingual kinematic data because EPG captures only patterns of lingual-palatal contact and not the fine details of movement.

One advantage of the cross-correlation approach used in the current investigation is that it is relatively robust to small differences in movement traces and is therefore likely to detect similarities across individuals. The relatively small standard error of the mean bars in Figures 4 and 5 indicate that the degree of movement trace similarity and the relative timing between pellets varied minimally across participants. The average standard deviation for each pellet pair is reported in Table 3. The standard deviations should be interpreted cautiously because they are based on a very small number of trials (usually 3–5) and should therefore be expected to be relatively high. Despite the variability, several systematic spatiotemporal pellet effects were observed (Figs. 4 and 5). Specifically, across participants, movement patterns of the anterior tongue regions were distinct from those of the posterior tongue regions and the average interval (lag) between the movements of the four tongue regions decreased systematically by approximately 50 ms from anterior to posterior.

Technical and Methodologic Considerations

A number of methodologic issues should be considered when interpreting the results of this investigation. First, although the XRMB system captures movement data in two dimensions, the results reflect

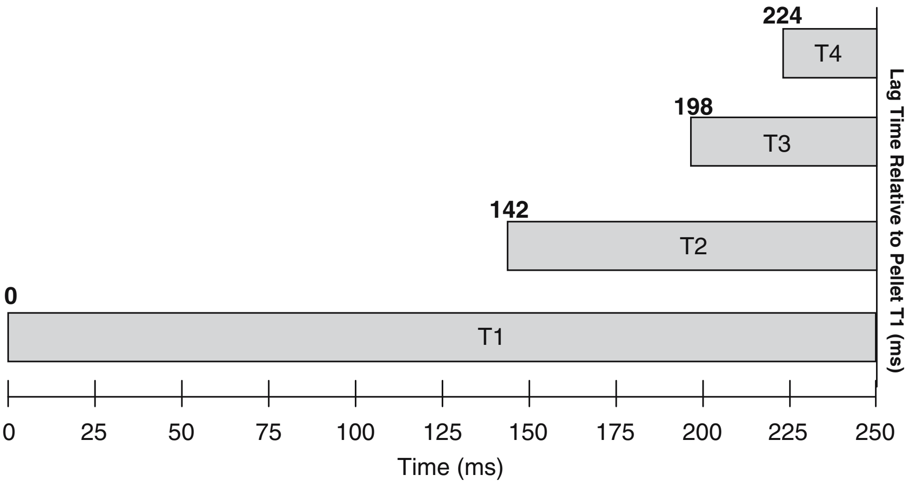

Fig. 6. Relative timing of the propulsive wave across tongue pellet regions. The gray lines indicate the average timing onset of movement for each pellet. It is assumed that the onset for T1 is at time zero, T2 onset = 142 ms, T3 onset = 198 ms, and T4 onset = 224 ms.

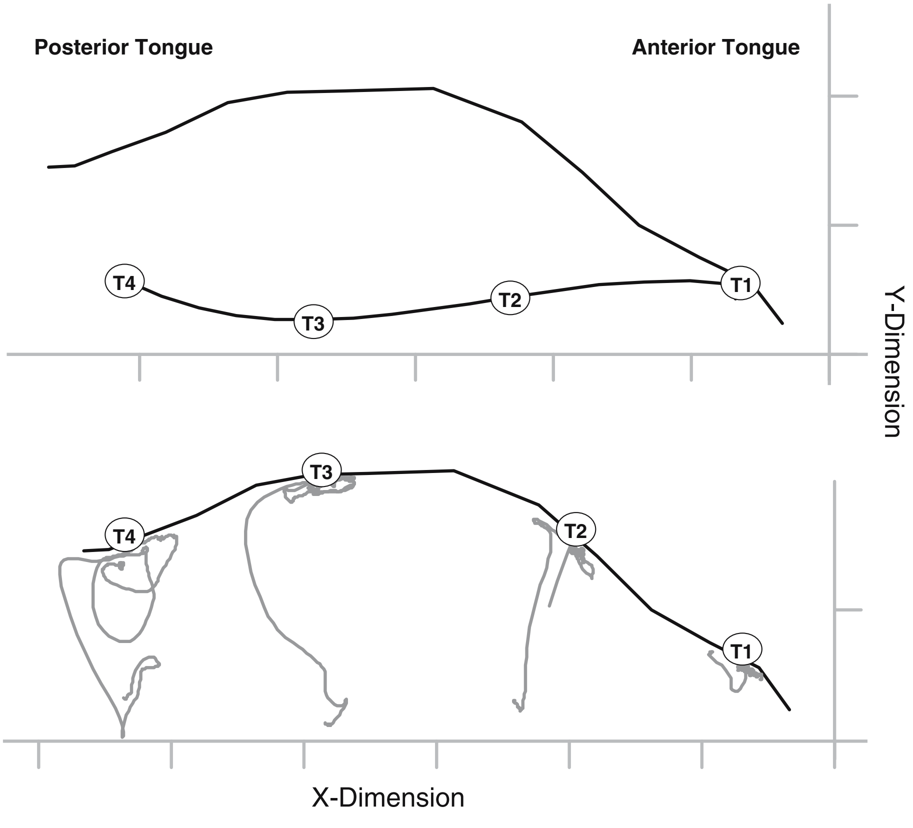

Fig. 7. (Top Panel) Example of tongue pellet positions before swallow. Note that T1 is elevated to the palate to secure the bolus in the oral cavity. **(Bottom Panel)** Movement trajectories for each tongue pellet during a single swallow. Note how the displacement of T1 in the *y*-dimension is minimal relative to the displacement of T2, T3, and T4.

movement in only the vertical dimension of the maxillary-occlusal plane. A more comprehensive assessment of lingual coordination will take into account multidimensional aspects of the swallow. Second, the motions of the extreme posterior tongue were not captured in this investigation because T4 was located anterior to the tongue root. Therefore, the present results are limited to the more anterior tongue and do not reflect movement of the tongue root. Third, although discrete swallows were the focus of the current investigation, additional research is needed to evaluate tongue coordination during sequential swallowing. The findings would provide important complementary information and further improve our understanding of tongue control for swallowing. Finally, the representation of lingual coordinative organization provided by this study was necessarily limited to experimental conditions (i.e., 10 cc of a clear liquid bolus) because the XRMB system tracks tongue motion during the swallowing of only thin liquids; other textures tend to obstruct pellet tracking. The work of Hiiemae and Palmer [22] and Steele and Van Leishout [23] showing that consistency changes influence oral transport highlights the need for additional studies on the effects of bolus consistency and size effects on lingual transit time and spatiotemporal coordination.

Clinical Implications

Because lingual discoordination is one of the most commonly reported symptoms of oral stage dysphagia [18], the development of objective and reliable measures of tongue performance during swallowing will have important implications for clinical practice. When compared with other methods, the time-series analysis used in this study requires only minimal input from the investigators, which makes it objective, reliable, and efficient. By contrast, videofluoroscopy (VFS), which is considered the "gold standard" [24] for assessing dysphagia, remains a relatively subjective clinical procedure. The motions of the tongue and other oral structures are difficult to quantify using VFS. As additional technologies for tracking tongue motion, such as electromagnetic midsagittal articulography (EMMA), become more widely available, the measures of tongue performance reported in this investigation could be used to track progress during treatment and to evaluate the effectiveness of specific treatment protocols. Steele and Van Lieshout [23] have recently described a clinical assessment procedure for using EMMA to evaluate swallowing function. Conceivably, the methods used in this investigation could also be adapted to VFS recordings that contain the motions of radiopaque pellets attached to the tongue.

Summary

In the present investigation, the timing characteristics and spatial similarity between the movements of four distinct tongue regions were studied to quantify the coordinative organization of lingual propulsion during the oral stage of the adult swallow. Several of the features of tongue performance that were identified may serve as useful points of reference for identifying impairments in tongue coordination. For example, LTT for a discrete water bolus is approximately 168 ms. Until more subjects are studied, however, this baseline should be interpreted cautiously because LTT is based on the average from a relatively small number of subjects (36) and trials (164). The present findings also suggest that the time interval between the movements of the posterior tongue regions (T3×T4) should be significantly shorter than the intervals between more anterior tongue regions (T1×T2 and T2×T3) and, on average, there was an approximately 50 ms decrease in lag time from anterior to posterior. In the spatial domain, it should be anticipated that the motion of the anterior tongue (T1) will be distinct from that of more posterior pellets (T2, T3, and T4) and that adjacent pairs are more highly similar in movement shape than nonadjacent pairs. Future work is needed to determine if the absence of the observed characteristics in tongue function is indicative of oral stage dysphagia.

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