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Food Transit Duration is Associated with the Number of Stage II Transport Cycles when Eating Solid Food

Takashi Hiraoka^{*,a,b}, Jeffrey B. Palmer^{a,c}, Martin B. Brodsky^a, Mitsumasa Yoda^a, Haruhi Inokuchi^a, and Akio Tsubahara^b

^aDepartment of Physical Medicine and Rehabilitation, Johns Hopkins University, Baltimore, MD, USA

^bDepartment of Rehabilitation Medicine, Kawasaki Medical School, Kurashiki, Okayama, Japan

^cDepartment of Otolaryngology-Head and Neck and Center for Functional Anatomy and Evolution, Johns Hopkins University, Baltimore, MD, USA

Abstract

Objective—When eating solids, stage II transport (St2Tr) propels triturated food into the pharynx for bolus formation and storage before swallowing. Although the existence of St2Tr is acknowledged, the reason for its existence remains unclear. Understanding it may facilitate development of food appropriate for individuals with dysphagia. The purpose of this study was to explore how measures of duration of eating and swallowing affect the number of St2Tr cycles.

Design—Videofluorography was performed on 13 healthy subjects eating 6-g squares of banana, tofu, and cookies. Measurements included the number of St2Tr cycles, duration of processing (from food entering the mouth to onset of swallowing), pre-upper esophageal sphincter (UES) transit duration (from onset of swallowing to onset of UES transit), UES transit duration (leading edge to trailing edge passing the UES), and total sequence duration (from onset of swallowing to terminal swallow). Principal component (PC) analysis was used to identify factors affecting the number of St2Tr cycles. Analysis of covariance was performed using the 1st PC as an independent variable for predicting the number of St2Tr cycles.

Results—All four duration measures were significantly positively correlated with the number of St2Tr cycles. Analysis revealed two orthogonal PCs with variable loading. The 1st PC was a function of the timing variables. The 2nd PC was a function of the number of swallows.

Conclusions—The number of St2Tr cycles was associated with measures of food transit duration and was greater with harder foods before processing and more viscous foods just before swallowing.

*Correspondence to: Takashi Hiraoka, MD, PhD, Kawasaki Medical School, 577 Matsushima Kurashiki, Okayama, Japan 701-0192, Telephone: (086)462-1111; Fax: (086)464-1186, hiraoka@med.kawasaki-m.ac.jp.

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Conflicts of Interest: None

Keywords

Eating; Mastication; Rheology; Swallowing

Introduction

In the traditional description of swallowing, the oral phase has been sub-divided into the oral preparatory phase and the oral propulsive phase (Logemann, 1998). During the oral preparatory phase, food is taken into the oral cavity, masticated, mixed with saliva, re-collected by the tongue, and shaped into a bolus in preparation for transport into the pharynx when swallowing is initiated. The oral propulsive phase of swallowing is the propulsion of the bolus into the pharynx. Although this simple, 2-phase model has served clinicians well as a rudimentary description of the oral stage of ingesting liquids, it does not accurately portray mastication and swallowing of solid foods (Dua, Ren, Barden, Xie & Shaker, 1997; Feinberg, 1993; Linden, Tippet, Johnston, Siebens & French, 1989). The Process Model of Feeding (Hiemae et al., 1996; Hiemae & Palmer, 1999; Palmer, 1997) describes 2-stages of antero-posterior movements of the bolus prior to swallowing, termed Stage I and Stage II transport. Stage I transport is the relatively immediate movement of solid food from the anterior oral cavity to the post-canine region and occlusal surfaces of the lower teeth (Mikushi, Seki, Brodsky, Matsuo & Palmer, 2014), and is followed by mastication. Stage II transport (St2Tr), is the propulsion of triturated food to the oropharynx for bolus formation and storage prior to swallowing (Matsuo & Palmer, 2008). Indeed, the bolus may remain in the pharynx for as long as 8–10 s prior to swallow onset in healthy adults (Hiemae & Palmer, 1999).

In St2Tr, the anterior tongue moves upward and presses against the alveolar ridge and anterior hard palate. The area of the tongue–palate contact then expands from the front to the back, “squeezing” the food posteriorly, as a finger squeezes toothpaste from a tube (Palmer, 1998). This squeezing action by the tongue is similar to that described in the oral propulsive stage of swallowing (Hayashi et al., 2013; Hiemae & Palmer, 2003). As St2Tr continues, the bolus is squeezed through the fauces into the pharynx. If food remains in the oral cavity, mastication continues, and additional St2Tr cycles each propel triturated food into the oropharynx before the swallow.

The specific factors that trigger St2Tr are not well understood. It is thought that sensory receptors in the oral cavity and pharynx relay inputs to the central pattern generators for mastication and swallowing (Matsuo & Palmer, 2008; Palmer, Rudin, Lara & Crompton, 1992). In recent years, the insula, cingulate gyrus, and sensorimotor area have been shown to be related to the initiation of swallowing, based on functional MRI studies (Daniels & Foundas 1997; Hamdy et al., 1996; Jean, 2001; Kern, Jaradeh, Arndorfer, & Shaker, 2001; Malandraki, Sutton, Perlman, Karampinos & Conway, 2009; Martin et al., 2007; Peck et al., 2010).

Liquids and solid foods have different effects on the initiation of St2Tr and swallowing (Mosier & Bereznaya, 2001). Although St2Tr is considered normal behavior while consuming solid foods (Jean, 2001; Kahrilas, Dodds, Dent, Logemann & Shaker, 1988;

Palmer, 1998; Palmer, Hiimeae, Matsuo & Haishima, 2007; Saitoh, 2007), the neural control of St2Tr and its relationship to food has received limited attention (Hayashi et al., 2013; Inokuchi et al., 2014; Mikushi et al., 2014; Palmer et al., 2007; Taniguchi et al., 2013).

Although the existence of St2Tr is increasingly acknowledged, the reason for the existence of such a phase is not yet clear. Yet, if the reason therefore and the relationship between St2Tr and the type of food is elucidated, it may facilitate development of food appropriate for individuals suffering from dysphagia. We think that St2Tr is a mechanism that allows humans to eat solid, hard-to-eat food safely by providing cues that allow individuals to judge whether a bolus can be swallowed safely. The decision whether or not to swallow has a notable effect on the physical properties of food immediately before swallowing. It changes based on combinations of multiple food property indices (e.g., hardness, adherability, cohesiveness, elasticity). Even then, adherability and cohesiveness are important in the decision of whether or not to swallow. Thus, this study measured swallowing time as an index of food adherability and cohesiveness. In addition, those who took more time to swallow were categorized as “difficulty swallowing” and for such subjects, multiple confirmations were needed to establish that the subject was in a state where they could swallow. This could be the reason for the increase in St2Tr frequency. In order to investigate frequency of St2Tr, time required to swallow, and other indices, three foods with varying adherability and cohesiveness were selected for subjects to ingest: banana (low adherability/high cohesiveness), tofu (low adherability/low cohesiveness), and a cookie (hard prior to mastication/chewing with low adherability/low cohesiveness that changes to high adherability/moderate cohesiveness as mastication/chewing progresses).

As an index for the degree of difficulty of eating food, we used the transit time of the bolus during the swallow and evaluated the relationship between the transport time of boluses of various types of food and St2Tr. We therefore here examined the duration of both eating and swallowing, as well as the number of St2Tr cycles during complete feeding sequences, from ingestion to the terminal swallow. We hypothesized that the number of St2Tr cycles would be associated with the duration of food transport and swallowing.

Materials and Methods

Subjects

The Johns Hopkins Institutional Review board approved this study (approval number: 26-06-25-03) and written informed consent was obtained from each study participant. This study presents an entirely new analysis of data described previously (Inokuchi et al., 2014). Healthy young adult volunteers between the ages of 18 and 31 years were included. Inclusion criteria included no history of major medical or dental problems or dysphagia. Each participant consumed a single sip of liquid barium during videofluorography (VFG) in both lateral and anterior–posterior views to confirm the normality of swallowing.

Data collection

Participants were seated upright in a VESS chair (VESS Chairs Inc., Milwaukee, WI) during the study. They were instructed to keep their head and neck as still as possible during

recording; this was facilitated by gentle contact of the back of the head with a posterior headrest. The examiner then presented each food portion (6 g each of banana, cookie, and tofu) on a toothpick to the participants. In each case, barium paste (1–2 ml) was spread on the food to enhance its radiopacity. The participants were instructed to chew and swallow in their usual manner.

VFG recordings were started as food was brought to the lips and entered the oral cavity. The recordings continued through the final swallow after complete oral clearance. Participants had no difficulty completing the protocol. VFG was recorded using an S-VHS video-recorder at 30 frames/s while the participants ingested each of the 3 types of solid foods. A video timer was coupled with a time signal to each frame of the video, recording in 33-ms increments. The experimental protocol provided for VFG in the lateral projection only, with a maximum exposure time of 5 min. VFG was performed at 90 kV and using a 12-inch image intensifier.

Definitions and data reduction

VFG recordings on S-VHS tapes were converted to .avi files using Adobe Premier Elements 2.0 (Adobe Systems Inc., San Jose, CA) and imported onto a desktop computer. The integrity of the recordings were reviewed in slow motion and analyzed visually frame-by-frame using the stop-motion capabilities of QuickTime (Apple Inc., Cupertino, CA). Finally, the video files were analyzed using digital image processing software (ImageJ, U.S. National Institutes of Health, Bethesda, MD). Measurements included, for each recording: 1) the number of St2Tr cycles and 2) the number of swallows per sequence; 3) processing, the period from food entering the oral cavity until the onset of pharyngeal swallow (marked by onset of brisk hyoid motion); 4) pre-upper esophageal sphincter (UES) transit duration (Pre-UTD), the period from onset of brisk hyoid motion until the head of the bolus entered the UES; and 5) UES transit duration (UTD), the period from onset of UES transit until the trailing edge of the bolus passed out of the UES. One St2Tr cycle was defined as a jaw motion cycle during which the tongue squeezed the bolus against the palate, propelling the bolus from the oral cavity to the pharynx without triggering swallowing. The recordings were compared among food types (Fig. 1). Thus, 39 sequences in total were analyzed (i.e., 13 participants $\times$ 3 food types: cookie, banana, tofu).

Data analysis

Bivariate correlations between St2Tr cycles and each of the other measures were evaluated using Spearman's rank-correlation coefficient. The Processing, Pre-UTD, UTD, number of swallows, and number of St2Tr cycles were compared among food types using a nonparametric multiple comparison test (the Steel–Dwass test). Principal component analysis (PCA) was used to identify factors affecting the number of St2Tr cycles. Analysis of covariance (ANCOVA) was performed using the 1st principle component (PC) as an independent variable for predicting St2Tr. Analysis was performed using JMP 9 (SAS Institute Inc., Cary, NC) and SPSS 19 (IBM, Chicago, IL). The alpha level was set at .05.

Results

Thirteen participants (mean: 22 years, SD: 4 years; range: 18–31 years), including 9 females, completed the study protocol. Each of the 3 duration measures (Processing, Pre-UTD, UTD) had a significant positive correlation with the number of St2Tr cycles (Spearman's r range: 0.44–0.68, $p < 0.05$; Table 1). Pre-UTD had a particularly strong correlation with the number of St2Tr cycles, but the number of swallows did not ($r = 0.07$; $p = 0.67$).

Processing, Pre-UTD, UTD, number of swallows, and number of St2Trs were compared among the 3 groups classified according to the type of food (Table 2, Fig. 2A–E). These figures show that the cookie required a substantially longer time to eat (i.e., mastication and transport) and a greater number of St2Tr cycles than either the banana or tofu. There were no significant differences ($P = 0.62$) in the number of swallows required among the foods.

PCA was performed using components with an eigenvalue ≥ 1 . The contribution ratio of each component is shown in Table 3, and the cumulative contribution ratio was 76.5%. PCA revealed 2 orthogonal components derived from these measures with variable loading. The main variables related to the first PC were Processing, Pre-UTD, and UTD. Of these, the loadings of Pre-UTD/UTD were especially large. The main variable related to the second component was the number of swallows; loadings were much lower for the duration variables (Table 3, Fig. 3).

Furthermore, the score plots were reviewed (Fig. 4A). The first PC was higher for the cookie (blue dots) than for the other foods. The ANCOVA of the first component showed a significant correlation with the number of St2Tr cycles for the cookie, but not the other foods (Fig. 4B). A pictorial representation of the associations among these variables is shown in Fig. 5.

Discussion

The durational measures Processing, Pre-UTD, and UTD each showed significant positive bivariate correlations with the number of St2Tr cycles. The number of swallows, however, did not. These associations were supported by the PCA, which revealed 2 PCs. The first PC was associated with the durational measures, and the second with the number of swallows. The Pre-UES transit duration (Pre-UTD) showed the strongest association with the number of St2Tr cycles. This was unexpected, since St2Tr actually occurred during Processing (Fig. 2).

Analysis by food type showed that the cookie was more strongly associated with the 1st PC and with higher numbers of St2Tr cycles than were the other 2 types of foods. The cookie was initially harder and drier than the tofu or the banana as it entered the mouth. Hard and dry foods require a greater number of both types of chewing cycles, as reported previously (Engelen, Fontijn-Tekamp & van der Bilt, 2005; Steele et al., 2015). The number of St2Tr cycles also varied among food types, consistent with the findings of Hayashi et al. (2013), who studied tongue “squeezing” (similar to St2Tr) using pressure sensors on the palate.

They found that, excluding swallows, the number of squeezes was greater for hard than for soft food. Interestingly, the number of swallows was not related to food consistency.

The relationship of Pre-UTD and UTD to the number of St2Tr cycles is not simply explained by the initial hardness of the food. Even after mastication and mixing with saliva, the cookie was likely more viscous than the other foods (Engelen et al., 2005). However, swallowing is also known to be affected by bolus consistency (Martin et al., 2007; Taniguchi, Tsukada, Ootaki, Yamada & Inoue, 2008). Viscosity is particularly significant in relation to the swallow duration, including swallow initiation and bolus transit through the pharynx and the UES; swallow duration becomes longer as viscosity increases. The number of swallows, however, did not differ among food consistencies, and did not correlate with the number of St2Tr cycles on bivariate analysis. These findings were confirmed by the PCA: the 2nd PC was closely related to the number of swallows but not to the durational measures or the number of St2Tr cycles.

We suggest that the rheological characteristics of the cookie accounted for both the greater number of St2Tr cycles and the longer duration of bolus transit in pharyngeal swallowing. The relationships among the variables are summarized in Fig 5. We are also suggesting that St2Tr is a mechanism that judges whether a bolus is in the state whereby it can be swallowed. At the same time, adherability and cohesiveness of food are particularly important as indices to determine whether food is in a swallowable state. Hence, the investigation was conducted focusing on adherability and cohesiveness as indices of St2Tr induction. Table 1 shows the correlation between St2Tr and food transport time. Level of adherability to the mucosa is related to prolongation of transport time (i.e., difficulty swallowing), and thus eventually correlating with increased frequency of St2Tr. Figs. 2A/4B show that the cookie affected the increase in frequency of St2Tr as compared to the banana or tofu. The characteristics of cookies is that prior to being put into the mouth, they are hard and both adherability and cohesiveness are low (because they crumble). As masticating/chewing progresses, the consistency changes into a form that facilitates adherability to the mucosa. For this to occur, both effort and time are required for processing and transport from the mouth to the pharynx, making them a form of food that is difficult to swallow. Figs. 2B–2D present the processing time in the mouth and the transport time from the mouth to the UES or esophagus. Similarly, in Table 2, one can see the characteristic that time is required for the processing of cookies. Table 3 and Fig. 3 show that the first component of PCA is related to food transport time, while the second component is related to frequency of swallowing. The “Pre-UTD/UTD” suggested that friction between the mucosa and bolus has a stronger effect than processing, and therefore, a larger effect was displayed in the first component. In addition, Fig. 4A shows that bolus transit time for the cookie by PCA (see Fig. 3) is longer than that of other food forms. Moreover, as shown in Fig 4B, food transport time (see Fig. 3) is likely a prognostic factor of St2Tr frequency for cookies only. Summarizing the findings presented in Figs. 4A/4B, among the various food forms, only the cookie is likely to be a prognostic factor for the onset of St2Tr.

In summary, the indices for r for the onset of St2,” which are unique to cookies immediately before swallowing include the level of adherability (inhibitory factor of transportation; time is required for transportation), hardness before mastication (the need to masticate/chew

when in the mouth), and low cohesiveness. These indices cause prolongation of bolus transit time, which is the first component, and that is presumed to have had a notable effect on the onset of St2Tr.

It is essential for the practitioner to recognize that St2Tr is a normal physiological behavior and is not a sign of pathology, and that the number of St2Tr cycles increases with harder foods before processing and more viscous foods just before swallowing.

Limitations

There are a number of limitations to this study. First, we enrolled a small sample of young participants. Although the small sample size may reduce the generalizability of the findings, we believe that these data form the basis for future studies addressing the intricate association between food processing and oral and pharyngeal functions during feeding. Second, we tested only a small range of food types and a single volume of food. These limitations, however, are inherent in the use of ionizing radiation to study healthy volunteers. To minimize the radiation risk, it is essential to limit the duration of exposure and to study the smallest number of subjects that will provide results that are meaningful both biologically and statistically. Finally, the frequency of mastication/chewing likely affects prolongation of processing time. However, in this study, an investigation that intertwined the frequency of mastication/chewing, St2Tr frequency, and physical properties of food could not be performed. This will be an issue for future investigation.

CONCLUSION

We infer from the factor loadings that the number of St2Tr cycles was significantly associated with the duration of swallowing, but not with the number of swallows. The hardness and dryness of food, such as a cookie, and the viscosity of food after mastication plays a fundamental role in determining the number of St2Tr cycles and bolus transit duration in swallowing. This investigation provided an initial understanding of the associations among oral transport and swallowing of 3 food types and human physiological responses over a time course. We encourage future studies to replicate and extend our findings to validate our results and to provide additional insights into the physiology of swallowing, which may facilitate development of food appropriate for individuals suffering from dysphagia.

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References

- Daniels SK, Foundas AL. The role of insular cortex in dysphagia. *Dysphagia*. 1997; 12:146–156. [PubMed: 9190100]
- Dua KS, Ren J, Barden E, Xie P, Shaker R. Coordination of deglutitive glottal function and pharyngeal bolus transit during normal eating. *Gastroenterology*. 1997; 112:73–83. [PubMed: 8978345]

- Engelen L, Fontijn-Tekamp A, van der Bilt A. The influence of product and oral characteristics on swallowing. *Archives of Oral Biology*. 2005; 50:739–746. [PubMed: 15958205]
- Feinberg MJ. Radiographic techniques and interpretation of abnormal swallowing in adults and elderly patients. *Dysphagia*. 1993; 8:356–358. [PubMed: 8269731]
- Hamdy S, Aziz Q, Rothwell JC, Singh KD, Barlow J, Hughes DG, Thompson DG. The cortical topography of human swallowing musculature in health and disease. *Nature Medicine*. 1996; 11:1217–1224.
- Hayashi H, Hori K, Taniguchi H, Nakamura Y, Tsujimura T, Ono T, Inoue M. Biomechanics of human tongue movement during bolus compression and swallowing. *Journal of Oral Science*. 2013; 55:191–198. [PubMed: 24042584]
- Hiiemae KM, Heath MR, Heath G, Kazazoglu E, Murray J, Sapper D, Hamblett K. Natural bites, food consistency and feeding behavior in man. *Archives of Oral Biology*. 1996; 41:175–189. [PubMed: 8712974]
- Hiiemae KM, Palmer JB. Food transport and bolus formation during complete feeding sequences on foods of different initial consistency. *Dysphagia*. 1999; 14:31–42. [PubMed: 9828272]
- Hiiemae KM, Palmer JB. Tongue movements in feeding. *Critical Reviews in Oral Biology & Medicine*. 2003; 14:413–429. [PubMed: 14656897]
- Inokuchi H, Brodsky MB, González-Fernández M, Yoda M, Hiraoka T, Matsuo K, Palmer JB. Frequency of Stage II oral transport cycles in healthy human. *Dysphagia*. 2014; 29:685–691. [PubMed: 25142241]
- Jean A. Brain stem control of swallowing: Neuronal network and cellular mechanism. *Physiological Reviews*. 2001; 81:929–969. [PubMed: 11274347]
- Kahrilas PJ, Dodds WJ, Dent J, Logemann JA, Shaker R. Upper esophageal sphincter function during deglutition. *Gastroenterology*. 1988; 95:52–62. [PubMed: 3371625]
- Kern M, Jaradeh S, Arndorfer R, Shaker R. Cerebral cortical representation of reflexive and volitional swallowing in humans. *American Journal of Physiology-Gastrointestinal and Liver Physiology*. 2001; 280:354–360.
- Linden P, Tippett D, Johnston J, Siebens A, French J. Bolus position at swallow onset in normal adults: preliminary observation. *Dysphagia*. 1989; 4:146–150. [PubMed: 2640187]
- Logemann, JA. Evaluation and treatment of swallowing disorders. 2nd. Austin, TX: Pro-Ed; 1998.
- Malandraki GA, Sutton BP, Perlman AL, Karampinos DC, Conway C. Neural activation of swallowing and swallowing-related tasks in healthy young adults: an attempt to separate the components of deglutition. *Human Brain Mapping*. 2009; 30:3209–3926. [PubMed: 19247994]
- Martin R, Barr A, MacIntosh B, Smith R, Stevens T, Taves D, Hachinski V. Cerebral cortical processing of swallowing in older adults. *Experimental Brain Research*. 2007; 176:12–22. [PubMed: 16896984]
- Matsuo K, Palmer JB. Anatomy and physiology of feeding and swallowing: normal and abnormal. *Physical Medicine & Rehabilitation Clinics of North America*. 2008; 19:691–707. [PubMed: 18940636]
- Mikushi S, Seki S, Brodsky MB, Matsuo K, Palmer JB. Stage I intraoral food transport: Effects of food consistency and initial bite size. *Archives of Oral Biology*. 2014; 59:379–385. [PubMed: 24606909]
- Mosier K, Bereznaya I. Parallel cortical networks for volitional control of swallowing in humans. *Experimental Brain Research*. 2001; 140:280–289. [PubMed: 11681303]
- Palmer JB. Integration of oral and pharyngeal bolus propulsion: a new model for the physiology of swallowing. *Japanese Journal of Dysphagia Rehabilitation*. 1997; 1:15–30.
- Palmer JB. Bolus aggregation in the oropharynx does not depend on gravity. *Archives of Physical Medicine & Rehabilitation*. 1998; 79:691–696. [PubMed: 9630151]
- Palmer JB, Hiiemae KM, Matsuo K, Haishima H. Volitional control of food transport and bolus formation during feeding. *Physiology & Behavior*. 2007; 91:66–70. [PubMed: 17350055]
- Palmer JB, Rudin NJ, Lara G, Crompton AW. Coordination of mastication and swallowing. *Dysphagia*. 1992; 7:187–200. [PubMed: 1308667]

- Peck KK, Branski RC, Lazarus C, Cody V, Kraus D, Haupage S, Kraus DH. Cortical activation during swallowing rehabilitation maneuvers: a functional MRI study of healthy controls. *Laryngoscope*. 2010; 120:2153–2159. [PubMed: 20938958]
- Saitoh E, Shibata S, Matsuo K, Baba M, Fujii W, Palmer JB. Chewing and food consistency: effects on bolus transport and swallow initiation. *Dysphagia*. 2007; 22:100–107. [PubMed: 17347905]
- Steele CM, Alsanei WA, Ayanikalath S, Barbon CE, Chen J, Cichero JA, Wang H. The influence of food texture and liquid consistency modification on swallowing physiology and function: a systematic review. *Dysphagia*. 2015; 30:2–26. [PubMed: 25343878]
- Taniguchi H, Matsuo K, Okazaki H, Yoda M, Inokuchi H, Gonzalez-Fernandez M, Palmer JB. Fluoroscopic evaluation of tongue and jaw movement during mastication in healthy humans. *Dysphagia*. 2013; 28:419–427. [PubMed: 23446812]
- 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. *Journal of Applied Physiology*. 2008; 105:791–799. [PubMed: 18556429]

Highlights

- The number of stage II transport (St2Tr) cycles were evaluated using videography
- Test foods (banana, tofu, cookie) varied in level of adherability and cohesiveness
- The duration for processing and swallowing correlated with number of St2Tr cycles
- St2Tr cycles more with harder foods pre-processing and viscous foods pre-swallowing

Fig. 1.
Study variables

Fig. 2.

Comparison of the number of St2Tr cycles, Processing, Pre-upper esophageal sphincter (UES) transit duration (Pre-UTD), UES transit duration (UTD), and number of swallows for each food type. Durations are presented as number of frames (at 30 frames/s).

A. Number of St2Tr cycles for each food type.

B. Processing for each food type.

C. Pre-UTD for each food type.

D. UTD for each food type.

E. Number of swallows for each food type.

* $p < 0.05$; ** $p < 0.01$ (Steel–Dwass test)

Fig. 3.
Loading plot of principal components analysis

Fig. 4.

Principal component analysis results

A. Score plot of principal component analysis by food consistency

B. Analysis of covariance using the 1st principal component as independent variable for predicting the number of St2Tr cycles

Fig. 5.
Relationships among the key variables

Table 1

Correlation between the Number of St2Tr cycles and duration measures

		Spearman's r	p-value
Number of St2Tr cycles	Processing	0.45	0.0040
Number of St2Tr cycles	Pre-Upper Esophageal Sphincter (UES) transit duration (Pre-UTD)	0.68	< 0.0001
Number of St2Tr cycles	UES transit duration (UTD)	0.44	0.0046
Number of St2Tr cycles	Number of swallows	0.07	0.6654

Table 2

Number of S42Tr cycles, swallows, processing, pre-upper esophageal sphincter (UES) transit duration (Pre-UTD) and UES transit duration (UTD) by participants for various types of food.

	Food	No. of S42Tr	No. of Swallows	Processing (frames)	Pre-UTD (frames)	UTD (frames)
Case 1	Banana	0	1	301	14	10
	Tofu	0	1	404	12	8
Case 2	Cookie	3	1	408	15	13
	Banana	4	2	284	15	7
	Tofu	2	2	274	15	5
	Cookie	2	2	443	13	8
Case 3	Banana	0	1	268	11	10
	Tofu	0	1	109	9	9
	Cookie	1	2	353	14	10
	Banana	outlier	outlier	outlier	outlier	outlier
Case 4	Tofu	1	2	248	14	10
	Cookie	5	2	515	21	11
	Banana	1	2	120	8	8
	Tofu	2	2	93	18	9
Case 5	Cookie	2	3	342	22	11
	Banana	1	2	176	10	8
	Tofu	1	1	165	17	8
	Cookie	4	2	416	19	9
Case 6	Banana	2	2	269	16	10
	Tofu	1	2	335	17	9
	Cookie	2	1	266	19	12
	Banana	2	1	196	18	12
Case 7	Tofu	1	1	217	18	12
	Cookie	6	2	562	20	14
	Banana	1	2	261	10	6
	Tofu	1	3	188	11	6
Case 8	Cookie	4	2	412	17	12
	Banana	1	2	261	10	6
Case 9	Tofu	1	3	188	11	6
	Cookie	4	2	412	17	12
	Banana	1	2	261	10	6
	Tofu	1	3	188	11	6

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	Food	No. of St2Tr	No. of Swallows	Processing (frames)	Pre-UTD (frames)	UTD (frames)
Case 10	Banana	1	1	286	17	10
	Tofu	1	2	310	14	11
	Cookie	1	2	392	16	10
Case 11	Banana	0	3	136	11	8
	Tofu	0	3	171	12	10
	Cookie	2	2	359	19	12
Case 12	Banana	0	2	206	10	8
	Tofu	0	2	205	11	8
	Cookie	0	2	347	10	8
Case 13	Banana	0	2	277	16	8
	Tofu	0	2	310	8	7
	Cookie	5	2	350	18	11

Durations are presented as number of frames (at 30 frames/s).

Table 3

Variable loading patterns of principal component analysis

Variables	1 st principal component Swallow Duration	2 nd principal component No. of swallows
Processing	0.71	0.35
Pre-UES transit duration (Pre-UTD)	0.84	0.18
UES transit duration (UTD)	0.85	−0.14
Number of swallows	−0.30	0.92
Contribution ratio	51.0%	25.5%
Cumulative contribution ratio	51.0%	76.5%
Eigenvalue	2.04	1.02

(Bartlett test of sphericity; $P < 0.001$)