

Variability in Tongue Movement Kinematics During Normal Liquid Swallowing

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Abstract. This study sought to develop a quantitative kinematic description of tongue movement for liquid swallowing in a group of 12 healthy subjects. X-ray microbeam technology was used to track the positions of six small pellets attached to the tongue and jaw while subjects swallowed water at 2- and 10-mL bolus volumes. A feature common to all subjects was a prominent rostral movement of the dorsal region of the tongue. In addition, all subjects consistently increased the displacement and maximum speed of this tongue movement with increased bolus volume. However, detailed movement analysis showed a variety of tongue movement patterns for the group. This variability across subjects was large enough that it was surprisingly difficult to provide a low-dimension quantitative description of the tongue kinematics during liquid swallowing.

Key words: Tongue — Swallowing — Kinematics — Normal — Deglutition — Deglutition disorders.

It is generally agreed that during liquid swallowing, the tongue assists in controlling liquid in the oral cavity prior to swallowing and in transporting the bolus into the pharynx in an efficient and timely manner [1]. Additionally, because of the close ana-

tomical relationship between the tongue and the hyo-laryngeal complex, it has been suggested that tongue movement facilitates elevation and anterior movement of the larynx, which is considered critical to airway protection and efficient pharyngeal bolus transport [2]. Lastly, altered tongue function is thought to contribute to a variety of neurogenic swallowing disorders [3].

Clearly, the comprehensive assessment and effective treatment of swallowing disorders that implicate altered tongue function necessitate establishing quantifiable features of normal liquid swallowing against which disordered patterns can be compared. The videofluoroscopic swallowing assessment is the most common instrumental technique used to evaluate oropharyngeal swallowing. While the technique is highly informative for characterizing bolus transport and for coarsely tracking the position of bony and cartilaginous structures such as the hyoid bone and epiglottis [1], it provides only limited resolution of soft tissues such as the tongue. Consequently, it is difficult to provide a quantitative expression of swallowing-related tongue movement using videofluoroscopy and descriptions have been largely qualitative and/or inferred from characteristics of bolus transport. Imaging technologies, such as ultrasound [4], computer-enhanced videofluoroscopy [5], or x-ray microbeam [6,7], can accurately track the position of marker points placed on the tongue, allowing for a detailed study of kinematics. However, only a limited number of studies have used these technologies to describe normal liquid swallowing-related tongue movement [4,6,7]. Although there are many similarities in findings, there are points of disagreement. For example, both Stone and Shawker [4] and Martin [7]

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suggest that swallowing-related tongue movement may be reliably segmented into four stages of primary movement direction. However, they do not agree regarding the kinematic details within each stage. Stone and Shawker [4] describe a movement sequence that begins with the tongue moving forward (stage one), followed by a rapid upward movement (stage two), formation of palatal contact and a small degree of slow forward movement (stage three), and ending with a return to a “rest position” (stage four). Martin [7] characterizes the sequence as beginning with a forward and upward movement (leg one), followed next by a downward movement (leg two), followed then by a rapid upward and backward movement (leg three), and ending with a forward movement along the palatal contour (leg four). There is also disagreement regarding the effect of bolus size on the features of tongue movement. Martin [7] reports a tendency for the amplitude and peak velocity of movement to positively scale with bolus size. Hamlet [6] found that while dry swallows clearly differ from water swallowing with respect to a number of kinematic features, the same could not be said for swallows with different bolus volumes.

It is uncertain whether such discrepancies reflect methodological differences, natural behavioral variation within the population, or both. Disambiguating these sources of variability requires a study of swallowing-related tongue point motion that collects data on a relatively large number of subjects using identical acquisition and analysis approaches. Recently, a database [University of Wisconsin X-ray Microbeam Speech Production Database (XRMB-SPD)] has become publicly available that provides data on speech, swallowing, and other oral movements of 57 healthy young adults [8]. X-ray microbeam technology was developed in the early 1970s for the study of oral articulator motion [9]. Although the technique does not allow for the visualization of the bolus or many pharyngeal structures, it offers a major advantage in that it provides very good spatial and temporal resolution of an array of discrete flesh points, typically hidden in the mouth, with extremely low levels of radiation exposure. Since the database includes normal liquid swallowing records across a large number of subjects using identical acquisition and processing techniques, it seems ideally suited for studying patterns of variation in swallowing-related tongue movement. Our study, which reports on 12 subjects randomly extracted from this database, was designed to help understand the sources of variation in the kinematic patterns exhibited by the tongue during normal liquid swallowing. Although this

study focuses on tongue kinematics, both tongue and jaw movements were evaluated because both structures are capable of modulating the shape of the oral cavity. Specifically, we were interested in addressing the following questions: (1) Is there a uniform and quantifiable oral movement pattern associated with liquid swallowing in a group of young healthy adults? (2) If so, can this pattern be expressed in low-dimensional terms? (3) Are the kinematic and spatial features of swallowing-related tongue movement influenced by bolus volume, as suggested by Martin [7]?

Methods

Subjects

Twelve healthy adults (six male, six female), with no reported swallowing difficulties, were randomly selected from the XRMB-SPD, a kinematic and acoustic collection of speech and nonspeech oral activities of 57 healthy young, primarily Midwestern subjects. Table 1 includes demographic information on the subjects.

Instrumentation

The University of Wisconsin x-ray microbeam system uses a unique technology for tracking the motion of structures hidden from view with the naked eye. This task is accomplished by directing a narrow high-energy x-ray beam to track the position of a number of 2–3-mm-diameter gold pellets glued to various structures in and around the oral cavity. Details regarding the operating principles of the x-ray microbeam system are available elsewhere for the interested reader [8,10,11]. Figure 1 graphically illustrates the approximate pellet positions and coordinate system used for this study. All analysis was performed on the spatial positions of four tongue (T1–T4) and two jaw pellets (MI and MM). Tongue pellets were placed along the longitudinal sulcus of each subject’s tongue. The specific position of each pellet for the individual subjects can be found in Table 1. Of the jaw pellets, one pellet (MI) was glued to the buccal surface of the central incisors in the pocket formed by the central diastema and the enamel–gingiva border, while the second pellet (MM) was attached in the vicinity of the juncture between the first and second left mandibular molars on the gingiva or at the enamel–gingiva border. Additionally, a representation of the midsagittal outline of the hard palate was determined for each speaker using methods previously described [8].

Swallowing Task

Water bolus volumes of 2 and 10 mL were administered to the subject using a graduated syringe. The subjects held the bolus in their oral cavity until cued to swallow by a tone (frequency = 1000 Hz, duration = 250 ms). Each subject performed a maximum of five swallows with each of the two volumes.

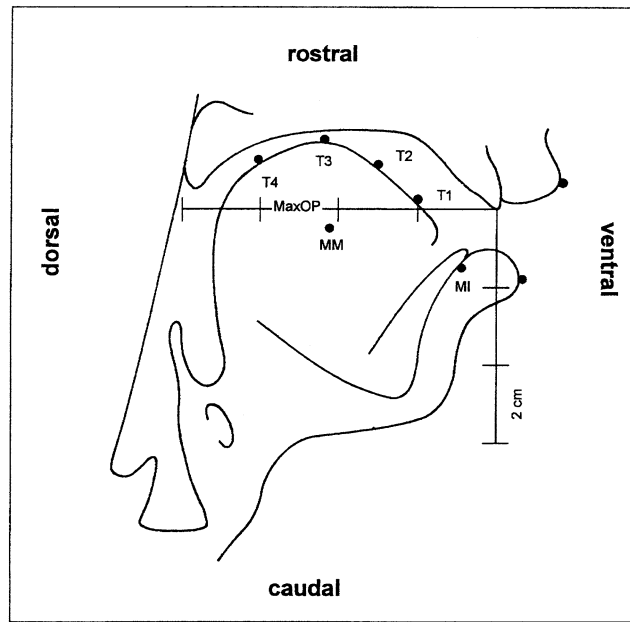


Fig. 1. Stylized drawing of the midsagittal section of the vocal tract. The small filled circles indicate the approximate pellet locations.

Table 1. Subject demographics and tongue pellet placement

Subject	Gender	Age	Height (in.)	Weight (lb.)	Lingual pellet position (mm dorsal to apex)			
					T1	T2	T3	T4
S1	M	19.38	69	170	8	28	46	62
S2	M	21.85	72	175	8	23	41	57
S3	M	19.21	73	165	9	24	43	62
S4	M	20.41	75	190	8	23	43	67
S5	M	21.24	69	173	9	26	43	57
S6	M	19.19	72	175	7	25	47	61
S7	F	36.98	65	165	9	26	44	58
S8	F	24.19	65	125	8	24	46	64
S9	F	20.61	66	125	9	27	45	62
S10	F	19.45	65	150	10	27	45	57
S11	F	21.33	61	150	7	22	40	58
S12	F	21.34	67	120	9	26	45	58

Data Acquisition and Processing

Pellet tracking commenced just prior to the tone and continued for 3 s. The position histories of the pellets were digitized at different sampling rates. This decision was made based on the need (1) to capture the bandwidth of each pellet movement and (2) to optimize proper tracking of the pellet, within a finite aggregate sampling rate. The MI and MM pellets were sampled at 40 Hz, the T2, T3, and T4 pellets were sampled at 80 Hz, and the T1 pellet was sampled at 160 Hz. Following acquisition, the position histories for each pellet underwent a series of processing steps. One of these involved re-expressing the data in an anatomically based Cartesian coordinate system in which the abscissa is located along the maxillary occlusal plane (Max OP) and the ordinate is normal to the abscissa at a point where the central maxillary incisor (CMI) meets the maxillary occlusal plane (Fig. 1). The position histories of the pellets were low-pass filtered at 10 Hz and resampled at 145 Hz.

The 3-s record containing the six pellets of interest was imported into a commercial data analysis software package for further processing. The XRMB system occasionally failed to track individual pellet(s) during the task. When these “mistracks” occurred, only the mistracked pellet was omitted from the subsequent analysis and correctly tracked pellets were retained. Therefore, in some cases, fewer than five replicates were available for analysis.

All analysis in the study was based on (a) the pellet position histories and (b) the pellet speed histories. Speed is defined as the magnitude of the rate of change of position with respect to time and was determined as:

$$\text{Speed} = \sqrt{\{\dot{x}(t)\}^2 + \{\dot{y}(t)\}^2}$$

where $\dot{x}(t)$ and $\dot{y}(t)$ represent the first-order time derivatives of each position channel calculated using a three-point central method of numerical differentiation.

Description of the Overall Swallowing Event

Prior to fine-grained analysis of individual pellet motion, the overall spatial-temporal pattern of motion of the tongue and jaw pellets during the swallow was evaluated. The most prominent kinematic feature across the six pellets during the swallowing event was a large transitory peak in the speed of T4. The time associated with this T4 event was used to time-align individual swallowing replicates for the subsequent generation of an ensemble average for each of six pellet trajectories for each subject and bolus volume. The T4 speed peak also served as the central point of a 1000-ms time window for data analysis. This duration was chosen because preliminary analysis indicated that this period included all of the prominent tongue and jaw kinematic events associated with the swallowing task.

Analysis of Individual Pellets

In addition to the pattern of movement of the pellet array, individual pellets were selected for detailed examination. Average pellet trajectories were generated for each subject and bolus volume over a 1000-ms time window centered on the respective pellet's prominent speed peak. Prior to signal averaging, trajectory replicates were aligned temporally and spatially. Temporal alignment of the trajectories was done with respect to the time position of the pellet's peak speed. Spatial alignment involved re-expression of the trajectories in a coordinate space where the origin represents the mean x and y coordinate positions. This procedure is strictly a spatial translation and overall trajectory shape is preserved.

Each pellet's speed peak also served to define the pellet's prominent movement. Some kinematic features of this prominent movement were extracted for quantitative analysis. Figure 2 illustrates an example of a T4 movement, with salient features labeled. Three measures were extracted: *Movement duration* is defined as the period between local speed minima (i.e., locations where the slope of the speed history trace changes sign from negative to positive) that bound the prominent speed peak. *Peak speed* is simply the maximum instantaneous speed attained between the onset and offset of movement. *Movement distance* is defined as the sum of the segment lengths along the movement trajectory.

Each of the three kinematic variables (i.e., peak speed, movement distance, and movement duration) was submitted to repeated-measures analysis of variance (ANOVA) with bolus volume, pellet identity, and gender serving as factors. Since three ANOVAs were performed (one for each dependent measure), experimentwise type I error rate was limited to less than 5% by applying a Boniferroni correction for multiple comparisons ($p < 0.016$).

Interpellet Movement Timing

The temporal relationship between the prominent movements of each pellet was explored by comparing the time associated with each pellet's peak speed. This allowed for the evaluation of the serial order of pellet movement events as well as the duration between pellet movement events.

Results

Description of the Overall Swallowing Event

Figure 3 illustrates how an "average" swallow was derived for general description. Figure 3A plots the T4 speed histories for five replicates aligned at peak pellet speed. The heavy line represents the mean speed history. In general, the speed histories are quite similar in shape for each of the individual replicates. Figure 3B plots all five replicates (light lines) and the mean positions (heavy lines) for the six pellet trajectories for the same subject after alignment. The filled circle indicates the position at the beginning of the analysis window and the unfilled circle indicates the spatial position of the pellets at the time of the T4 speed peak.

Although Figure 3 provides an adequate summary of the path that each pellet took over the 1000-ms period, the manner in which each pellet's movement is coordinated in time cannot be appreciated. Figure 4 plots the coarse-grained coordination of the six pellets for a typical subject. For descriptive ease, the 1000-ms time window around the average T4 speed peak was arbitrarily divided into three time periods (period 1, initial 400 ms; period 2, middle 200 ms; period 3, final 400 ms). The top three panels plot the resulting trajectories for each of these three periods. Lines join adjacent tongue pellets and the two jaw pellets at 20-ms intervals. These lines reveal the spatial location of different pellets on a particular structure at a given point in time, and the spacing of these lines roughly indicates pellet speed over time.

The swallow begins (period 1) with a ventral-caudal movement of the T3 and T4 and a ventral-rostral movement of the T1 and T2. The opposing directions of movement of the dorsal and ventral regions of the tongue create an apparent point of "rotation" between the T2 and T3. MI and MM exhibit a small rostral movement followed by an equally small caudal movement. The nearly equal line spacing between adjacent pellets indicates that pellet speed is uniform across the pellets. During period 2, there is minimal motion of the T1 and T2, which are proximal to the hard palate. T3 and T4 exhibit a large rostral-dorsal movement with T3 slightly leading T4. The wide line spacing indicates that T3 and T4 are moving rapidly. MI and MM exhibit minimal motion. During period 3, there is little pellet activity, with the exception of a small caudal movement by T4.

To summarize, at swallow initiation, the ventral pellets move toward the palate while the dorsal pellets move in a caudal direction away from

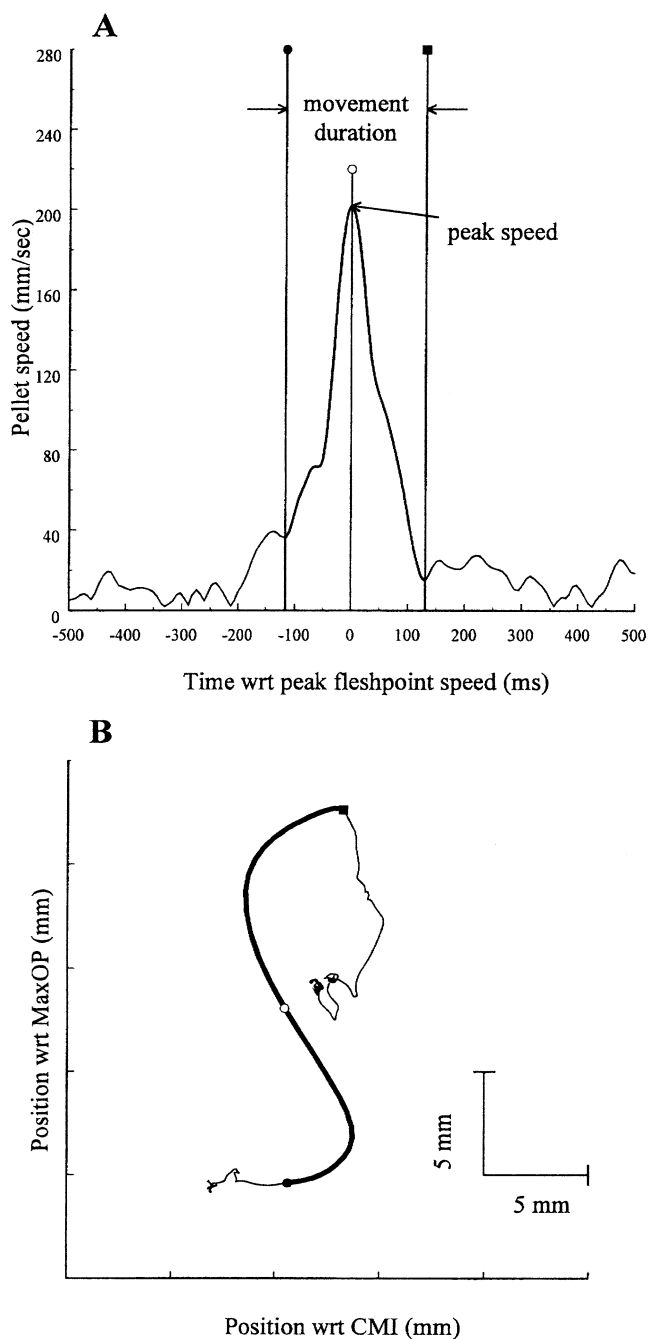


Fig. 2. Illustration of the kinematic measures that serve as the dependent variables. **(A)** The pellet speed history for a single swallowing replicate (S4, 10-mL volume, T4). Movement onset (●) and offset (■) is determined by identifying local speed minima (where slope changes sign from negative to positive) around the prominent speed peak. Movement duration and peak speed are marked. **(B)** The pellet trajectory for the same replicate. The spatial positions associated with movement onset, peak speed, and movement offset are marked with ●, ○, and ■, respectively. The kinematic measure movement distance, represented by the heavy line, is the sum of the segment lengths between adjacent samples along the length of the trajectory between onset and offset.

the palate. As the ventral pellets reach the vicinity of the palate, the dorsal pellets begin moving in a rostral direction toward the palate at a relatively high speed. Once the dorsal pellets reach the region of the palate, little or extremely slow motion is

observed. Throughout the swallow, the jaw pellets respectively move rostrally and caudally, although the magnitude is quite small.

Plots identical to Figure 4 were generated for all subjects and bolus volumes for qualitative

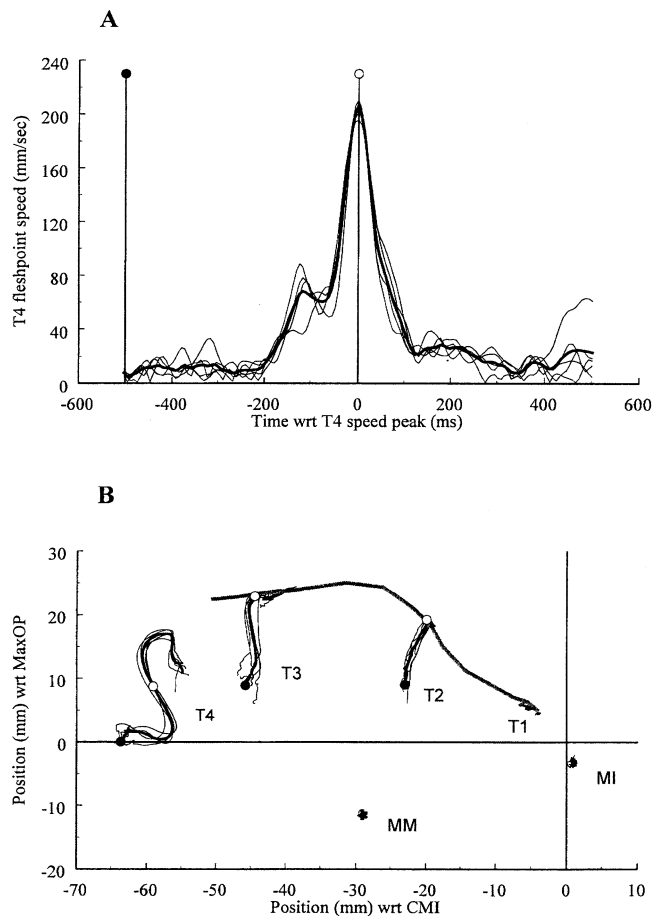


Fig. 3. Illustration of the process for generating an average swallow from individual replicates. **(A)** The T4 pellet speed histories for each of five swallowing replicates for a single subject (S4, 10-mL volume). All replicates are time aligned with respect to their peak speed and cropped to a 1000-ms time window centered on that speed peak. The heavy line represents the ensemble average of the replicates. **(B)** The trajectories of the six-pellet array for each of the five swallowing replicates. The heavy lines represent the mean trajectories for each pellet. (●) The onset of the trajectory; (○) the pellet position at the T4 peak speed. The gray line is a midsagittal outline of the hard palate. MaxOP = maxillary occlusal plane and CMI = central maxillary incisor.

analysis. The majority of subjects behaved in ways similar to the plot in Figure 4 and the coarse-grained description in the last paragraph above. For example, all subjects exhibited the relatively large T3 and T4 movement toward the palate. The pattern of ventral pellets temporally leading the dorsal pellets was also observed in all subjects' average swallows. However, there was also evidence of intersubject variation. Only about 50% of the subjects exhibited rostral jaw movement during the early stages of the swallow. About 20% of the subjects did not exhibit opposing directions of movement between the dorsal and ventral regions of the tongue exhibited in Figure 4. Movement of T1 was quite variable across the duration of the swallow. About 60% of the subjects demonstrated some movement of T1 while the remaining subjects showed very little T1 movement. Detailed analysis

of individual pellet behavior is outlined in the next section.

Individual Pellet Trajectories

Due to limited or inconsistent excursions of T1, MI, and MM, further analysis was limited to T4, T3, and T2. Figure 5 plots individual and average T4 trajectories across all 12-subjects for the 10-mL volume condition. Both individual replicates (light lines) and average trajectories (heavy lines) are plotted. Filled circles mark the average trajectory onset and unfilled circles mark the location of peak speed. Embedded in the upper-right corner of each box is a plot of the average trajectory for the 2-mL volume. An exception is S3's data, where, for demonstration purposes, all 2-mL trials are included along with the average

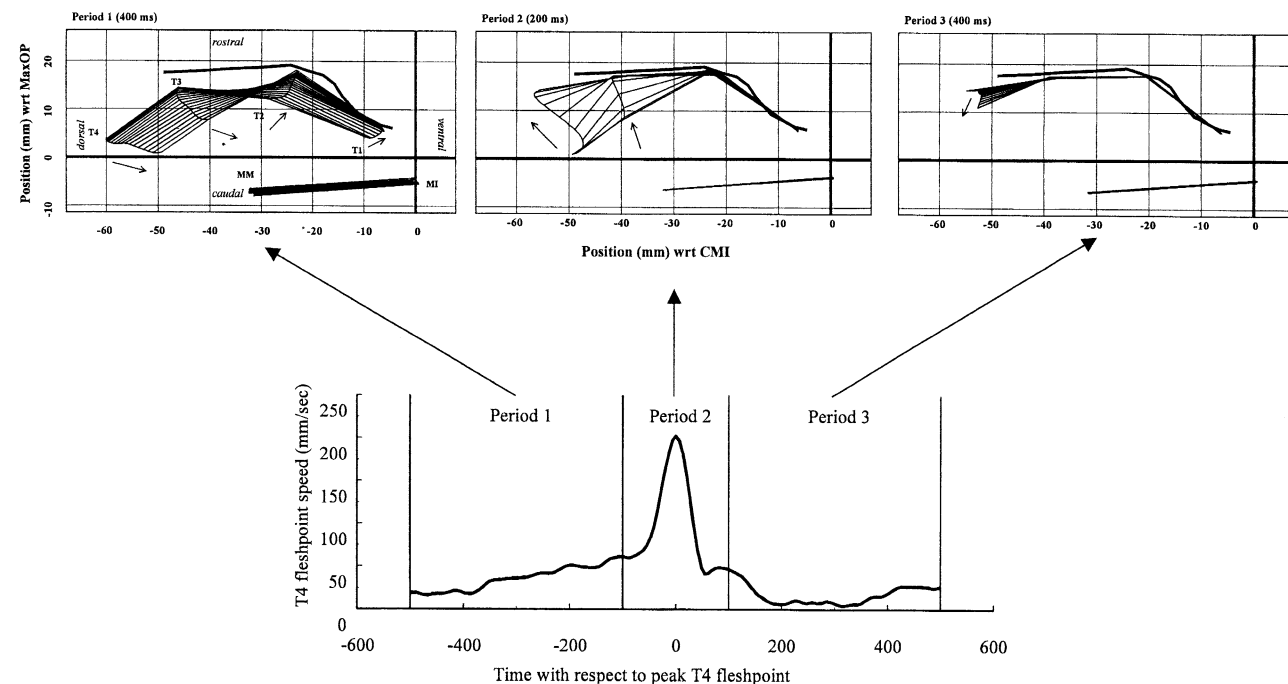


Fig. 4. Illustration of how swallowing-related movement unfolds in time for a single subject (S8, 10-mL volume). For clarity, the swallow has been arbitrarily divided into three time periods (period 1, first 400 ms; period 2, middle 200 ms; period 3, final 400 ms). The top three plots each reflect activity of the six pellets within each period. Lines join adjacent tongue pellets and jaw pellets at 20-ms intervals and serve to provide a crude contour of the tongue and link the pellet trajectories in time. Periods where lines are far apart represent relatively fast movement, and periods where lines are close together represent relatively slow movement. The heavy line represents a midsagittal outline of the hard palate. Each arrow indicates each pellet's principal movement direction.

trajectory. These plots allow for a more detailed comparison of the variability of the T4 trajectories within subjects, between subjects, and between volumes. Within a subject and a volume, the average trajectory reasonably represents the shapes of the individual replicates. One exception is S3 at the 2-mL volume. This subject exhibited far more intertrial variability than any of the other subjects. As a result, S3's average trajectory cannot be considered an accurate reflection of the individual trials. Across the subject pool, it appears that subjects are differentially affected by bolus volume. For example, S4 exhibits remarkably similar trajectories across the two different bolus volumes, but the early part of S7's trajectory is quite different across the two volumes. The degree of between-subject variability appears large during the early period of the swallow. The trajectory's starting position is highly variable as is the prominent direction and shape of the trajectory. As the trajectory moves toward the point of peak speed, there is diminishing variability in the trajectory across subjects. For all subjects, the leg of the trajectory around the speed peak is associated with a rostral and/or dorsal movement. However, the angle with respect to the maxillary occlusal plane (x axis) of the principal movement does vary from subject to sub-

ject. For example, S1 exhibits a movement that is more oriented in the dorsal–ventral dimension, while S7 exhibits movement that is oriented along the rostral–caudal dimension. The later component of the trajectory also exhibits a great deal of across-subject variability, although many exhibit a ventrally oriented movement, presumably along the surface of the palate.

Figure 6 plots identical information as in Figure 5 but for the T3 pellet. Within most subjects, the variability between trials is relatively small. However, there are exceptions, S3 being the most notable. When comparing individual subjects across the different volumes, the overall trajectory shape is similar for most subjects, although the trajectories do appear to scale up in size at the larger volume. However, S3, S7, and S8 exhibit marked qualitative differences as a result of changing bolus volume. The prominent T3 movement direction for S7 at 2 mL is orthogonal to the prominent direction at 10 mL. Between subjects, as with T4, the early phase of the swallow is highly variable. The starting point and direction of the early movement differ markedly across subjects. Movement near peak speed is more consistent across subjects and is typically associated with primarily rostral and/or dorsal movement (for

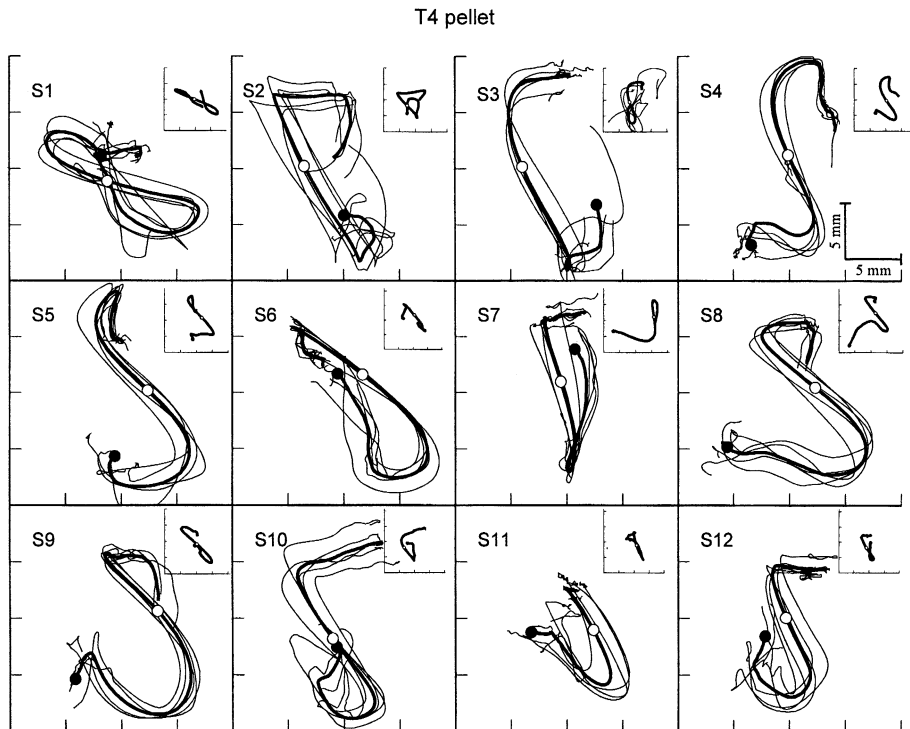


Fig. 5. Plots of time-aligned and mean position-corrected T4 trajectories at the 10-mL bolus volume. Each box represents an individual subject. Within each box, the light lines represent trajectories for individual replicates. The heavy line is the mean trajectory determined by averaging the spatial positions of the individual replicates. (●) The onset of the average trajectory; (○) the point where peak speed is attained. The axis ticks are in 5-mm increments. To compare the effect of bolus volume, the average T4 trajectory for the 2-mL volume is embedded in the upper-right corner of each plot. To demonstrate inter-replicate variability, S3 includes both the average and individual trajectories. As with the large plots, axis ticks are in 5-mm increments.

exceptions, see S7 and S8). For the majority of subjects, a ventrally oriented movement characterizes the later component of the trajectory.

Figure 7 plots trajectory information for the T2 pellet. The intertrial consistency varies for each subject. For example, at the 10-mL volume, S7, S8, and S10 have individual trials with trajectory orientation dramatically different from each other. With the exception of S3, volume does not appear to strongly influence trajectory shape. However, it does appear to influence the scaling of the trajectory. All subjects appear to produce relatively simple trajectories although their orientation at peak speed differs dramatically in some cases. Specifically, S7 and S8 have trajectories oriented in the dorsal–ventral dimension while the remaining subjects’ trajectories are decidedly oriented in the rostral–caudal dimension.

When comparing across the T4, T3, and T2 trajectories, it appears that trajectory complexity is highest for T4 and gets progressively simpler moving from T3 to T2. It should also be noted that S3 at the 2-mL volume exhibited the largest degree of variability on all three pellets.

Quantitative Analysis of Pellet Kinematics

Table 2 provides summary statistics for peak speed, movement distance, and movement duration across gender and bolus volume. Repeated-measures ANOVA revealed a number of significant findings. For peak speed, significant main effects were observed for bolus volume ($p < 0.0005$) and pellet identity ($p < 0.0005$) but not gender ($p = 0.036$). Furthermore, there was a significant pellet identity-by-bolus volume interaction ($p = 0.005$). For movement distance, significant main effects were observed for bolus volume ($p < 0.0005$), pellet identity ($p < 0.0005$), and gender ($p = 0.008$) as well as a pellet identity-by-bolus volume interaction ($p = 0.014$). For movement duration, main effects were observed for gender ($p = 0.007$), but not for bolus volume ($p = 0.018$) or pellet identity ($p = 0.239$). No significant interactions were observed. To summarize, the overall speed and distance of movement increased with a more dorsal pellet location. Increasing bolus volume resulted in an increased speed and distance of tongue move-

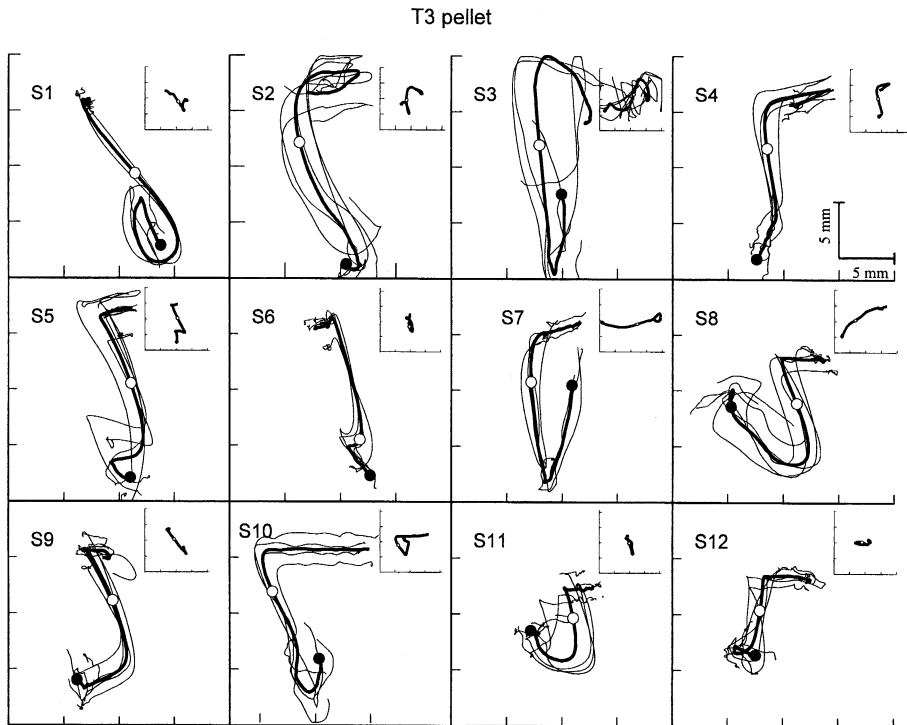


Fig. 6. Plots of time-aligned and mean position-corrected T3 trajectories at the 10-mL bolus volume. See Figure 5 for details.

ment, but the interaction suggests that the degree of volume-related change in speed and distance was not the same across the pellets. Finally, males tended to have movements that were longer and larger than females.

Interpellet Movement Timing

It was noted earlier that subjects' ensemble-averaged swallows exhibit gross similarities in the movement timing between pellets. The prominent movement of ventral pellets typically preceded that of dorsal pellets. Figure 8 provides more specific information about the relative timing of the individual pellets during the swallow. Each point represents the median time of the T2 and T3 speed peaks with respect to (wrt) the T4 speed peak. For example, if the peak speeds of T2, T3, and T4 occurred simultaneously, the data point would be located at the origin of the plot. Values that fall above the line $y = x$ indicates a T2–T3–T4 sequence. A point below the line $y = x$ indicates a T3–T2–T4 sequence. Therefore, this plot is potentially revealing about the serial order as well as the absolute temporal relations of the three pellets. Note that all of subjects' data points are located in the upper-right quadrant of the plot, above the line $y = x$, indicating a T2–T3–T4 sequence. The clustering of the data suggests that the duration

between each pellet's peak speed is smaller for the 10-mL bolus as compared with the 2-mL bolus. However, there is significant variation in the absolute timing of the events. This is particularly true for the time of the T2 peak. Also note S6 and S8, whose 2-mL volumes exhibited a large lead in both T2 and T3 with respect to T4. It should also be highlighted that these data points are based on subject medians and therefore do not reflect the within-subject variability. It turns out that the range of within-subject variability was large.

Figure 9 plots individual replicates for S6 and S11. These two subjects were selected because they represent the range of variability possible for individual subjects. Additionally, the variability in the two subjects' data appears volume-dependent. For S11, there is very little data scatter for the 10-mL volume. However, at the 2-mL bolus volume, there is a large amount of variability. Not only are the absolute timing differences apparent, but also the sequencing is different for one replicate. S6 exhibits even more extreme values for the 2-mL bolus.

Discussion

First, certain tongue movement patterns are common to the subject group. These include a large, princi-

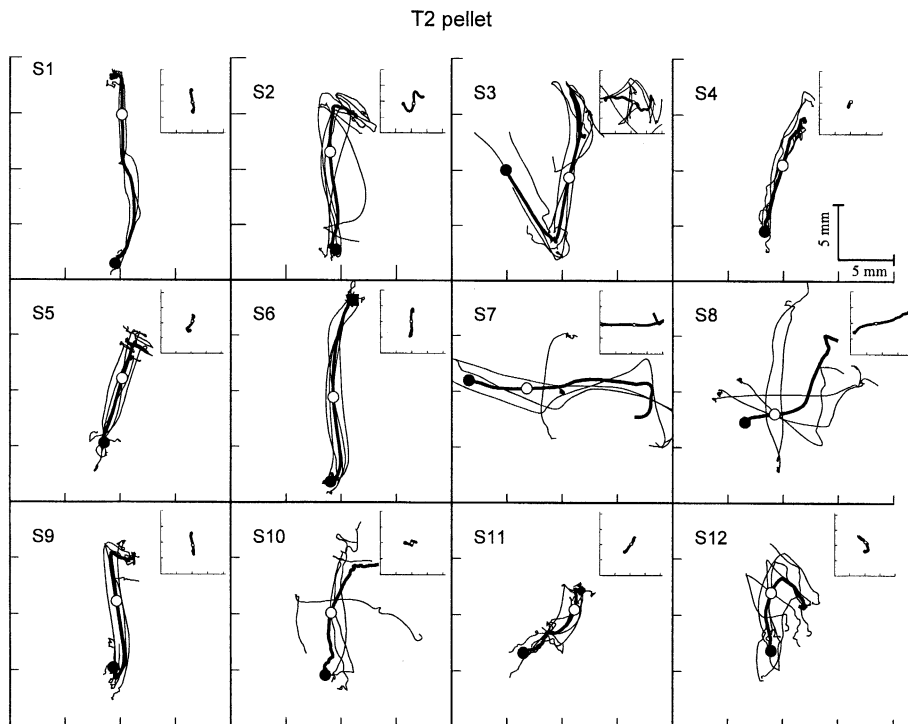


Fig. 7. Plots of time-aligned and mean position-corrected T2 trajectories at the 10-mL bolus volume. See Figure 5 for details.

Table 2. Descriptive statistics (mean and standard deviation) for kinematic measures.

Fleshpoint	Gender		Duration (ms)		Distance (mm)		Peak speed (mm/s)	
			2 mL	10 mL	2 mL	10 mL	2 mL	10 mL
T4	M	\bar{x}	169	192	15.0	19.1	173	206
		s_y	22.5	49.2	3.54	2.38	26.0	24.0
	F	\bar{x}	146	151	12.0	14.1	153	180
		s_y	16.8	22.3	2.58	3.05	37.5	26.1
T3	M	\bar{x}	167	179	9.6	15.2	115	164
		s_y	28.8	36.1	0.53	2.92	27.8	17.4
	F	\bar{x}	131	152	6.1	10.0	85	129
		s_y	33.2	34.2	3.45	2.86	35.4	28.7
T2	M	\bar{x}	137	193	5.3	10.5	63	106
		s_y	28.1	57.60	2.38	4.53	29.4	31.0
	F	\bar{x}	147	139	4.7	6.4	53	78
		s_y	13.0	29.0	1.78	3.00	20.8	33.6

pally rostral movement of the tongue and a ventral-to-dorsal temporal progression of this movement. Furthermore, dorsal tongue movement is typically larger and faster than ventral tongue movement. Presumably these patterns reflect the movement associated with bolus propulsion through the oral cavity and into the pharynx and have been observed in previous studies [6,7]. There is also a consistent trend for the subjects to use larger movement excursions and speeds when swallowing larger bolus vol-

umes. This finding is also consistent with some previous reports [7]. Finally, males exhibit movement excursions of larger extent and duration than females. Although the source of these gender differences is uncertain, the men probably have larger oral cavities than the women. As a result, men would require larger tongue excursions to make the appropriate palatal contact in order to efficiently move the bolus through the oral cavity. While we did not attempt to disambiguate the influences of gender and maxillo-

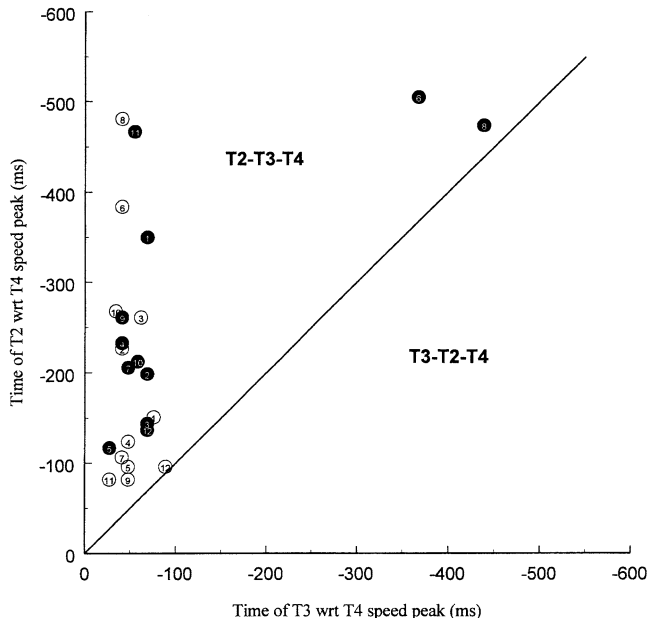


Fig. 8. The time of the T2 speed peak versus the time of the T3 speed peaks with respect to the T4 speed peak. Each point represents the median of the individual's replicates. The (●), the 2-mL bolus volume; (○), the 10-mL bolus volume. The number inside each symbol identifies the subject. Each region of the plot that contains data has been labeled to aid in identification of the event order of the pellet speed peak.

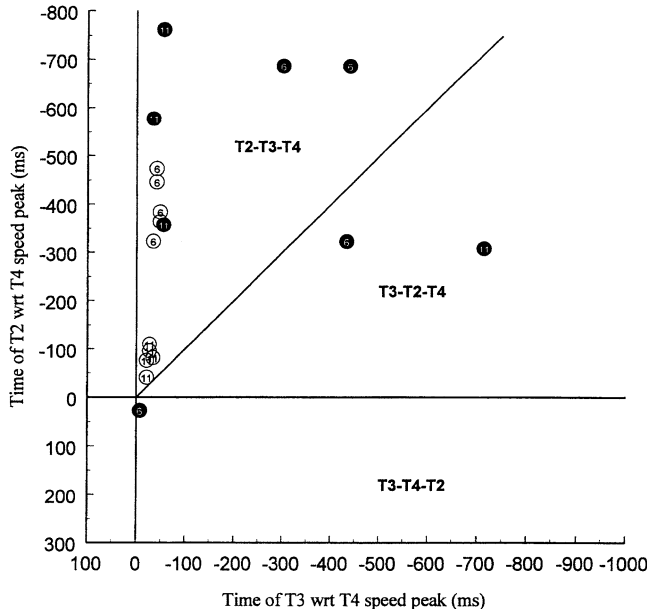


Fig. 9. The time of the T2 speed peak versus the time of the T3 speed peaks for two subjects (S6 and S11) at a 2-mL (●) and 10-mL (○) bolus volumes. Each region of the plot that contains data has been labeled to aid in identification of the event order of the pellet speed peak.

facial morphology on tongue movement patterns during swallowing, the x-ray microbeam database does contain some anthropomorphic data that may be used to address this issue [8]. Regardless of the reason, these results suggest that the development of normative measures of tongue kinematics for swallowing should be sensitive to gender influences.

A striking finding of this study is the range of unexplained variation across the data. For example, there is substantial intersubject variation in T1 and jaw (MI and MM) activity. While some subjects kept the jaw largely immobile, others elevated it in the early phase of the swallow, possibly to assist the tongue as it moved toward the palate. T1 either

exhibited rostral movement or was immobile in the region of the hard palate. This may reflect different bolus-holding strategies. Subjects with minimal T1 activity may be holding the bolus behind T1 and only using T2–T4 to propel the bolus into the pharynx. In such a case, the palatal contact of T1 may serve to prevent anterior leakage of the bolus. Subjects using T1 during liquid swallowing probably hold their bolus more ventrally and require T1 to assist in transporting the bolus. However, these accounts must be considered speculative since the bolus cannot be observed during x-ray microbeam studies.

Those pellets whose trajectories were evaluated in detail (T2–T4) typically exhibited large rostral movement qualitatively similar to that found in Stone and Shawker's [4] stage two and Martin's [7] leg three. However, the early and late components of the swallow, while often consistent within an individual, were highly variable across individuals. Although the functional role of these early and late components can only be inferred because bolus position is not known, one may speculate that, with the exception of the basic rostral excursion, there exists a rather large margin of freedom in permissible tongue trajectories during liquid swallowing. Although our sample size of 12 subjects is larger than equivalent studies to date [4–7], it is still not large enough to establish whether modal patterns of tongue movement exist or if the patterns are represented by a continuous distribution.

A large margin of freedom also appears to be allowed with respect to the relative timing of T2, T3, and T4 movement. Although there is a general tendency for the prominent movement of each pellet to be timed in the same rank order, the absolute timing between each pellet's movements was quite variable across subjects and bolus volumes. The permissible spatial and temporal variability appears to be particularly large for a few individuals at the 2-mL bolus volume (for example, S3 in Figs. 5–7 and S6 and S11 in Fig. 9). One might speculate that for these individuals, the presence of a larger bolus provides greater somatosensory input, which in turn may produce more stable movement patterns. Functionally, this may serve to reduce the risk of poorly timed bolus transport into the pharynx and possible aspiration.

While the variability observed in the fleshpoint patterns is not entirely consistent with previous reports of a unitary movement sequence [6,7], it is consistent with other recent reports showing considerable intersubject variability in tongue, larynx, and other movements during deglutition [12–14]. This variability probably has several sources, including the aforementioned anatomic [12], gender [13], and bolus volume influences, as well as differences in patterns of

tongue–palate contact [14]. Additionally, such variability is consonant with recent work that shows that swallowing is controlled by distributed neural networks that involve several areas of cortex as well as a number of subcortical structures [16–19]. This complex neural control system serves to adjust the pattern of deglutition, at least in the oral stages, to a number of different factors. It may be the case that individual subjects probably can exercise a considerable degree of voluntary control over the detailed pattern of movements.

This study and others that use x-ray microbeam technology serve to complement other methods that typically reveal bolus movement, interstructural coordination, or gross movements of a structure such as the tongue. The ultimate goal is to assemble the data from different methods into a coherent picture of swallowing movements. To aid in this goal, future studies should address the following issues: First, it should be established whether the subject's bolus-holding strategy plays a significant role in determining the tongue movement patterns that follow. Second, we need to distinguish gender-based differences from those attributed to different maxillofacial morphology. Third, kinematic studies with larger sample sizes would help determine if individual subjects cluster into a finite set of tongue movement patterns. As noted earlier, the x-ray microbeam database, which has in excess of 50 subjects, may serve this purpose. Alternatively, other fleshpoint tracking technologies such as electromagnetometry may be exploited. Last, the application of data transformation procedures similar to those used in speech production research for subject normalization [20] may effect a reduction in overall intersubject variability and ultimately provide more interpretable data. From this study, we may conclude that although broad similarities were observed, the variability across subjects is large enough to make it surprisingly difficult to provide a low-dimension quantitative description of the tongue kinematics during liquid swallowing.

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