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Stage I intraoral food transport: Effects of food consistency and initial bolus size

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ABSTRACT

Objective: We examined the temporospatial characteristics of stage I oral food transport, in which a piece of solid food is moved from the anterior oral cavity to the postcanine region for chewing. Anteroposterior transport is accomplished by carrying food posteriorly on the surface of the tongue, in contrast to the squeeze-back mechanism of stage II transport from the oral cavity to the pharynx.

Design: There were two experiments (Exp1 and Exp2): In Exp1, Twelve healthy young adults ate 2 g, 4 g, 6 g, 8 g 12 g initial bolus sizes of banana and cookie; in Exp2, fourteen similar subjects ate 6 g of banana and cookie with and without radiopaque tongue surface makers. Motions were recorded with videofluorography in lateral projection.

Results: Stage I transport duration was longer for cookie than banana ($P \leq .025$), but there were no significant durational differences among initial bolus sizes. With cookie, tongue pullback was more frequent for small (2 g and 4 g) than large (12 g) bolus sizes ($P \leq .048$). With banana, however, the frequency of pullback was independent of initial bolus size. Kinematic analysis of tongue pullback revealed that the lower jaw opened as the tongue and hyoid bone moved both posteriorly and inferiorly; the magnitude of these displacements did not vary significantly between banana and cookie.

Conclusions: We conclude that stage I transport is a complex behaviour involving posterior and inferior displacement of the tongue, jaw and hyoid bone. Its frequency of occurrence is related to initial bolus size and consistency, but the magnitude of displacement is relatively constant.

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1. Introduction

Human swallowing is traditionally divided into sequential oral preparatory, oral propulsive, pharyngeal, and oesophageal stages.[1] Development of this model was based on observations of liquid barium swallows, but it does not fully reflect the sequence of events in eating solid food. Several investigators have used cine- or video-fluoroscopy to examine mastication and oral food transport in non-human mammals eating solid food.[2–7] These reports led to the development of the "Process model of Feeding" by Hiiemae and colleagues.[8]

The Process model describes two distinct processes of anteroposterior oral food transport. In stage I transport, an ingested and/or incised piece of solid food is moved from the anterior oral cavity to the post-canine region for mastication. In stage II transport, triturated (fully reduced) food is squeezed posteriorly between the tongue and palate and thus propelled from the oral cavity to the pharynx for swallowing.

The present study addresses the mechanism of stage I transport. Prior studies suggested that stage I transport includes two sequential behaviours. Firstly, food is carried posteriorly as it sits on the superior surface of the tongue; we call this mechanism "tongue pullback" to differentiate from the "squeeze-back" mechanism of stage II transport. Secondly, the tongue rotates and deposits the food bolus on the occlusal surfaces of the postcanine teeth in preparation for chewing.[11] Stage I transport has been studied with foods of differing physical consistencies.[8,12,13] Okada et al.[14] reported that the duration of transport was closely bound to the texture recognition process in subjects eating rice sticks. Tongue pullback was noted in all subjects.

In the present study, we examine the frequency and duration of stage I transport in relation to bolus size and consistency and analyse the kinematics of stage I transport in healthy adult volunteers.

2. Material and method

2.1. Data collection

Healthy asymptomatic young adults were recruited to determine patterns of normal movement during eating and swallowing with videofluorography. This study consisted of two experiments; both protocols were approved by the Institutional Review Board. All participants gave oral and written informed consent. Participants had normal dentition with class I occlusion. No participant had a history of major medical problems, dysphagia, or gastroesophageal reflux disease. Each participant demonstrated normal oral and pharyngeal swallowing of liquid barium (barium/water, 50%, w/v ratio) on videofluorography (VFG) in the lateral and anteroposterior projections. We use the term VFG to emphasise that these were not clinical videofluoroscopic swallowing study protocols. The experiments were performed sequentially; data collection for experiment 1 were was completed prior to experiment 2. Different subjects were included in the two experiments to avoid excessive radiation exposure.

Participants were instructed to eat the foods in their usual manner while seated comfortably in a chair. Subjects were instructed to minimise head movements; this was facilitated by placing a firm headrest in gentle contact with the occiput.

2.2. Experiment 1

There were 12 participants in experiment 1 including 7 males (age 24.1 ± 2.3 years [mean ± *SD*], range 22–29) and 5 females (age 22.4 ± 1.1 years, range 21–24). Each participant ate 2 g, 4 g, 6 g, 8 g and 12 g samples of banana and cookie (shortbread fingers; Carr's of Carlisle, Carlisle, UK). These foods were selected to provide a soft food (banana) and a hard food (cookie). Food samples were presented in random order with respect to both bolus size and consistency. Foods were lightly coated with barium sulphate powder and placed in the participant's anterior oral cavity by the examiner.

2.3. Experiment 2

There were 14 different participants in experiment 2 including 5 males (age of 22.4 ± 4.5 years, range 19–30) and 9 females (age 21.6 ± 4.1 years, range 18–31). Radiopaque markers (small lead discs of 4 mm diameter and 0.4 mm thickness) were glued to the buccal (lateral) surfaces of the right upper and lower canines and right upper first molars with dental cement (Ketac, ESPE-Premier Sales Corp., Norristown, PA); these served as reference points for kinematic analysis (see Data Reduction). Two additional radiopaque markers were glued to the dorsal surface of tongue. The tongue markers were placed in the midline: an anterior tongue marker (*ATM*) as close to the tongue tip as possible and a posterior marker (*PTM*) as far posterior as possible without eliciting the gag reflex. The distance between the tongue markers thus varied slightly among subjects but averaged about 2 cm. To prevent injury of soft tissue, the tongue markers and dental cement were gently removed after the experiment using dental instruments. The dental cement did not adhere so tightly to the mucosa as to cause tissue injury by its nature.

Each participant ingested 6 g of banana and 6 g of cookie with and without tongue markers for a total of four trials each. Foods were lightly coated with barium sulphate paste (Varibar; E-Z-EM Inc. NY USA) and placed in the anterior oral cavity by the examiner. No barium was used in the trials with tongue markers as barium occluded the markers on fluoroscopy. Positioning and instructions were as described for experiment 1.

2.4. Data reduction

Each VFG recording included the complete feeding sequence from ingestion through the completion of the terminal swallow. VFG was performed in the lateral projection at 30 frames per second and archived on a digital video recorder. A time stamp was simultaneously recorded and overlaid on each video frame. Recordings were converted to digital video files (.avi) for kinematic analysis.

We examined movement of the lower jaw (LCM), tongue markers and hyoid bone and the barium bolus (when present) during stage I transport using the slow-motion and stop-frame functions of Quicktime software (Version 7.6, Apple, Cupertino, CA). After reviewing the videos, stage I transport cycles were each divided into two phases: pre-transport phase and transport phase. Pre-transport phase onset was defined as the moment the leading edge of the food passed the incisors (generally occurring at the time of maximum gape [widest jaw opening]). Offset of the pre-transport phase was the moment that the food began moving posteriorly from the anterior oral cavity (this was also the onset of the food transport phase). Food transport phase offset was defined as the first three-way contact of the lower teeth, food and upper teeth in the post-canine region (the time of tooth–food–tooth contact). Tongue pullback, when present, was observed during the food transport phase only. Tongue pullback was defined as rapid anteroposterior movement of the tongue and food. It ended when the tongue and food reached their most posterior position in the oral cavity.

The radiopaque markers were used to measure movements of the dorsal tongue surface and the lower jaw relative to the occlusal plane of the upper teeth (approximated by a straight line passing through the markers on the right upper canine and molar. The right lower canine marker (LCM) was used as a marker for jaw motion (jaw gape), and the superior-anterior corner of the hyoid bone shadow was the reference point on the hyoid bone. The tongue markers were used similarly to measure motions of the tongue surface.

Cartesian coordinates for all reference points were acquired for each video frame and entered into MS Excel® (Microsoft, Redmond, WA) spreadsheets (Fig. 1). The Cartesian coordinate system was defined by anatomical structures: the origin (0,0 point) was defined as the location of the upper canine marker in each image; the X axis passed through the upper molar marker. Head movements were minimal. Any minor head movement in the sagittal plane was corrected with this coordinate system since the coordinate system was defined by the instantaneous position of the upper teeth.

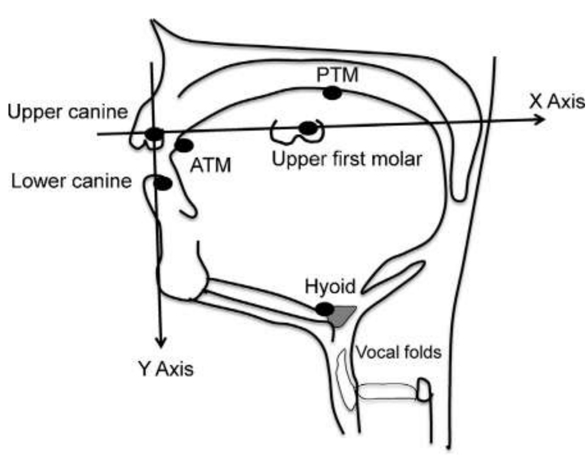

Fig. 1 – Illustration of the coordinate framework used to prepare the data. The X axis is drawn between upper canine and first molar markers, roughly parallel to the occlusal plane of the upper teeth. The origin was at the upper canine marker. Movement in the X axis is antero-posterior and Y axis is supero-inferior in direction.

Trials in which participants mashed food between the hard palate and tongue (instead of chewing between the upper and lower teeth) were excluded from the analyses.

Each data set was inspected for its distribution. Parametric statistics were used to analyse data that was normally distributed; non-parametric statistics were used to analyse data that were not normally distributed, including counts. Statistical analyses were performed with JMP 9 (SAS institute Inc., Cary, NC). The critical value for rejecting the null hypothesis was set at .05.

3. Results

3.1. *Experiment 1*

The duration of stage I transport and frequency of tongue pullback were analysed with respect to initial bolus size in Experiment 1.

3.2. *Duration of stage I transport*

Each participant was presented with 1 trial each of 2 g, 4 g, 6 g, 8 g and 12 g banana and of cookie. We compared stage I transport duration among the bolus sizes of banana and cookie (Fig. 2). Initial bolus size had no significant effect on duration of stage I transport or its phases (pre-transport and transport phases) with either food (Steel-Dwass test, $P > .05$).

3.3. *Frequency of tongue pullback*

Participants demonstrated tongue pullback in every recording with 2 g and 4 g boluses and most recordings with 6 g, 8 g and 12 g boluses (Fig. 3). With cookie, Tongue pullback was significantly more frequent for small (2 g and 4 g) than large (12 g) boluses ($P = .04$ and $P = .048$, respectively, Fisher's exact test). However, with banana, bolus size had no significant effect on the frequency of pullback ($P > .05$).

3.4. *Experiment 2*

The duration of stage I transport and frequency of tongue pullback were analysed with respect to food consistency and initial placement of the bolus in the oral cavity. Additionally, we performed a kinematic analysis of mandible, tongue, and hyoid bone motions during tongue pullback.

3.5. *Duration of stage I transport*

Food consistency effects. In recordings with no tongue markers, there was one trial each of 6 g banana and 6 g cookie boluses in each of 14 participants (Fig. 4). Duration of the pre-transport phase ($t = -2.48$, $P = .020$) and total duration ($t = -2.43$, $P = .025$) were both significantly longer for cookie than banana. Duration of the food transport phase did not differ significantly between cookie and banana ($P = .60$).

Food placement effects. Review of the VFG recordings revealed unintended small differences in initial food bolus position in the oral cavity. In order to determine whether initial position affected stage I transport duration, we examined one trial each

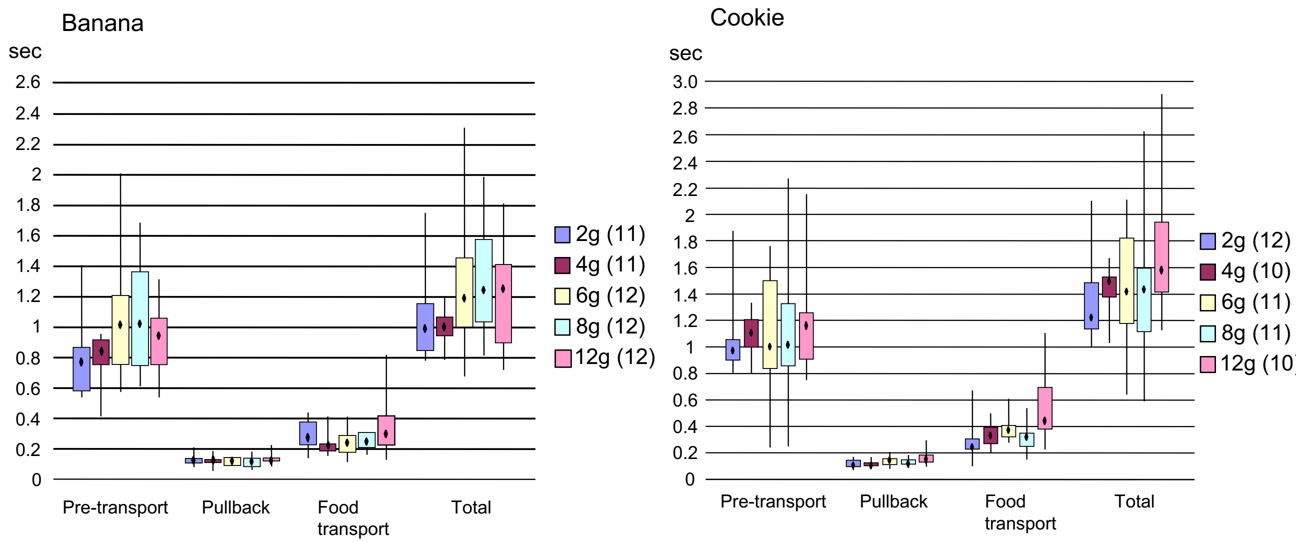

Fig. 2 – Duration of stage I transport – 3 phases and total (box-and-whiskers plot, data from Experiment 1). Differences were not statistically significant (Steel-Dwass test, P > .05). The legend shows initial bolus size (number of trials included).

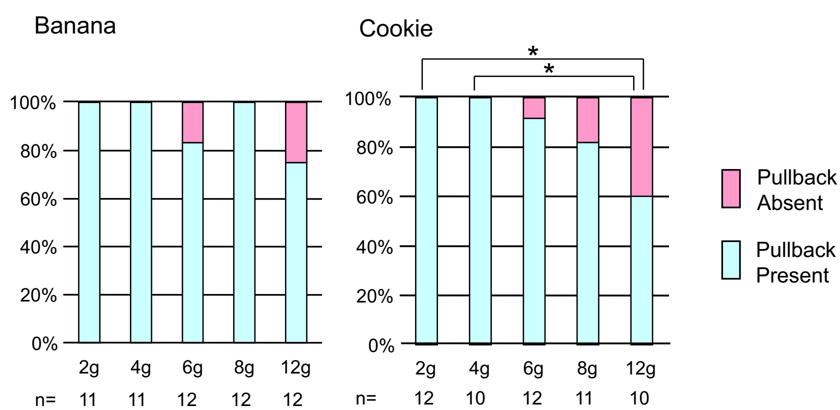

Fig. 3 – Frequency of tongue pullback by initial bolus size (by percent of trials; data from Experiment 1). Frequency of pullback did not differ significantly among initial bolus sizes with banana. But when eating cookie, tongue pullback was significantly more frequent with 2 g or 4 g than 12 g initial bolus sizes. *P < .05

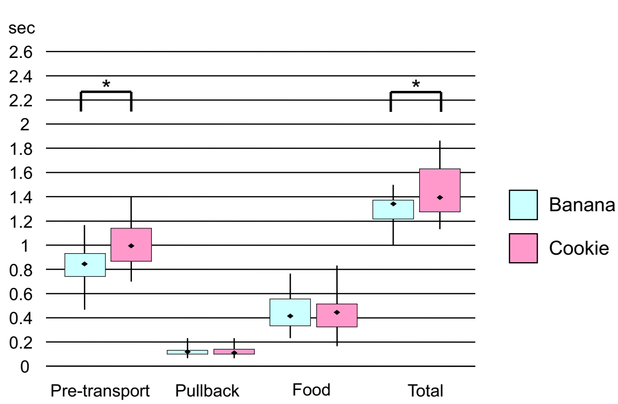

Fig. 4 – Duration of stage I transport by phase (data from Experiment 2).
The mean pre-transport and total stage I transport durations were significantly longer for cookie than banana boluses. *P ≤ .025.

of 6 g banana and 6 g cookie boluses in 14 participants (Fig. 5). Initial placement was classified as either ‘‘premolar’’ or ‘‘molar’’ depending on position of the posterior margin of the food. With banana, initial placement was premolar for 5 of 12 recordings. For cookie, initial placement was premolar in 6 of 14 recordings. Food transport phase duration was longer for premolar than molar placement with both banana (t = 3.50, P = .006) and cookie (t = 2.97, P = .023)

3.6. *Frequency of pullback*

Food consistency effects. The effect of food consistency on the frequency of tongue pullback was analysed with 6 g banana and 6 g cookie boluses (no tongue markers). The frequency of pullback was 83.3% (10 of 12 recordings) and 85.7% (12 of 14 recordings) for banana and cookie, respectively. There was no significant difference in pullback frequency between foods (P > .05; Fisher’s exact test).

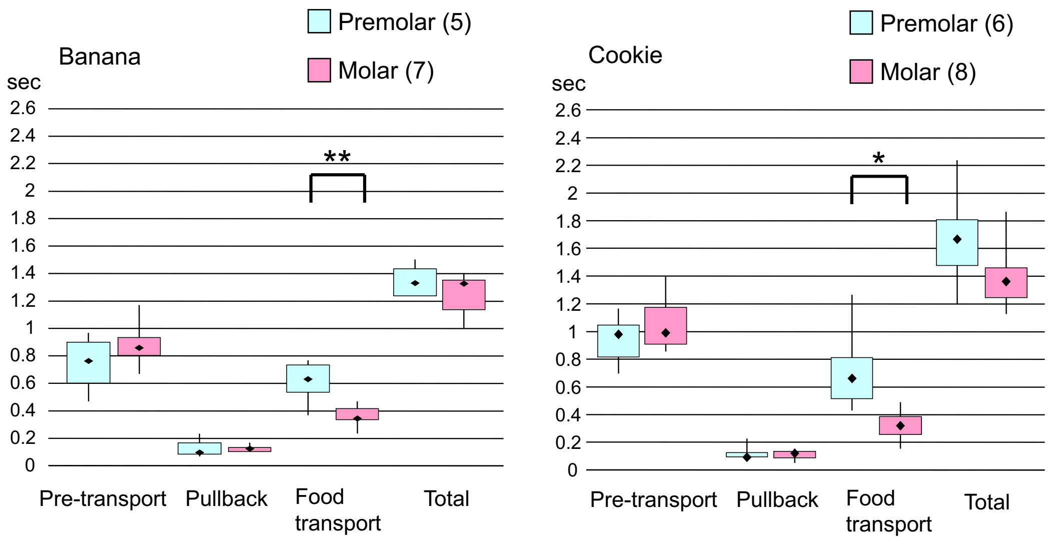

Fig. 5 – Effect of initial bolus placement on stage I transport duration by phase (Experiment 2). Initial placement was categorised according to the position of the bolus (posterior margin) relative to the adjacent dentition. Transport phase duration was longer for premolar than molar placement with both banana and cookie. *P = .023; **P = .006

Food placement effects. The frequency of tongue pullback with banana boluses was 60.0% (3 of 5 recordings) for premolar and 100% (7 of 7 recordings) for molar placement, and with cookie was 83.3% (5 of 6 recordings) for premolar and 87.5% (7 of 8 recordings) for molar placement, respectively. Initial food placement had no significant effect on tongue pullback frequency with either food (Fisher's exact test, $P > 05$).

3.7. *Kinematic analysis of tongue pullback*

Two-dimensional kinematic analysis of the tongue pullback mechanism was performed in recordings with tongue markers. Motions were measured relative to the occlusal plane of the upper teeth. During tongue pullback, the lower jaw opened widely as the tongue and hyoid bone moved posteroinferiorly (Fig. 6A). In recordings with no tongue pullback, rapid anteroposterior tongue movement was not observed and tongue rotation started at the onset of the transport phase. The hyoid bone did not move inferiorly during the food transport stage (Fig. 6B).

Jaw, tongue, and hyoid bone movements during pullback were analysed for differences between food consistencies. There were no significant differences in vertical (superoinferior) or horizontal (anteroposterior) displacement between recordings with banana and cookie (see Table 1; Mann–Whitney test, $P > .05$).

4. Discussion

4.1. *Duration of stage I transport*

The duration of stage I transport was longer for hard (cookie) than for soft food (banana). The difference between their average durations was 0.24 s in experiment 2, findings similar to previous reports,[8,13] however the mechanism for these differences is unclear. While they may result from interaction of food hardness with intraoral structures, they could reflect variation in the shape, orientation, and precise positioning of the cookie and banana food samples when they were placed into the mouth. Indeed, initial placement of the food bolus was an unintended source of variance in our study. The duration of food transport was shorter when the posterior margin of the bolus was further posterior (molar rather than pre-molar). Placing the bolus more posteriorly could facilitate stage I transport by reducing the required distance of posterior bolus transport.

Our examination of the effects of planned variations in initial bolus size is a unique feature of the present study. We were surprised to find no significant differences in the duration of stage I transport over a six-fold range of initial bolus sizes. In a published study, Okada et al. allowed their subjects to eat sushi rice sticks *ad libitum*; the average weight of the initial bite of food was 11.5 ± 3.7 g. The duration of stage I transport was 1.91 ± 0.31 s and was not significantly different among subjects despite differences in bolus size.[14] Our data are similar, demonstrating robustness of the observations across methodologies and food consistencies.

The duration of tongue pullback was not significantly affected by food consistency, initial bolus size, or the location of initial bolus placement. The displacements of the tongue markers and lower jaw were also not significantly affected by food consistency. This suggests that tongue pullback is stereotypical and relatively insensitive to peripheral stimuli.

Frequency of pullback Pullback was observed in the majority of trials during this study. Moreover, the frequency of pullback was not significantly different between food consistencies or initial bolus placements (locations). The frequency of pullback, however, was lower in trials of large

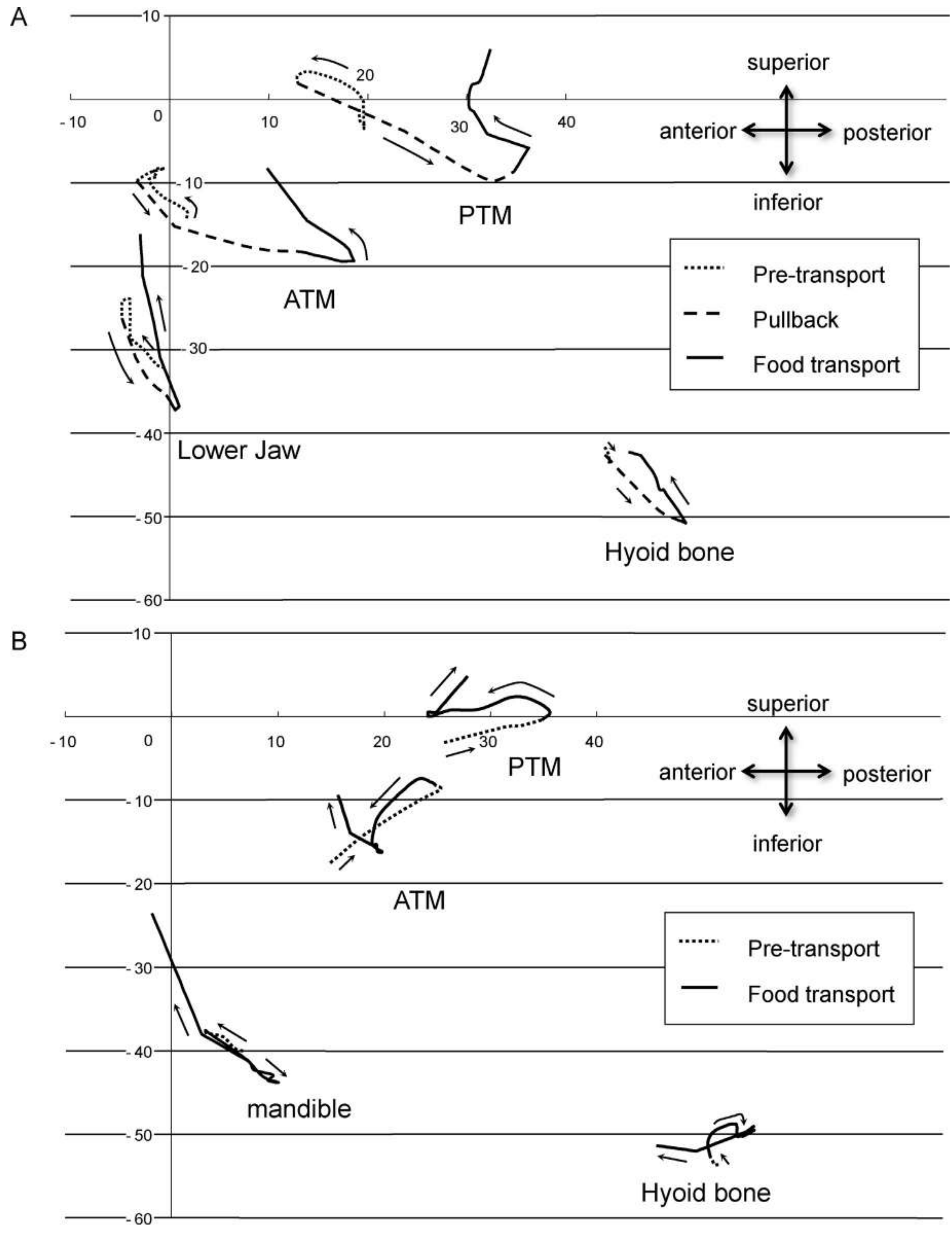

Fig. 6 – (A) Example of Stage I Transport *with* Tongue Pullback. Motion pathways of the lower jaw, tongue surface markers and hyoid bone during a typical stage I transport cycle. During pullback, the tongue markers and hyoid bone moved infero-posteriorly as the jaw opened. *ATM*, anterior tongue marker; *PTM*, posterior tongue marker. (B) Example of Stage I Transport *without* Tongue Pullback. Motions of the lower jaw, tongue surface markers and hyoid bone during a stage I transport cycle without pullback. Rapid anteroposterior tongue movement was not observed; the hyoid bone did not move inferiorly during transport. *ATM*, anterior tongue marker; *PTM*, posterior tongue marker.

Table 1 – Displacement during tongue pullback.

Mean ± SD (mm)	Jaw (LCM)		AT		PTM		Hyoid bone	
	AP	Vertical	AP	Vertical	AP	Vertical	AP	Vertical
Banana	1.9 ± 2.3	5.7 ± 3.3	12.2 ± 4.9	3.4 ± 5.9	9.8 ± 5.5	4.9 ± 4.6	3.3 ± 2.0	3.1 ± 2.0
Cookie	2.4 ± 1.7	6.0 ± 3.3	12.7 ± 5.2	3.6 ± 3.2	10.8 ± 5.1	4.2 ± 4.1	4.0 ± 1.8	4.5 ± 2.9

Differences between cookie and banana were not statistically significant. LCM, lower canine marker; ATM, anterior tongue marker; PTM, posterior tongue marker; AP, antero-posterior.

cookie boluses. We hypothesise that pullback was inhibited with large initial boluses because a large bolus would require greater capacity in the oral cavity. This merits further investigation.

Given the structure of the mandible, oral cavity and pharynx, pullback would seem to be particularly important for mammals such as the rodents and lagomorphs (hares, rabbits, and pika) that have a diastema (gap) between the anterior and posterior dentition, requiring a greater magnitude of posterior transport.[2,6] German et al., however, reported that the macaque demonstrates stage I transport via pullback though the diastema is relatively small.[4] Okada et al. reported observing pullback in all of their healthy human subjects eating rice sticks.[14] In contrast, pullback was observed in most, but not all trials during the present study.

Hiiemae et al. described movement of the hyoid during tongue pullback as posterior and somewhat inferior, and that the mandible was open during tongue pullback.[8,11,12] Our findings were similar. The ATM and PTM both moved posteriorly but the ATM more than the PTM, shortening the distance between them. This suggests that tongue pullback includes contraction of the mid-tongue on its antero-posterior axis as well as translation of the whole tongue toward the back of the mouth. We infer that the tongue is shortened by contraction of its longitudinal muscles, while translation of the tongue is produced primarily by its extrinsic muscles (and by displacement of the hyoid bone to which the tongue is attached).

5. Conclusion

The duration of stage I transport was affected by texture and initial placement of the bolus, but not initial bolus size. Frequency of pullback was lower for large boluses with hard cookie, but not banana. Kinematic analysis revealed that the mandible opened and the tongue and hyoid bone moved posteriorly and inferiorly during tongue pullback. Additional studies are warranted to determine how the size and shape of food; its physical orientation in the mouth; food properties such as brittleness, stickiness, and temperature; and a variety of pathological conditions affect the mechanism of stage I transport. Imaging of tongue movement in the anteroposterior projection is necessary for understanding the kinematics of tongue movement during stage I transport in three dimensions.

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Competing interests: We declare that there are no conflicts of interest.

Ethical approval: The study protocol was approved by the Institutional Review Board (No. 86-06-25-03).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.archoralbio.2014.01.002.

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