ORIGINAL ARTICLE

Fluoroscopic Evaluation of Tongue and Jaw Movements During Mastication in Healthy Humans

**Hiroshige Taniguchi · Koichiro Matsuo · Hideto Okazaki · Mitsumasa Yoda ·
Haruhi Inokuchi · Marlis Gonzalez-Fernandez · Makoto Inoue · Jeffrey B. Palmer**

Abstract When chewing solid food, part of the bolus is propelled into the oropharynx before swallowing; this is named stage II transport (St2Tr). However, the tongue movement patterns that comprise St2Tr remain unclear. We investigated coronal jaw and tongue movements using videofluorography. Fourteen healthy young adults ate 6 g each of banana, cookie, and meat (four trials per foodstuff). Small lead markers were glued to the teeth and tongue surface to track movements by videofluorography in the anteroposterior projection. Recordings were divided into jaw motion cycles of four types: stage I transport (St1Tr), chewing, St2Tr, and swallowing. The range of horizontal tongue motion was significantly larger during St1Tr and chewing than during St2Tr and swallowing, whereas vertical tongue movements were significantly larger during chewing and St2Tr than during swallowing. Tongue movements varied significantly with food consistency. We conclude that the small horizontal tongue marker movements during St2Tr and swallowing were consistent with a "squeeze-back" mechanism of bolus propulsion. The vertical dimension was large in chewing and St2Tr, perhaps because of food particle reduction and transport in chewing and St2Tr.

Keywords Swallowing · Mastication · Tongue · Mandible · Fluoroscopy · Biomechanics

H. Taniguchi · H. Okazaki · M. Yoda · H. Inokuchi ·
M. Gonzalez-Fernandez · J. B. Palmer
Department of Physical Medicine and Rehabilitation,
Johns Hopkins University, Baltimore, MD, USA

H. Taniguchi (✉) · M. Inoue
Division of Dysphagia Rehabilitation, Niigata University
Graduate School of Medical and Dental Sciences,
2-5274 Gakkocho-dori, Chuo-ku, Niigata 951-8514, Japan
e-mail: taniguchi1649@dent.niigata-u.ac.jp

K. Matsuo
Department of Special Care Dentistry,
Matsumoto Dental University, Nagano, Japan

J. B. Palmer
Department of Otolaryngology, Head and Neck Surgery,
and Center for Functional Anatomy and Evolution,
Johns Hopkins University, Baltimore, MD, USA

Introduction

Feeding behavior requires complex and integrated activation of muscles in the jaw, face, tongue, pharynx, and larynx. The glossal muscles play a particularly important role because of their extraordinary dexterity. Numerous studies have assessed the functional contribution of tongue muscles to food intake, bolus formation, and transport from the oral cavity to the pharynx during mastication using videofluorography (VFG) and photographic images [1–4], usually in the lateral projection. Recent technological advances have enabled accurate measurement of tongue–palate pressure during chewing and swallowing using an intraoral appliance with multiple pressure sensors [5–9], thus recording precise measurements of tongue activity during mastication and swallowing. Nonetheless, our knowledge of these complex processes is rather limited. Most quantitative information has been obtained through the study of jaw movements and the mechanics of occlusion during chewing [2, 10], with little attention paid to the role of the tongue in these processes.

Palmer et al. [3] reported that solid food can be processed and transported through the fauces to the pharynx before the onset of the swallowing reflex, while most of the food is still in the oral cavity, and proposed a "process model" of human feeding. According to this model, the feeding sequence is divided into several distinct phases of preparing food for

swallowing, namely, ingestion, stage I transport (St1Tr), processing (chewing), and stage II transport (St2Tr). Initially, food enters the mouth (ingestion) and a bolus of this food is moved (by St1Tr) from the anterior oral cavity to the post-canine teeth where it is processed (chewed). The chewing phase modifies the food texture in preparation for swallowing (i.e., reduces food particle size and mixes it with saliva for lubrication). Finally, the bolus is moved toward the pharynx (by St2Tr) to be imminently swallowed. St2Tr is a significant oral behavior distinct from chewing and swallowing [2, 11]. Although the patterns of jaw and tongue movements during St2Tr are similar to those during chewing (i.e., tongue movement is cyclical and is linked to jaw movement in both spatial and temporal domains), St2Tr is further characterized by exaggerated upward movements of the tongue that compress food against the palate during the jaw-closing phase. In addition, the area of tongue–palate contact is initially anterior before expanding posteriorly, squeezing triturated food through the fauces for storage in the pharynx prior to swallowing. Transport is described as occurring during the occlusal and jaw-opening phases of the jaw motion cycle. During chewing, food particle reduction occurs particularly during the jaw-closing phases, so it may be possible for chewing and St2Tr to occur during the same jaw motion cycle.

Swallowing is a finely tuned response driven by a central pattern generator but which varies with afferent inputs associated with bolus volume, consistency, and taste [12, 13]. Many studies have explored the effects of bolus consistency on tongue movement during mastication [14] and swallowing [8, 9, 15–17] and have suggested that the action of swallowing triturated hard food involves prolonged oral transit and higher tongue–palate pressure, in contrast to the situation when swallowing softer foods. On the other hand, it remains to be determined how bolus viscosity, cohesion, and adhesion affect tongue–palate pressures. Other reports have provided preliminary evidence on how the tongue, jaw, and hyoid are affected by food toughness [3, 18, 19]. However, the effect of food texture on tongue movement per se has not been studied explicitly during St2Tr. Similarly, few studies have employed anteroposterior (A-P) imaging with VFG to investigate St2Tr in the coronal plane. The present study was designed to record VFG in the A-P projection and to evaluate the spatial characteristics of tongue and jaw movements during St2Tr and the effects of food texture on St2Tr.

Materials and Methods

Participants

Fourteen healthy subjects (eight males and six females) between 19 and 34 years of age [23.0 ± 4.0 years (mean ± SD)] participated voluntarily in the project.

A prestudy questionnaire revealed no history of dysphagia, speech or voice disorders, dental problems, otolaryngeal pathology, pulmonary or neurological disease, or structural disorders, and that no subjects were taking any medications likely to perturb swallowing. Each participant gave verbal and written informed consent prior to the experimental procedures, which were approved by the relevant institutional review board.

Data Collection

Small lead discs (4-mm diameter × 0.4-mm thickness) were glued to the labial surfaces of the right (RC) and left (LC) lower canines as radiopaque markers of lower-jaw movement (Fig. 1). Markers were also glued bilaterally to the buccal surfaces of the upper first molars to serve as reference points for data reduction and analysis. The subject was seated comfortably in a chair with the occiput resting lightly against a headrest to reduce head movement during the procedures.

VFG recordings of each participant were made at 90 kV using a 12-in. image intensifier during the complete feeding sequence from ingestion to terminal swallow. Prior to data collection, each subject swallowed liquid barium during
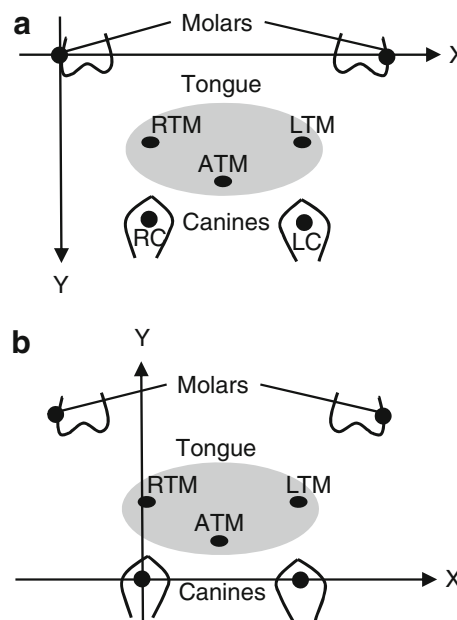

Fig. 1 Position of *upper* and *lower* jaw and tongue markers, visualized in the anteroposterior projection. Lead discs were attached to the buccal surfaces of the lower right canine (RC), lower left canine (LC) and the upper first molars, and to the dried dorsal surface of the tongue (*ATM* anterior tongue marker, *RTM* and *LTM* right and left side lateral tongue markers, respectively). **a** Marker positions are expressed as *X* and *Y* coordinates relative to the upper occlusal plane. **b** Data were analyzed relative to the lower occlusal plane, with the *X* axis formed by a *line* between the lower canine markers. See text for details

VFG in both the A-P and lateral projections to ensure that there were no visible structural or coordination abnormalities in swallowing. VFG images were collimated to visualize the entire mouth and pharynx such that the borders of the image were the lips (anteriorly), hard palate (superiorly), and cervical esophagus (inferiorly). The experimental protocol used VFG in the A-P projection, with the maximum exposure time limited to 5 min.

Each subject was asked to perform two protocols. In protocol 1, subjects ingested 6 g each of banana (soft texture), cookie (brittle texture), and meat (fibrous texture) without any tongue markers (WoT). Foods were always presented in that order for each trial, and all food samples were dusted with barium sulfate powder (Varibar; EZ–EM Inc., Westbury, NY, USA) before ingestion. This trial was performed once for each food. Protocol 2 was similar to protocol 1 but was performed with tongue markers in place (WT). Three additional radiopaque markers were attached to the dried dorsal surface of the tongue using dental cement. These were an anterior tongue marker (ATM; placed on the midline of the tongue 1 cm posterior to the tongue tip) and two lateral markers placed on the right (RTM) and left (LTM) edge of the tongue as posteriorly as possible without eliciting the gag reflex (about 2 cm posterior to the ATM, see Fig. 1). Subjects ate the same foods twice in the same order as in protocol 1. In protocol 2, however, barium was not used since it can obscure the radiopaque tongue markers. Six subjects completed this protocol (six trials), but six other subjects had long masticatory sequences that precluded the completion of the full experimental procedure within the 5-min limit of radiation exposure time. Of the remaining two subjects, one completed three of six trials, and the other completed two (Table 1). All subjects were included in the analysis despite the data being partially incomplete because exclusion of slow-eating individuals had the potential to create experimental bias.

All recordings were made at 30 frames per second with a digital video recorder. A time stamp was simultaneously recorded and overlaid on each video frame, and every recording was converted to a digital video file for analysis.

Data Reduction and Analysis

Jaw and tongue movements were visually evaluated using the slow-motion and stop-frame functions of VirtualDub

Table 1 Trials completed by number of subjects in protocol 2

No. of subjects	6	4	2	1	1
Banana	2	2	2	2	1
Cookie	2	1	1	0	0
Meat	2	2	1	1	1

software (ver. 1.9.11). After careful reviewing of the videos, we performed a four-step data reduction procedure, as follows:

Step 1 Each recorded sequence (from ingestion to the end of the first swallow) was divided into jaw motion cycles, and each cycle was classified as one of four types: St1Tr, chewing, St2Tr, or swallowing (Figs. 2a and 3a). St1Tr was defined as beginning at the time of maximum jaw opening (maximum gape) prior to transport from the anterior oral cavity to the postcanine region. The end of St1Tr was defined as the moment of the first tooth–food–tooth contact in the postcanine region, which was followed by chewing. Thereafter, jaw motion cycles of chewing and St2Tr were defined as starting at the time of a local maximum gape (maximum jaw opening) and ending at the next. For protocol 1, which included barium but no tongue markers, St2Tr was identified by observing the tongue squeezing food against the palate during jaw closing and propelling it posteriorly through the faucial arches during the following phase of jaw motion (Fig. 2b). However, when a jaw motion cycle appeared to include food transport but did not clearly show the tongue squeezing food against the palate, the cycle was designated as a chewing cycle so as to maximize homogeneity among St2Tr cycles. If a cycle included food reduction during the jaw-closing phase and met the precise definition of St2Tr during the occlusal and jaw-opening phases, it was classified as a St2Tr cycle. In contrast, the food was poorly visualized in protocol 2, which had tongue markers but no barium, necessitating a different mechanism to distinguish between chewing and St2Tr cycles. St2Tr cycles were classified by first identifying the characteristic jaw movement seen during St2Tr in protocol 1, where the tongue moves upward to squeeze against the palate during the occlusal and jaw-opening phases (Fig. 3b). The onset of swallowing was defined for protocol 1 as beginning at the time of maximum gape just prior to the pharyngeal phase of swallowing and ending when the trailing edge of the bolus passed through the upper esophageal sphincter. For protocol 2, the classification of the swallowing phase was predicated on rapid pharyngeal elevation and contraction of the muscles in the lateral wall of the pharynx

Step 2 St2Tr cycles were identified by two expert observers who selected an appropriate range of images that were then assessed by consensus of

Fig. 2 Representative recordings of subjects without tongue markers. **a** Line graph of marker position over time for a representative digitized sequence of a subject consuming banana (*X* and *Y* range of right canine is denoted by RCX and RCY, respectively; *X* and *Y* range of left canine is denoted by LCX and LCY, respectively). The whole sequence from mastication until first swallow was divided into four stages: stage I transport (St1Tr), chewing (chew), stage II transport (St2Tr), and swallowing (swal).
b Anteroposterior fluorographic images showing the hard palate (*solid line*), dorsal surface of the tongue (*dotted line*), and the position and shape of the foods (*shaded*). St2Tr was defined as a squeezing motion of the tongue upward into the hard palate during jaw closure (*left*) and as the presence of food beyond the hard palate during the jaw-opening phase (*right*)
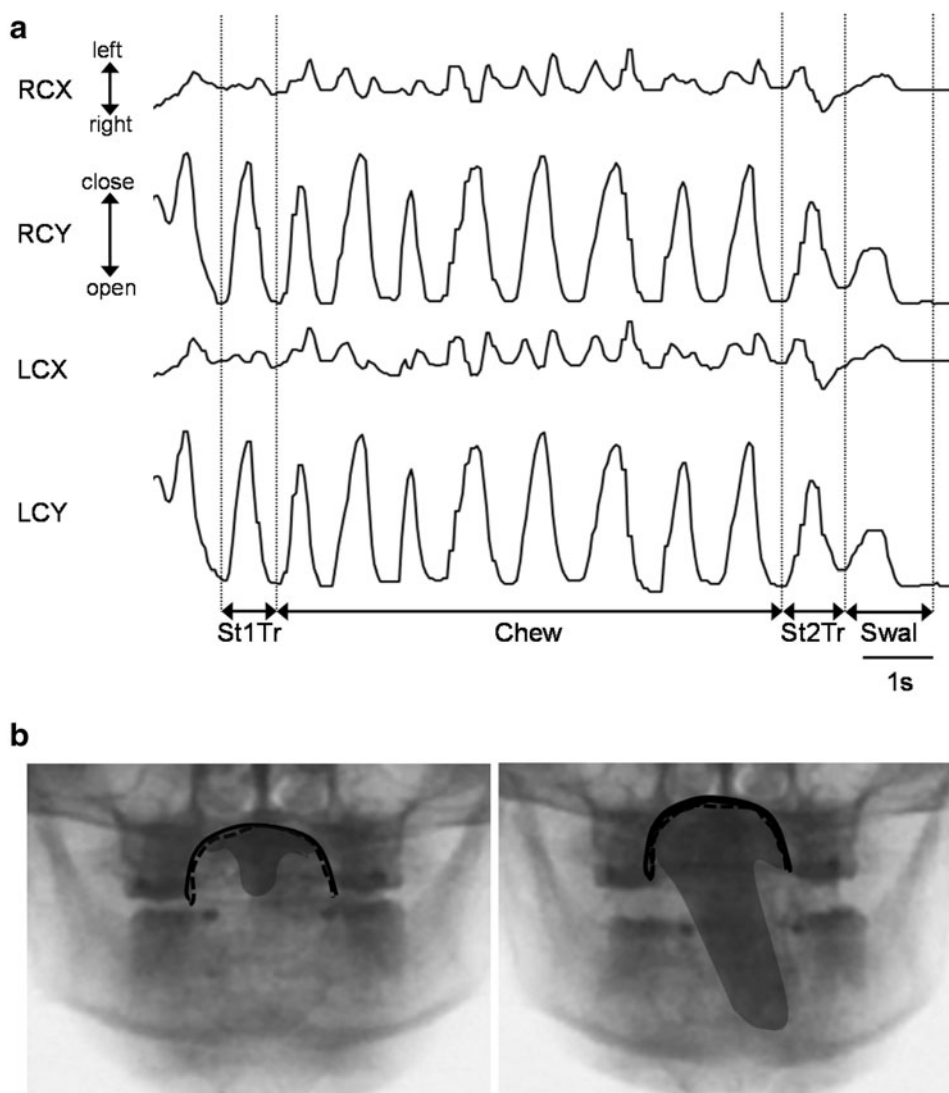

five expert observers. The number of St1Tr, chewing, St2Tr, and swallowing cycles was counted for each recording in protocol 1, without tongue markers. In protocol 2 (with tongue markers), the radiopacity and constant motion of the teeth, jaw, and tongue made it difficult to visualize the position of the tongue markers and the precise shape of the food in some video frames, so only frames for which the cycle type was clearly discernible were included in the analysis

Step 3   The position of the canine and tongue markers in the recordings was identified on each frame by an experienced research assistant. Positions were expressed as Cartesian (*X* and *Y*) coordinates relative to the upper and lower reference frames. The *X* axis approximated the occlusal planes of the upper and lower teeth, respectively. The horizontal

or *X* axis of the upper reference frame passed through the upper molar markers on each side (Fig. 1a). The right upper molar marker served as the origin (0,0 coordinate), while a line perpendicular to the *X* axis passing through this marker defined the vertical or *Y* axis. The reference frame was automatically recalculated for every video frame, thus correcting for head movement. The horizontal or *X* axis of the lower reference frame passed through the lower canine markers on each side, and its vertical or *Y* axis passed through the right lower canine marker (Fig. 1b). This lower reference frame enabled us to differentiate between jaw motion and tongue marker movements

Step 4   The positions of the lower canine markers and tongue markers (where present) were expressed as Cartesian coordinates relative to the upper and lower reference frames in every frame. These motions

Fig. 3 Representative recordings in subjects with tongue markers. **a** Line graph of motion over time for a representative digitized sequence of a subject consuming meat. The whole sequence from mastication until first swallow was divided into four stages: stage I transport (St1Tr), chewing (chew), stage II transport (St2Tr), and swallowing (swal). RCX and LCX denote the X range of right and left canines, respectively; RCY and LCY denote the Y range of right and left canines, respectively; ATMX, RTMX, and LTMX denote the X range of the anterior and right and left tongue markers, respectively; ATMY, RTMY, and LTMY denote the Y range of the anterior and right and left tongue markers, respectively. **b** Anteroposterior fluorographic images showing the hard palate (*solid line*) and dorsal surface of the tongue (*dotted line*). St2Tr cycles were defined as an upward squeezing movement of the tongue into the hard palate during jaw closure (*left*), distinct from non-St2Tr cycles that did not have this upward thrust (*right*)
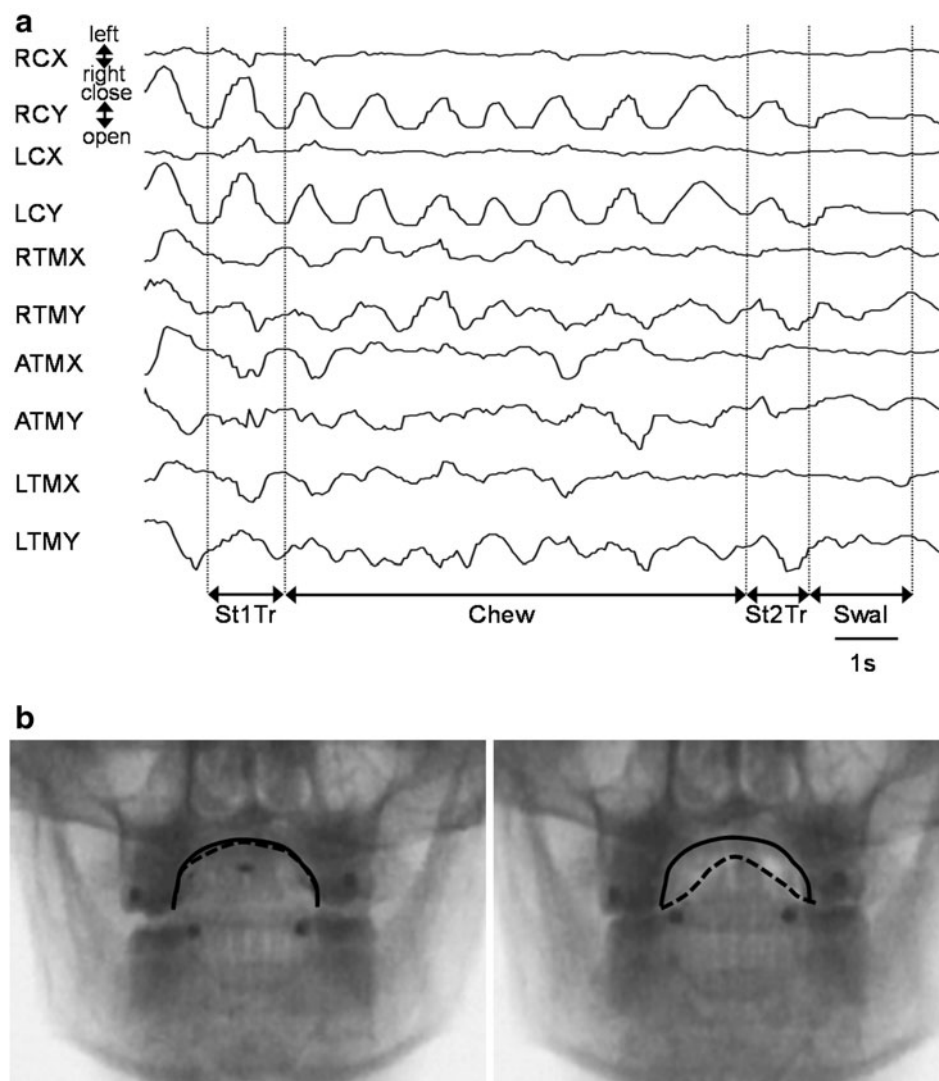
were recorded numerically in spreadsheet files. Tongue and jaw motion patterns were displayed in two-dimensional scatterplots of vertical versus horizontal movement during specific cycles. Motions were further illustrated in graphs of position over time. For each marker, we calculated the magnitude of the horizontal (X) and vertical (Y) components of marker movement as the difference between the maximum and minimum values in each cycle

horizontal or vertical component of motion by cycle. Factors included cycle type (four variables: St1Tr, chewing, St2Tr, and swallowing) and food (three variables: banana, cookie, and meat). The critical value of P was 0.05. All values are expressed as mean $\pm$ SD.

Results

In this study, we examined jaw and tongue movements during a feeding sequence recorded in the A-P VFG projection.

Table 2 shows the number of cycles clearly identified for analysis. Table 3 shows the number of identified cycles in recordings with (WT) and without (WoT) tongue markers. All WoT recordings were used to measure movements of the canine markers (and thus the jaw), described as the X and Y ranges of the RC and LC markers. WT recordings were used to measure tongue movements,

Statistical Analysis

STATISTICA software (ver. 7; Systat, San Jose, CA, USA) was used for statistical analyses. Data sets were analyzed for any significant differences by repeated-measures analysis of variance (ANOVA) with Tukey's test for pairwise comparisons. In the motion analyses, the independent variable was the

Table 2 Number of motion cycles included and excluded from analysis

	876 (WoT)	1,637 (WT)
Cycles included	848	1,449
Cycles excluded	28	188

WoT without tongue markers, *WT* with tongue markers

Table 3 Number of St1Tr, chewing, St2Tr, and swallowing cycles included

		No. of subjects	Total no. of trials	St1Tr	Chewing	St2Tr	Swallowing
WoT				42	732	32	42
	Banana	14	14	14	117	12	14
	Cookie	14	14	14	277	14	14
	Meat	14	14	14	338	6	14
WT				63	1,275	46	65
	Banana	14	27	25	340	15	27
	Cookie	14	17	16	336	15	16
	Meat	14	24	22	599	16	22

WoT without tongue markers, *WT* with tongue markers, *St1Tr* stage I transport, *St2Tr* stage II transport

described as the X and Y ranges of the ATM, RTM, and LTM. There was no significant interaction between stage and food for any of these variables (Tables 4, 5). Furthermore, there were no significant differences between males and females for any variable (Student's t-test; $P = 0.6$–0.9).

Stage-Specific Differences in Jaw Movements

Figure 4a shows the RC and LC ranges for each cycle for comparing the magnitude of jaw movement in each stage. In the horizontal dimension, the average X range of both RC (RCX) and LC (LCX) during chewing was significantly larger than those in St1Tr and St2Tr ($P < 0.05$). In the vertical dimension, the average Y range of both RC (RCY) and LC (LCY) in St1Tr and chewing was significantly larger than that in St2Tr and swallowing ($P < 0.05$). There was no significant difference between St2Tr and swallowing in either the X or the Y range plane. Furthermore, data from the right and left sides were nearly identical.

Stage-Specific Differences in Tongue Movements

Tongue marker movements were initially evaluated relative to the occlusal plane of the upper teeth. Figure 5a shows the ATM, RTM, and LTM ranges for each cycle to compare the magnitude of tongue movement in each stage. The average X range in St1Tr and in chewing was significantly larger than that in St2Tr and in swallowing ($P < 0.05$). There was no significant difference in X ranges between St2Tr and swallowing. The average Y range was generally smaller in swallowing than those in other stages, but this was not identical among the positions. There were no significant differences in Y ranges between chewing and St2Tr.

Effects of Food Consistency on Jaw and Tongue Movements

Figures 4b and 5b show the ranges of jaw and tongue movements for each cycle to compare among foods. Food consistency had significant effects on the range of certain jaw and tongue markers.

For horizontal jaw movements, RCX and LCX were significantly larger for cookie than for banana ($P < 0.05$).

In the vertical dimension, RCY and LCY were significantly larger for cookie and meat than for banana ($P < 0.05$). This was the case on both right and left sides.

For horizontal tongue movements, the only significant difference was in the ATM, which was larger for cookie than for banana ($P < 0.05$). There were no significant differences between RTM and LTM for any food. In the vertical dimension, the RTM and LTM were significantly larger for meat than for banana ($P < 0.05$).

Tongue Movements Relative to the Lower Occlusal Plane

The tongue movements described above were measured relative to the occlusal plane of the upper teeth. We performed a secondary analysis using the occlusal plane of the lower teeth as the reference frame. The secondary analysis revealed qualitatively identical patterns of tongue marker movement as in the primary analysis, so these results are not reported any further.

Discussion

Numerous reports have used combinations of EMG, VFG, and intraoral pressure recordings to investigate the functional role of the tongue in chewing and swallowing. St2Tr is now recognized as being distinct from chewing and swallowing, but few reports have explored the tongue movements that occur during St2Tr in human feeding [3, 11]. This study investigated patterns of jaw and tongue movements in the A-P projection, with particular focus on the movements comprising St2Tr during the feeding sequence.

Table 4 Analysis of variance: canine marker range of motion

		RCX		RCY		LCX		LCY	
	DF	F ratio	P	F ratio	P	F ratio	P	F ratio	P
Stage	3	6.2	<0.001	22.9	<0.001	5.6	<0.001	25.1	<0.001
Food	2	2.5	0.085	6.7	<0.01	2.5	0.083	6.3	<0.01
Stage × food	6	1.5	0.16	1.9	0.0733	1.4	0.988	1.9	0.726

DF degrees of freedom, *RCX* movement of the right lower canine in the *X* axis, *RCY* movement of the right lower canine in the *Y* axis, *LCX* movement of the left lower canine in the *X* axis, *LCY* movement of the left lower canine in the *Y* axis

Table 5 Analysis of variance: tongue marker range of motion

		RTMX		RTMY		LTMX		LTMY		ATMX		ATMY	
	DF	F ratio	P	F ratio	P	F ratio	P	F ratio	P	F ratio	P	F ratio	P
Stage	4	26.2	<0.01	19.1	<0.01	23.9	<0.01	16.4	<0.01	28.6	<0.001	23.1	<0.001
Food	2	5.2	<0.001	5.5	<0.001	6.8	<0.001	9.2	<0.001	10.5	<0.001	10.5	<0.001
Stage × food	8	0.5	0.82	1.6	0.118	0.2	0.988	0.5	0.837	0.6	0.749	1	0.443

DF degrees of freedom, *RTMX X* range of right tongue marker, *RTMY Y* range of right tongue marker, *ATMX X* range of anterior tongue marker, *ATMY Y* range anterior tongue marker, *LTMX X* range of left tongue marker, *LTMY Y* range of left tongue marker

Range of Jaw Movement During St2Tr

Jaw movements during feeding in man and other mammals have been recorded by various techniques, including VFG [10, 20–22]. Previous reports revealed a wide variety of chewing patterns but concluded that these could be represented by a small number of characteristic patterns of movement. From our results, the horizontal component of movement (RCX and LCX) was generally larger during chewing than during St1Tr and St2Tr. On the other hand, the vertical component (RCY and LCY) was not significantly different between St1Tr and chewing, although it was still larger than in St2Tr and swallowing. As no significant difference was noted between St2Tr and swallowing in either the X or Y range planes, this suggests that jaw movement patterns during St2Tr resemble those during swallowing, at least in terms of magnitude in the horizontal and vertical planes.

Schwartz et al. [23] described patterns of jaw movement during mastication in conscious animals and showed that the whole sequence of mastication from ingestion to swallowing can be divided into three consecutive series, distinguished by the form of jaw movement, termed "preparatory," "reduction," and "preswallowing." The authors suggested that food was transported back to the molar teeth during the preparatory series, ground up during the reduction series, and formed into a bolus for swallowing during the preswallowing series. In this respect, these series are ostensibly identical to the St1Tr, chewing, and St2Tr phases in the present study. Although Schwarz et al. did not measure any parameters of swallowing per se, the cycle duration of the preswallowing (probably St2Tr) series was much longer than that of the reduction (chewing) series. Naganuma et al. [24] also demonstrated that jaw movement was more prolonged during swallowing than during chewing. Although the neuronal mechanisms that regulate the muscle activities related to jaw movements in these discrete stages have not yet been clarified, we hypothesize that jaw movements during St2Tr may be distinct from those during chewing and adjust in response to feedback relating to bolus position or texture in order to prepare the bolus for swallowing.

Motion of the Tongue Surface During St2Tr

The horizontal component of tongue movement (ATMX, RTMX, and LTMX) was generally larger during St1Tr and chewing than during St2Tr and swallowing. There were no significant differences in X ranges between St2Tr and swallowing. On the other hand, the vertical component of range (ATMY, RTMY, and LTMY) was generally smaller during swallowing than at any other stage. Thus, the range of tongue movement during St2Tr seems to be similar to that during swallowing in terms of horizontal direction but not vertical direction, in agreement with previously published results comparing jaw movements in the sagittal plane [3]. Significant differences have also been noted between food transport and other masticatory functions in macaques, where rostrocaudal tongue spread was at its largest in food transport cycles [20], and several other reports have characterized and compared the shape changes that occur in the tongue during swallowing and feeding [25–28]. These reports suggested that the tongue has an array of possible movements and that enormous dexterity
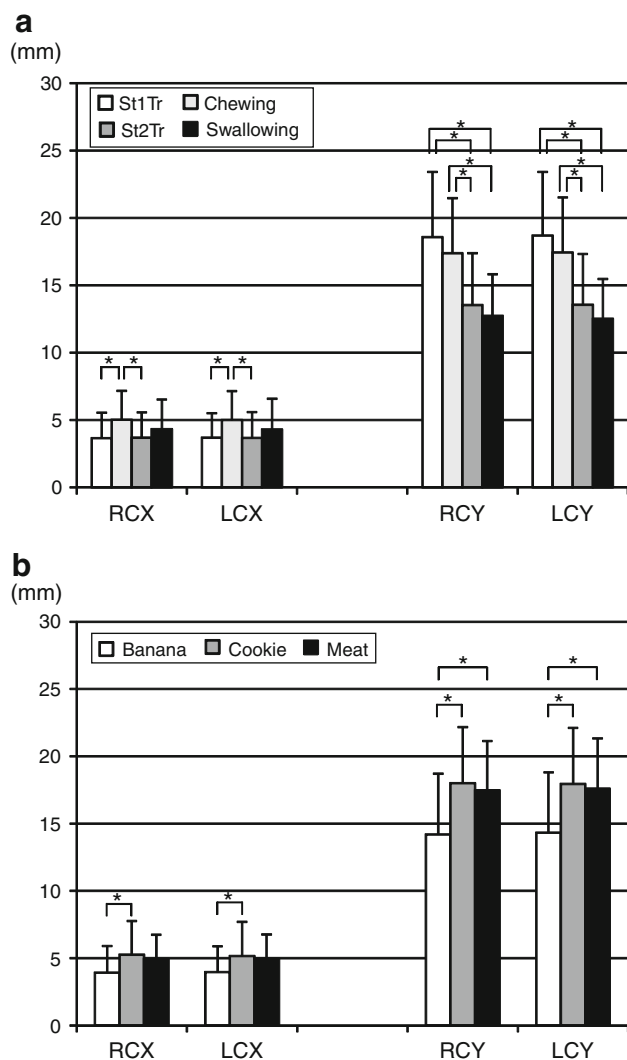
Fig. 4 Average range of canine marker movement for each type of cycle in subjects without tongue markers. **a** X and Y values were compared among stages. **b** X and Y values were compared among foods. RCX and RCY denote the X and Y range of the right canine, respectively; LCX and LCY denote the X and Y range of the left canine, respectively

Fig. 5 Average range of canine marker movement for each cycle type in subjects with tongue markers. **a** X and Y values were compared among stages. **b** X and Y values were compared among foods. ATM, RTM, and LTM denote the range of the anterior and right and left tongue markers, respectively

of the tongue is required not only to aid mastication and shape the food bolus, but also to propel it sequentially through the oral cavity from the lips to the esophagus. The tongue is particularly closely linked to the later stages of this process, namely, St2Tr, which is accomplished by squeezing the food upward against the palate and requires vertical dynamic movement of the tongue surface. The area of tongue–palate contact expands posteriorly, squeezing the bolus back toward the pharynx. We suggest that the small X range of tongue marker motion in the horizontal dimension during St2Tr and the oral propulsive stage of swallowing reflects their shared squeeze-back mechanism of food transport from the oral cavity to the pharynx.
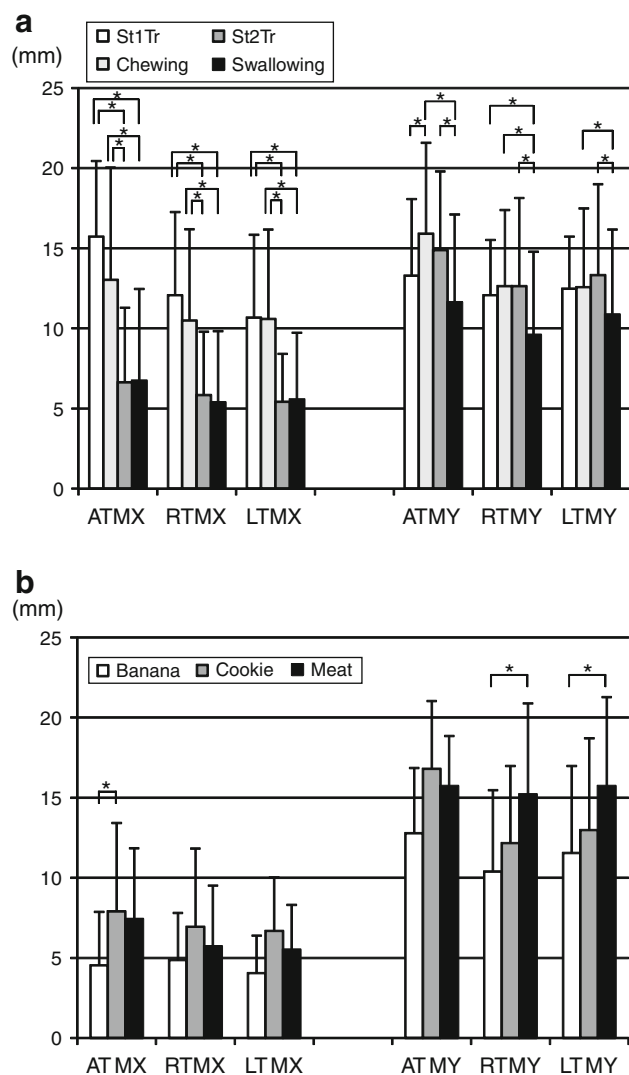
Effects of Food Consistency on Jaw and Tongue Movement During St2Tr

The effect of food consistency on swallowing has been reported, with hard foods leading to a prolongation of oral transit time [1–4] and a decrease in the velocity of lingual and pharyngeal peristalses [4, 6]. German et al. [26] indicated that the timing of jaw motion cycles in macaques depended on intraoral sensory feedback; the duration of slow-closing phases and of slow-opening phases were correlated directly and inversely, respectively, with food hardness. Furthermore, a previous study in humans indicated that tongue movements in the sagittal plane were

similar during late food transport and swallowing, regardless of food consistency [2].

In the present study, we found that differences in tongue surface movement during St2Tr were associated with food consistency. It can be assumed that during St2Tr, the horizontal range of the ATM when eating cookie and the vertical range of the lateral tongue markers when eating meat were significantly larger than their respective ranges when eating banana, perhaps because reduction of food particle size continues in St2Tr as it does in chewing. The number and type of chewing cycles also vary substantially with food consistency. Future studies could investigate the effects of specific physical and hedonic characteristics of food on the motions of the jaw and tongue in mastication, oral food transport, and swallowing.

Conflict of interest The authors have no conflict of interest to disclose.

References

1. Abd-El-Malek S. The part played by the tongue in mastication and deglutition. J Anat. 1955;89:250–4.
2. Palmer JB, Hiiemae KM, Liu J. Tongue-jaw linkages in human feeding: a preliminary videofluorographic study. Arch Oral Biol. 1997;42:429–41.
3. Palmer JB, Rudin NJ, Lara G, Crompton AW. Coordination of mastication and swallowing. Dysphagia. 1992;7:187–200.
4. Thexton AJ. Mastication and swallowing: an overview. Br Dent J. 1992;173:197–206.
5. Hori K, Ono T, Nokubi T. Coordination of tongue pressure and jaw movement in mastication. J Dent Res. 2006;85:187–91.
6. Kieser J, Singh B, Swain M, Ichim I, Waddell JN, Kennedy D, Foster K, Livingstone V. Measuring intraoral pressure: adaptation of a dental appliance allows measurement during function. Dysphagia. 2008;23(3):237–43.
7. Ono T, Hori K, Nokubi T. Pattern of tongue pressure on hard palate during swallowing. Dysphagia. 2004;19:259–64.
8. Steele CM, Bailey GL, Molfenter SM. Tongue pressure modulation during swallowing: water versus nectar-thick liquids. J Speech Lang Hear Res. 2010;53:273–83.
9. Steele CM, Van Lieshout PH. Influence of bolus consistency on lingual behaviors in sequential swallowing. Dysphagia. 2004;19:192–206.
10. Hiiemae K, Heath MR, Heath G, Kazazoglu E, Murray J, Sapper D, Hamblett K. Natural bites, food consistency and feeding behaviour in man. Arch Oral Biol. 1996;41:175–89.
11. Hiiemae KM, Palmer JB, Medicis SW, Hegener J, Jackson BS, Lieberman DE. Hyoid and tongue surface movements in speaking and eating. Arch Oral Biol. 2002;47:11–27.
12. Jean A. Brain stem control of swallowing: neuronal network and cellular mechanisms. Physiol Rev. 2001;81:929–69.
13. Martin RE, Murray GM, Kemppainen P, Masuda Y, Sessle BJ. Functional properties of neurons in the primate tongue primary motor cortex during swallowing. J Neurophysiol. 1997;78:1516–30.
14. Mioche L, Hiiemae KM, Palmer JB. A postero-anterior videofluorographic study of the intra-oral management of food in man. Arch Oral Biol. 2002;47:267–80.
15. Dantas RO, Kern MK, Massey BT, Dodds WJ, Kahrilas PJ, Brasseur JG, Cook IJ, Lang IM. Effect of swallowed bolus variables on oral and pharyngeal phases of swallowing. Am J Physiol. 1990;258:G675–81.
16. Sugita K, Inoue M, Taniguchi H, Ootaki S, Igarashi A, Yamada Y. Effects of food consistency on tongue pressure during swallowing. J Oral Biosci. 2006;48:278–85.
17. Taniguchi H, Tsukada T, Ootaki S, Yamada Y, Inoue M. Correspondence between food consistency and suprahyoid muscle activity, tongue pressure, and bolus transit times during the oropharyngeal phase of swallowing. J Appl Physiol. 2008;105:791–9.
18. Hiiemae KM, Palmer JB. Food transport and bolus formation during complete feeding sequences on foods of different initial consistency. Dysphagia. 1999;14:31–42.
19. Matsuo K, Palmer JB. Kinematic linkage of the tongue, jaw, and hyoid during eating and speech. Arch Oral Biol. 2010;55:325–31.
20. Hiiemae KM, Hayenga SM, Reese A. Patterns of tongue and jaw movement in a cinefluorographic study of feeding in the macaque. Arch Oral Biol. 1995;40:229–46.
21. Proschel P, Hofmann M. Frontal chewing patterns of the incisor point and their dependence on resistance of food and type of occlusion. J Prosthet Dent. 1988;59:617–24.
22. Woda A, Mishellany A, Peyron MA. The regulation of masticatory function and food bolus formation. J Oral Rehabil. 2006;33:840–9.
23. Schwartz G, Enomoto S, Valiquette C, Lund JP. Mastication in the rabbit: a description of movement and muscle activity. J Neurophysiol. 1989;62:273–87.
24. Naganuma K, Inoue M, Yamamura K, Hanada K, Yamada Y. Tongue and jaw muscle activities during chewing and swallowing in freely behaving rabbits. Brain Res. 2001;915:185–94.
25. Atkinson M, Kramer P, Wyman SM, Ingelfinger FJ. The dynamics of swallowing. I. Normal pharyngeal mechanisms. J Clin Investig. 1957;36:581–8.
26. German RZ, Saxe SA, Crompton AW, Hiiemae KM. Food transport through the anterior oral cavity in macaques. Am J Phys Anthropol. 1989;80:369–77.
27. Hiiemae KM, Palmer JB. Tongue movements in feeding and speech. Crit Rev Oral Biol Med. 2003;14:413–29.
28. Stone M, Shawker TH. An ultrasound examination of tongue movement during swallowing. Dysphagia. 1986;1:78–83.

Hiroshige Taniguchi PhD, DDS

Koichiro Matsuo PhD, DDS

Hideto Okazaki PhD, MD

Mitsumasa Yoda PhD, MD

Haruhi Inokuchi MD

Marlis Gonzalez-Fernandez PhD, MD

Makoto Inoue PhD, DDS

Jeffrey B. Palmer PhD, MD