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RESEARCH ARTICLE

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Bolus rheology of texture-modified food: Effect of degree of modification

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Abstract

Swallowing disorders, or dysphagia, require an intake of texture-modified foods progressively softer, smoother, and moister depending on the severity of the disorder. Bolus rheology was determined for five healthy subjects for a set of such solid foods regularly given to dysphagia patients. The softest class was gel food, then a smooth timbale which both were compared to the corresponding regular, un-modified food. The foods investigated were bread, cheese, tomato, and the combination as a sandwich, all for the respective texture class: gel, timbale, and regular food. The subjects chewed until ready to swallow and the expectorated bolus was immediately measured for complex shear modulus and viscosity, and moisture and saliva content were determined. Rheology show that texture-modification influenced bolus rheology with decreased viscosity and modulus for increased degree of modification. Also saliva content as well as chews-to-swallow decreased with degree of modification. Overall, the bolus saliva content was lower for the combination (sandwich) than for the individual components. Saliva content was fairly constant irrespective of food moisture content. The phase angle for all boluses was also relatively constant, indicating a similar bolus structure. All boluses of the texture-modified foods showed high extensional viscosity, which is important for bolus cohesiveness. Bolus rheology rather than food texture determines if a food is safe to swallow and the results show that the intended texture-modification is reflected in the flow properties of the respective boluses.

KEYWORDS
bolus, dysphagia, rheology, saliva, solid food, texture-modification

1 | INTRODUCTION

As more of us live longer, age-related problems both become increasingly important and demand more health and care resources. Compared to 50 years ago the average person now lives 20 years longer (WHO, 2015). For preserved health and good quality of life at an older age, two important factors include sufficient food intake and physical exercise. Insufficient food intake, especially of those foods that provide energy and protein, leads to malnutrition, sarcopenia, frailty, hospitalization and even death. A common reason for insufficient food intake is a variety of different types of swallowing disorders, or dysphagia, which affects 10–30% of all people aged 65 and above

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(Barczi, Sullivan, & Robbins, 2000). In Sweden, the fraction of the population older than 65 is 20% and in Japan, it is approaching an outstanding 30%, as compared to the global average, which is <10%. Furthermore, life expectancy is also expected to increase globally. Age-related dysphagia is rarely curable and requires a supply of texture-modified foods and drinks that are possible to swallow without any difficulty (Ekberg, 2019). The texture is modified according to the degree of dysphagia by making the food gradually softer and more moist facilitating even chewing without using teeth and making it more smooth by reducing particle size. Solid foods are prescribed as long as the patient can manage them and beyond this fluid foods are prescribed with gradually decreased viscosity.

Texture-modified food as well as regular food needs to be formed into a bolus before even attempting to swallow. This involves the breakdown of solid food into small, often sub-millimeter-sized pieces, mixing it with saliva, collecting it into a suitably sized, cohesive, lubricated bolus, and then transporting it to the posterior of the oral cavity. For a healthy person, this complex process is rarely even noticed, whereas for someone suffering from dysphagia, the required skills are challenging or even impossible (Wada, Kawate, & Mizuma, 2017). Criteria for when a bolus is ready to be swallowed has been discussed, but the specific physiological threshold is not known. Hutchings and Lillford postulated that the bolus has to reach a certain degree of structure and lubrication to be swallowed (Hutchings & Lillford, 1988). Prinz and Lucas proposed a maximum cohesive force and exemplified it with boluses of Brazil nut and carrot, but did not measure the cohesiveness (Prinz & Lucas, 1997). The particle size distribution has been studied extensively, but has been concluded to depend on dental state, food volume consumed, as well as the food mechanical properties (Loret et al., 2011). There is a natural variation in the oral duration and it has been shown for healthy subjects eating sausage that the oral duration influences bolus properties (Devezeaux de Lavergne, Derks, Ketel, de Wijk, & Stieger, 2015). An extended oral phase led to a higher saliva content and smaller particles in the bolus. Rheological parameters have also been studied and there is a consensus that the bolus has to be sufficiently viscous and cohesive to be swallowed (Chen & Lolivret, 2011; Coster & Schwarz, 1987; Loret et al., 2011; Lorieau et al., 2018; Nicosia & Robbins, 2001; Prinz & Lucas, 1997). The rheological properties of boluses of solid foods have been studied for dry cereal products (Loret et al., 2011), soft porous bread (Assad-Bustillos, Tournier, Septier, Della Valle, & Feron, 2019; Jourdren et al., 2016) and moist dairy products (cheeses) (Drago et al., 2011; Lorieau et al., 2018). Emulsion filled gels have been investigated by penetration tests (Devezeaux de Lavergne, van de Velde, van Boekel, & Stieger, 2015).

Assad-Bustillos and co-workers studied boluses of soft porous bread for seniors (aged 65 years and over) and related bolus shear viscosity to salivary flow and chewing duration, and concluding that oral status is important for many parameters (Assad-Bustillos et al., 2019). They also concluded that an increased amount of fat in soft, porous bread lowered the role of saliva flow rate. In addition, viscosity significantly influenced oral comfort, which could be useful in designing food for seniors. Lorieau and co-workers similarly studied the influence of bolus properties on senior oral comfort but for different cheeses (Lorieau et al., 2018). They concluded that both the smaller amount of saliva required and a softer bolus were perceived as more comfortable. All cheese products had the same protein and fat composition, but were processed differently to give textures from hard to soft. The softest cheese product was quite soft but elastic and the texture was perceived as dry and sticky, and the bolus was difficult to form. The seniors considered this product the least comfortable, despite being the softest. "Toppings" such as cheese and spreads on bread have been shown to facilitate bolus formation and reduce oral duration (van Eck et al., 2019). Other authors have concluded that eating is perceived difficult when it is difficult to form a bolus, as is the case for hard products (Laguna & Sarkar, 2016). The perception of eating, which is a multi-dimensional concept, has been described as "Oral comfort" (Vandenberghe-Descamps, Labouré, Septier, Feron, & Sulmont-Rossé, 2018). To understand and quantify the oral comfort of food, especially for seniors, the authors developed a questionnaire. They assessed the oral comfort for seniors (aged 65 years and over) for a range of meat and cereal products and concluded that oral comfort mainly depends on the ease of chewing, moisturizing the bolus and swallowing, as well as on the textural softness of the food. They also noticed that both melting and taste intensity have a positive impact on oral comfort.

Any solid food must be broken down and reassembled to a swallowable structure during the oral processing (Lillford, 2011). This renders a complex structure of aggregated particles held together by saliva, and for fatty foods emulsified lipid droplets (Rodrigues, Young, James, & Morgenstern, 2014), which in turn means that the bolus is a viscoelastic fluid with complex rheology. It also means that rheometry is challenging regarding choice of methods and experimental details. The bolus is subjected to both shear and extensional flow during mastication and swallowing (Chen & Lolivret, 2011; Hadde, Cichero, Zhao, Chen, & Chen, 2019; Nystrom, Qazi, Bülow, Ekberg, & Stading, 2015; Waqas, Wiklund, Altskär, Ekberg, & Stading, 2017). Thus, both large deformation shear and extensional rheometry need to be considered to mimic the flow properties of the bolus. To follow structural changes and to fingerprint the bolus microstructure linear viscoelastic measurements are required, such as small amplitude oscillatory shear (SAOS). Careful consideration has to be given to sample extraction and handling as saliva and bolus properties change over time and depend on collection (Schipper, Silletti, & Vingerhoeds, 2007; Stading & Röding, 2020).

The aim of the present study was to determine rheological and physiology-related characteristics of boluses of normal and texture-modified, solid foods for young healthy persons. In a later study, the results will be compared to results from seniors aged 65 years and over. The texture-modified foods represent texture classes of solid foods from normal food to gel food, which have been studied previously (Stading, 2021).

2 | MATERIALS AND METHODS

2.1 | Ingredients

Strained tomatoes without peel and seeds, produced in Italy were obtained as "Coop Passerade Tomater" (COOP Sweden, Stockholm).

Gelatine made from pigskin, Tørsleffs Favorit Gelatin was sold by Haugen-Gruppen (Norrköping, Sweden). A starch-based thickener, "Thick&Easy" (Hormel Health Labs, MN) was kindly provided by Findus Special Foods (Malmö, Sweden).

2.2 | Food products

Regular foods were obtained from the local supermarket.

- Bread: Kavring (Skogaholms Bageri, Sweden), a dark brown homogeneous bread without any seeds. The bread is sold pre-sliced in 8 mm thick slices.
- Fresh tomatoes: The peel, interior fluid and seeds were removed before serving.
- Cheese: "Grevé", 17% fat (COOP Sweden, Stockholm), a Swedish semi-soft cheese similar to the Swiss Emmental or British Cheddar.

Timbale foods were graciously provided by Findus Special Foods (Malmö, Sweden) as bread timbales and tomato timbales. Timbales are made from puréed food, reconstituted by modified starch and egg to create a soft, moist consistency similar to the texture of an omelette. Timbales were distributed frozen, then thawed at room temperature (21°C) before measurements were made. In the Swedish system, processed cheese spread is used for both the timbale and gel food classes, and a processed soft cheese with 17% fat was used in this study ("Fjällbrynt Storsjö", Foodmark, Sundbyberg, Sweden).

The gelled bread was prepared according to how it is made in elderly and clinical care centres. For 30 min, a piece of bread was soaked in water thickened with oil (15 ml rapeseed oil and 7.5 ml Thick & Easy in 100 ml water heated to 80°C and cooled to 20°C). The gelled tomato was prepared from 100 ml strained tomatoes heated above 80°C and 18 g of gelatine was added and stirred into the solution. The solution was cooled and kept at 8°C overnight before measurements were made. The set of food products has been evaluated in detail in a previous paper regarding mechanical and rheological properties (Stading, 2021).

2.3 | Subjects

Five healthy subjects, three women and two men, aged 32–58 years, participated in the study. The experiments reported here were conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki, and prior to the start of the experiment, the participants gave their informed consent to participate in the study.

2.4 | Bolus sampling procedure

Six samples were prepared for each food, 4 g each. The subject was instructed to chew and swallow the first two samples and count the number of chews before swallowing. The remaining four samples were chewed one by one until the subject was ready to swallow and the bolus was then expectorated on a small plate. About 0.5 ml of each sample was immediately applied in the rheometer and the rest was weighed and placed in an oven at 105°C overnight for at least 18 hr for gravimetric determination of moisture content (MC). Evaporation of other components at 105°C was assumed negligible.

2.5 | Simulated boluses

Boluses for extensional viscometry were produced by mixing the foods with a saliva substitute at the same average MC found for the five subjects. The saliva substitute consisted of a buffer of salts corresponding to human saliva as described by Leung & Darvell, (1991). The saliva substitute did not contain enzymes nor mucins. The foods were mixed by hand in the saliva substitute to mimic the blending during mastication.

2.6 | Physical and oral status of the subjects

The general status of the subjects' physical and oral strength was previously evaluated by a set of well-established tests created to predict frailty (Kito et al., 2019).

2.6.1 | Physical strength

Hand grip strength: Measurements were carried out in triplicate for each hand with a digital hand dynamometer (Jamar Plus Dynamometer, Jamar, Cedarburg, WI). The mean maximum grip strength for each hand was used for the analysis.

One-foot balance: The subjects were asked to balance on one foot at a time with eyes alternately open and closed, for as long as they could, but for a maximum of 60 s.

2.6.2 | Oral function

Tongue pressure: A tongue pressure sensor balloon probe connected to a digital tongue pressure meter (JMS, Hiroshima, Japan) was placed on the dorsal tongue surface. Participants were asked to press up against the probe with the tongue towards the hard palate at maximum strength for 3 s (Kito et al., 2019). After several practice movements, tongue pressure was assessed three times for calculation of mean values.

Tongue and lip motor function: Oral diadochokinesis tests were used. Participants were instructed to say the syllables /pa/, /ta/, or /ka/ as many times as possible for 5 s. The number was counted by a digital counter (Kenkokun Handy, Takei Scientific Instruments Co., Ltd, Japan) and used for analysis (Yamada, Kanazawa, Komagamine, & Minakuchi, 2015).

Salivary flow: The flow of stimulated saliva was obtained by chewing on a piece of tasteless parafilm (0.3 g; Parafilm "M", American National CanTM, Chicago, IL). Mechanically stimulated saliva was collected over a period of 3 min. Before collection, the mouth was emptied by an initial swallow. At 30 s-intervals saliva was expectorated into a pre-weighed container and flow rates (ml/min) were calculated. The weight of saliva in grams was assumed to equal the milliliters of saliva secreted, as the specific density of saliva is close to 1.0 (Richardson & Feldman, 1986).

2.6.3 | Saliva content in bolus

The saliva content of each bolus was calculated from the measure MC of the bolus and the MC of the individual foods (Stading, 2021) as previously published by Drago et al. (Drago et al., 2011) as

$$\text{Saliva content} = \frac{MC_{\text{bolus}} - MC_{\text{food}}}{1 - MC_{\text{food}}} \quad (1)$$

where MC_{bolus} is the moisture content of the bolus and MC_{food} is the moisture content of the food.

2.6.4 | Rheometry

SAOS and viscometry were performed using an ARES-G2 (TA Instruments, New Castle, DE) equipped with a 20 or 40 mm-diameter parallel plate system. The gap was 1–2 mm depending on sample. Fast loading was prioritized due to bolus changes over time, to loading of exact amount of sample (Stading & Röding, 2020). The bottom plate was temperature controlled and the measuring system was enclosed in a solvent-trap enclosure with water to humidify the air surrounding the sample. Bolus measurements were performed at 37°C. A measuring sequence was performed with a mechanical spectrum (SAOS) for 0.1–20 Hz (one sample of each food 0.01–20 Hz) at 0.5% strain, followed by a flow curve for 0.01–1 s^{-1}. An amplitude sweep, 0.05–10% strain, was performed for one of the samples after the mechanical spectrum. The measurements were optimized to give results as quickly as possible as the rheological properties of the bolus changes with time (Stading & Röding, 2020).

2.6.5 | Extensional viscometry

The transient extensional viscosity of the thickened solutions was determined by the Hyperbolic Contraction Flow method (HCF) method using an Instron 5542 (Instron Corp., Norwood). The HCF method measures the force on a hyperbolic nozzle subjecting the sample to constant extension rate and is previously thoroughly described and evaluated (Nyström, Jahromi, Stading, & Webster, 2012; Stading & Bohlin, 2001; Wikström & Bohlin, 1999). The hyperbolic nozzle used for the measurement had an inlet radius of 10 mm and outlet radius of 0.83 mm which gives a total Hencky strain of typically 6.5–8.5 for the range of boluses investigated.

2.6.6 | Statistical evaluation

Measured values are presented as mean values with error bars denoting the standard deviation. Samples were compared pairwise using a two-sample T-test.

3 | RESULTS AND DISCUSSION

The solid foods used for the study were selected to represent texture-modified foods: lightly modified timbale food and more modified gel food. These were compared to the corresponding regular food. Timbale food is the least modified food, according to the Swedish modification system, and consists of puréed regular food without particles, reconstituted to a solid, easily mashable food using starch and egg (Möller, 2007; Wendin et al., 2010). The same puréed food is used to form the gel food, using gelatine or other thickeners. The specific foods, bread, cheese and tomato were selected because they are eaten at room temperature (to avoid temperature effects on the bolus) and can be combined to a composite dish, a sandwich. This model set is described in a previous paper regarding physical properties and correspondence to other national systems for texture modification (Figure 1; Stading, 2021).

The general and oral physiological state was determined for the five subjects by a set of established tests (Kito et al., 2019). The tests for general status included hand strength and one-legged standing. The oral physiological state was characterized by both tongue strength and oral diadochokinesis tests. Table 1 shows the results that demonstrate that all subjects were healthy, fit and had good oral strength. The main objectives of determining the physiological status was to prepare for future comparisons with senior subjects and to conclude that the group of subjects can be classified as healthy.

FIGURE 1 Model foods used in the study. Note that processed cheese spread is used for both timbale and gel diets, and that the figure shows food appearance and texture and does not reflect the size served nor the exact composition of the sandwiches

3.1 | Physiology-related properties of the bolus

The physiology-related properties associated with the boluses are presented in Figure 2. The overall figure shows that the texture modification has the desired effects on the boluses in most cases. The exception of tomato will be discussed further below together with the bolus rheological properties. Despite the personal variations between the five subjects, the number of chewing cycles required before swallowing, decreased from regular food over timbale to gel food. The same applies for the bolus saliva content, that is, less saliva was needed for the modified foods, which is positive from a patient perspective as many suffering from dysphagia also suffer from xerostomia, or dry mouth, often as a side effect of medication (Ekberg, 2019).

The saliva content is calculated from the moisture content (MC) of the individual boluses and the moisture content of the food itself, see Equation 1. The moisture content of boluses from regular tomato is dominated by the high moisture content of the tomato tissue that masks the individual variations in bolus saliva content. The same applies for the tomato gel. Further, the acidity of the tomato also stimulates saliva secretion. When the bolus MC is low, or the food MC is high, the sampling is crucial for accuracy in the measurement of saliva content. The saliva inclusion during expectoration can then lead to a calculated saliva content of zero as for some subjects for boluses of processed cheese spread and gel samples, see Figure 2.

The individual variations may reflect different chewing patterns, as well as liking or disliking of specific products. There are studies available where subjects are grouped according to chewing strategy or "mouth-behavior": Chewers, Crunchers, Smooshers, and Suckers (Jeltema, Beckley, Vahalik, & Garza, 2020).This grouping has mainly been correlated with food texture preferences but could possibly explain some of the differences between the subjects regarding chews-to-swallow. In this context and only considering regular tomatoes, subjects one and five would belong to one group whereas subjects two to four would be long to another, but this is merely a speculation. However, this does not apply to other foods in our study and it has been shown that classification based on chewing strategy classes has very little to do with texture preferences and that the classes cannot be predicted from physiological measurements (Franks et al., 2020; Kim & Vickers, 2020; Wilson et al., 2018). When asking the subjects in the present study with a high chew-to-swallow number for regular tomato they replied that they really liked chewing it, so the effect of liking cannot be ruled out despite clear instructions for the procedure.

In general a cause of individual variations is the individual capacity to produce saliva. Figure 3 presents the measured stimulated salivary flow rate of the five subjects. It has many similarities to the individual variations of bolus saliva content in Figure 2. The boluses, especially from subject 3, have a lower saliva content as compared to subjects 1 and 3 for regular and timbale foods. The gelled tomato does not show the same trend, possibly because it is processed differently in the mouth as a gelatine gel melts and releases excess fluid in the mouth. The combination of the regular bread, cheese and tomato into sandwich foods also breaks the trend, and the synergy of the individual components combined will be discussed further below. These observations point to the strong effect of individual variations and a possible connection to salivary flow, but the number of subjects ($n = 5$) is too small to draw any general conclusions.

Other studies have found a reverse dependence of chews-to-swallow and salivary flow rate for healthy subjects eating dry products (Assad-Bustillos et al., 2019; Engelen, Fontijn-Tekamp, & Bilt, 2005). The only food in the present study that could be considered as dry is the regular bread where we actually can observe this negative proportionality, c.f. Figures 2 and 3.

TABLE 1 Physiological data of the subjects

	Median	Average	*SD*
Age (years)	34	38	11
Tongue pressure (kPa)	44	44	6.5
Hand strength			
Left hand (N)	35	35	7.3
Right hand (N)	38	39	9.5
Diadochokinesis			
/Pa/per 5 s	34	34	2.5
/Ta/per 5 s	35	34	3.4
/Ka/per 5 s	32	32	2.5
One-legged-standing			
Left foot, open eyes (s)	60	60	0.0
Right foot, open eyes (s)	60	60	0.0
Left foot, closed eyes (s)	60	54	13
Right foot, closed eyes (s)	60	59	2.2

3.2 | Rheological properties of the bolus

SAOS reflects the bolus structure rather than bolus flow properties, and as oral processing and swallowing involves both shear and extensional flow, shear and extensional viscosity was measured. Extensional viscometry requires larger amounts of fluid than that which single boluses contain, and were thus performed on the foods mixed with saliva substitute.

Figure 4 shows rheological raw data for one of the subjects: mechanical spectra by SAOS, shear and extensional viscosity by viscometry and HCF, respectively. The mechanical spectra are similar for all foods but at a different magnitude of G', except for the processed cheese spread bolus. This makes sense from a structural point of view, as the processed cheese spread in itself has quite a different structure as compared to the other samples. It is a fat-in-water emulsion where the continuous water phase is stabilized by a milk protein matrix. The modulus G' at 37°C (Figure 4b) for the bolus is high. Figure 5 however shows that the average G' over all subjects (3200 Pa) is more similar to that of the processed cheese spread itself, 1200 Pa at 1 Hz (Stading, 2021). The bolus behaves as a soft gel with G'–G'' crossover

FIGURE 2 Physiology-related properties of the boluses for the five subjects. The first row shows results for bread, second for tomato, third for cheese and fourth for the combination into a sandwich. The first column is the required chews until swallow, the second column the bolus moisture content and the third column the calculated bolus saliva content. Each group shows bars ranging from subject one to subject five from left to right

(δ = 45°) at 0.01 Hz in contrast to all other samples that behave as strong gels without a G'–G'' crossover within the measured frequency range. The phase angle of the boluses showed little variation between the different foods (see Figure 4) as well as between subjects (Figure 5). Figure 5 further shows that the phase angle of the bolus was similar and slightly higher for the boluses as compared to the food products, except for regular tomato where the cellular tissue structure have a high G' and phase angle. Similarly, solid regular cheese has a much higher modulus than it's corresponding bolus. The phase angle will not be further analyzed. The only notable difference between foods is that the boluses of cheese (regular and processed cheese spread, Figure 4b) hade phase angles in the range of 20–30° compared to 15–20° for the other food boluses (Figure 4a,c,d).

The shear viscosities of all boluses exhibit Power Law dependence on shear rate. As the rheological fingerprints of the different foods overall are similar, distinct values selected for further analysis of the boluses of all subjects: G' at 1 Hz, shear viscosity at 0.1 s^{-1} and extensional viscosity at 20 s^{-1}. These specific points were chosen because the complex shear modulus is commonly measured at 1 Hz as a "de facto" standard. The choice is a compromise of a frequency low enough to avoid influence of instrument inertia yet giving fast measurements. The shear viscosity was picked at 0.1 s^{-1} because it is in the middle of the shear rate range covered. Higher shear rates would be interesting, as the flow during swallowing extends to >200 s^{-1} but would also induce edge fracture in the bolus sample during measurement (Qazi, Ekberg, Wiklund, Kotze, & Stading, 2019). The extension rate range of the HCF method depends on the level of viscosity as compared to the load cell range of the instrument, high viscosity enables low shear rates and vice versa. The extensional viscosity at 20 s^{-1} was measurable for all samples.

The extensional viscosity of boluses in contrast to the shear viscosity exhibited a different behavior depending on food modification class, especially noticeable for tomato boluses. These exhibit less dependence on extension rate going from regular tomato to tomato timbale to tomato gel.

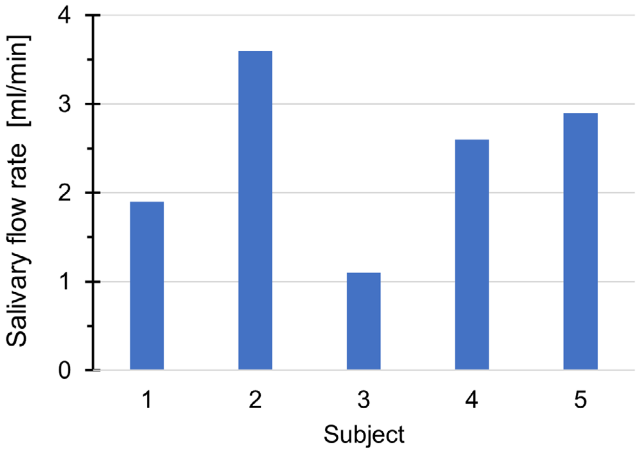

FIGURE 3 Stimulated salivary flow rate for the five subjects, one to five from left to right

The Trouton ratio describes the ratio of extensional to shear viscosity as

$$T_R = \frac{\eta_e(\dot{\varepsilon})}{\eta_{\text{shear}}(\dot{\gamma})} \tag{2}$$

It is preferably expressed at low rates where at least the shear viscosity plateaus out, but current measuring techniques for extensional viscosity are not suited to low extension rates, as also applies to the HCF method used in the current study. It is still possible to get an estimate of the ratio of extensional to shear viscosity at a selected extension rate = shear rate, for example, at 1 s^{-1}. Figure 4 shows that the ratio at 1 s^{-1} ranged from about 3 for the tomato gel bolus to 20 for the bread gel bolus. In general, high molecular weight, and especially branched polymers contribute to elasticity, whereas particles in a dispersion do not, which could be an explanation for the difference in elastic behavior between bread and tomato. Tomato boluses consist mainly of cells and cell fragments from the tomato tissue whereas the starch in the bread may contribute to the more elastic behavior. None of the observed boluses show any pronounced elastic behavior as compared to for example, fluid thickeners for dysphagia which yield considerably higher Trouton ratios (Waqas et al., 2017).

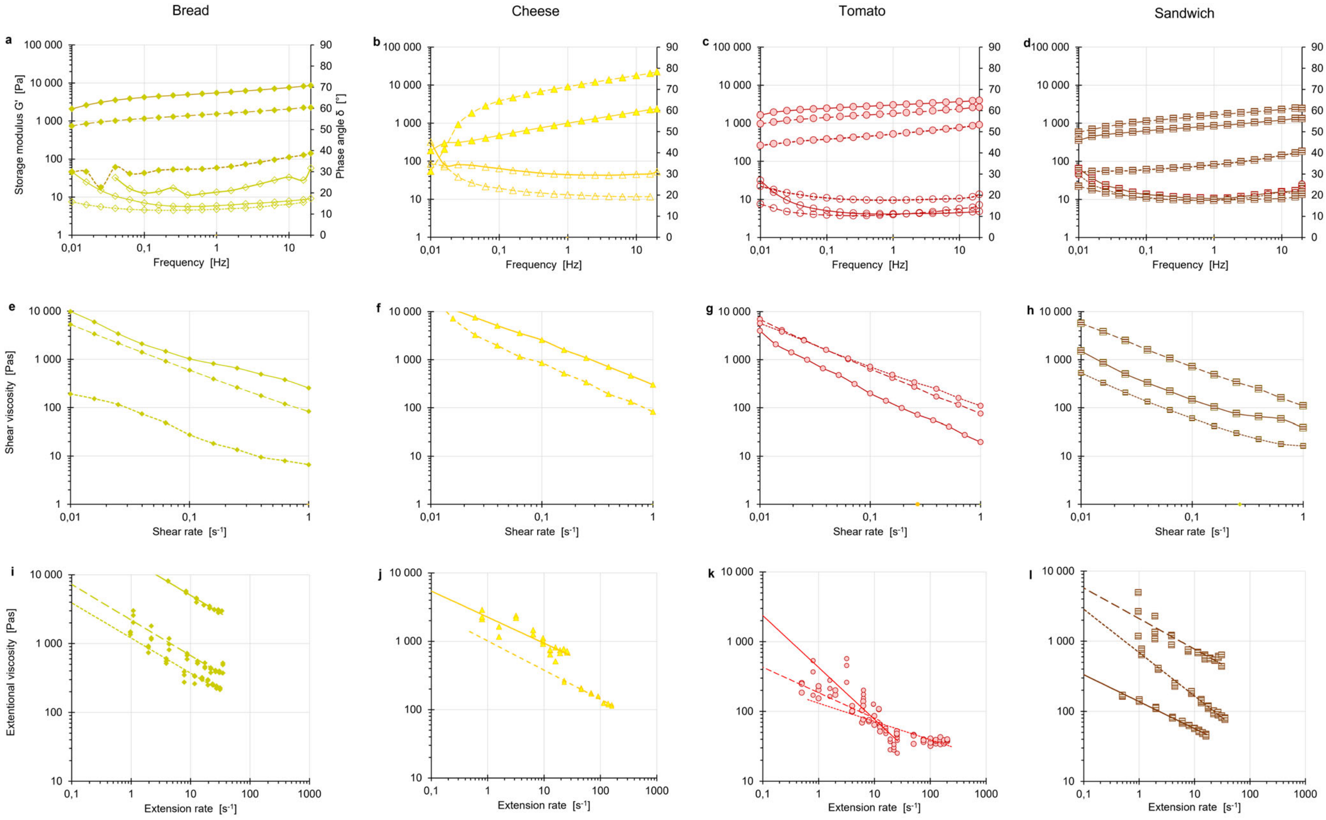

FIGURE 4 Typical mechanical spectra and shear viscosity curves for boluses from one of the subjects (top and center), and extensional viscosity curves (bottom) for the different foods. Regular food: solid lines, timbale food: dashed line, gel food: dotted line. For the mechanical spectra: *G*' has filled symbols and the phase angle has open symbols

FIGURE 5 Rheological properties of the boluses for the five subjects in shear. Each group shows bars ranging from subject one to subject five from left to right. Averages over all subjects are presented with diagonally striped bars. Where comparable data exists for the food products, these are presented as gray bars

Figure 5 shows bolus rheology for all subjects and foods. Viscosity and modulus decrease with modification level, regular > timbale > gel for bread and cheese but not for all parameters for tomato and sandwich. As mentioned previously, the phase angle has little variation with level of modification and more reflects character of the fluid that a bolus is. G' for tomato follows the modification level as it reflects the bolus structure rather that it's flow properties. Shear and extensional viscosity on the other hand reflects the flow resistance and the dispersion of crushed tomato cells in regular tomato therefore have low viscosities.

It is interesting to note that when comparing rheological properties of regular sandwiches and timbale sandwiches, modulus and viscosities are lower or equal for regular as compared to timbale sandwiches. It does not depend on moisture nor saliva content (c.f. Figure 2) and needs to be further studied. The practical interpretation is however that a patient prescribed timbal consistency should equally well be able to swallow a regular sandwich as a timbale sandwich.

Individual variations were observed for rheological properties similar to the physiology-related properties presented in Figure 2 and can at least partly be explained by the individual salivary flow rate of the subjects (Figure 3). This is not the full explanation, however, and other factors such as chewing pattern and personal liking also influences the subject variations.

Boluses of the manufactured timbales (bread and tomato) showed more consistent modulus and viscosity compared to boluses of regular bread and tomato, which can be explained by the fact that the reconstitution in the manufacturing process is aimed at producing timbales with consistent texture and structure.

A further general observation from Figures 2 and 5 is that boluses of the sandwiches appear to have lower values of saliva content, G' and shear viscosity than the individual components eaten separately, especially for the regular and gel sandwiches. This would mean that less saliva is needed to form boluses from the combination of components than for the individual components. This would be an advantage for the many seniors suffering from xerostomia. It would also mean that the combination, the sandwich, would be easier to swallow due to the lower shear viscosity than the components alone. The hypothesis, however, needs to be tested.

Table 2 therefore presents a comparison of parameters for the individual components and the same parameters of the sandwich, that is, the combination of the components. Including all observations the probabilities presented in Table 2 show the probability of a measured parameter for sandwich, for example, saliva content being different

TABLE 2 Probability of parameters for sandwich bolus being different than the individual food component boluses

Food class	Probability of *saliva content* in sandwich being different than respective components		
	Bread	Cheese	Tomato
Regular	**1.00**	**0.94**	0.31
Timbale	*0.84*	*1.00*	0.05
Gel	0.73	0.80	**1.00**

Food class	Probability of modulus *G'* in sandwich being different than respective components		
	Bread	Cheese	Tomato
Regular	**1.00**	**1.00**	**1.00**
Timbale	**0.93**	**0.97**	**1.00**
Gel	0.86	**1.00**	**1.00**

Food class	Probability of *shear viscosity* in sandwich being different than respective components		
	Bread	Cheese	Tomato
Regular	**1.00**	**1.00**	**0.97**
Timbale	*0.93*	**0.98**	*0.41*
Gel	0.29	**1.00**	*0.98*

Food class	Probability of *number of chews* for sandwich being different than respective components		
	Bread	Cheese	Tomato
Regular	**0.99**	*0.30*	*0.99*
Timbale	*0.26*	*1.00*	0.58
Gel	*0.70*	*0.99*	*0.95*

Food class	Probability of *extensional viscosity* in sandwich being different than respective components		
	Bread	Cheese	Tomato
Regular	**1.00**	**1**	*0.94*
Timbale	*0.20*	*0.96*	0.07
Gel	**0.93**	**0.99**	*1.00*

Note: Regular text shows the probability of the sandwich value being lower than the individual, and italic text shows the opposite. Bold text indicate significant differences.

from the saliva content in boluses of the individual components. Saliva content, modulus, shear viscosity, extensional viscosity, and chews-to-swallow for all sandwich bolus samples were pairwise compared to the saliva content of the boluses of the respective components.

The modulus G' reflects the internal structure of the boluses and Table 2 shows that there is a distinct difference between the sandwich boluses and the individual components. Most of the comparisons for the shear viscosity of the boluses also show lower viscosity for the sandwich boluses than the individual components. For saliva content, the picture is not as clear. For the regular sandwich, the required saliva amount was lower as compared to bread and cheese alone, but not compared to tomato. As tomatoes contain 95% fluid in the tissue this would be an expected outcome. When comparing the amount of saliva in boluses of gel sandwiches to the individual gel components only the tomato gel has a significant difference. The reasons are less obvious for the gel foods, especially as the boluses of the gel sandwich have higher moisture content than both timbale and regular sandwiches, and the tomato gel itself has almost as high of a water content as a regular tomato (90% vs. 95%, Figure 2). The gel foods had higher variations between the subjects for the saliva content overall, which likely can be explained by both different chewing strategies and liking of the texture, as well as on individual salivary capacity.

Timbales are made from puréed food reconstituted with starch and egg to form a consistent, moist, and smooth structure. This means that all timbales could be expected to need similar amounts of saliva for bolus formation, as well as similar bolus rheology, and thus also have similar properties also for the sandwiches. The processed cheese spread is, however, not reconstituted for timbale consistency but rather is used “as is” because it fits in the timbale diet. Furthermore, the saliva amount and bolus rheology in the sandwich bolus are therefore not significantly lower compared to the processed cheese spread alone. The processed cheese spread also has a somewhat sticky texture on its own and the oral processing to handle this caused individual variations.

The required chewing cycle to swallow the sandwiches is higher for most samples, as compared to the individual components. The apparent interpretation is that the oral processing needs more mastication to combine the components into a swallowable bolus, even if the resulting bolus shear viscosity and G' is lower than the components alone. Regular bread is the exception, as it requires more chewing alone than as part of a sandwich.

The difference in saliva content between the composite food, the sandwich, and the individual components could be explained partly by the fat added by the cheese. It has previously been observed that butter, cheese, and spreads on bread enhances lubrication in the mouth and reduces the chewing cycles before swallowing and facilitate bolus formation (Assad-Bustillos et al., 2019; Engelen et al., 2005; van Eck, Hardeman, et al., 2019). Fat in cheese has also been observed to affect bolus properties and chewing strategies (Lorieau et al., 2018; Yven et al., 2012). Similarly fat from mayonnaise contributed to faster bolus formation of carrots (van Eck, Wijne, Fogliano, Stieger, & Scholten, 2019).When cheese is chewed and mixed with saliva it forms an emulsion that could facilitate lubrication thus decreasing the necessary amount of saliva for swallowing.

The extensional viscosity gives a mixed impression for the correlations in Table 2. Some food boluses had a lower extensional viscosity when combined into a sandwich whereas other showed the opposite. Elastic behavior as expressed by the extensional viscosity has previously been shown to favor safe swallowing, but it is not obvious if the rather low Trouton ratios observed for the food boluses here would contribute significantly (Chen & Lolivret, 2011; Nystrom et al., 2015). Elastic behavior could also influence the oral processing for the squeeze flow caused by compressing the bolus between the tongue and the palate, and further research is needed on the relative contribution of shear and extensional flow during oral processing and swallowing. This also applies to the effects on dysphagia management as previously pointed out by Andersen et al. (2013).

4 | CONCLUSIONS

The main observation from this study is that modifications in food texture were reflected by bolus properties, at least as in this case for healthy subjects. This is not reflected in all parameters for all foods and continued studies would be beneficial. A texture modification intended to promote easier chewing and swallowing had the intended effect on the food boluses in most cases. In general but not for all foods and all parameters, the texture-modified foods needed less chews-to-swallow, less saliva, had lower bolus viscosity and modulus going form regular to timbale to gel food.

The saliva addition to the food is adjusted for the moisture content of the food and remained notably constant when food moisture content varies from 60% (regular cheese) to almost 100% (regular tomato). The salivary flow rate varied between the subjects and was a contributing factor for variations between subjects, but other factors including liking, personal chewing strategy, oral residence time, and social factors would need to be studied to fully explain the variations between subjects.

None of the texture-modified foods showed pronounced elasticity, which previously has been shown favorable for bolus cohesivity and safe swallowing. The ratio between extensional viscosity and shear viscosity (Trouton ratio) was higher for the regular foods, but still remained below 20, which is less than what has been shown for thickened fluids for dysphagia management. The timbales are manufactured to have uniform texture and consequently showed fairly consistent behavior with larger subject differences than between food sources.

Combining the individual food components (bread, cheese, and tomato) into a sandwich generally had a positive impact on ease of chewing as indicated by saliva content, bolus modulus and bolus viscosity. These parameters were all lower for the sandwich than for the components alone with the addition of fat from the cheese as a likely contributing factor. The sandwich generally needed more chews-to-swallow than the components alone likely due to the more complex composition requiring more mechanical mixing to form a cohesive bolus.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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