Multiple dimensional rheology approach for oral texture prediction of yogurts

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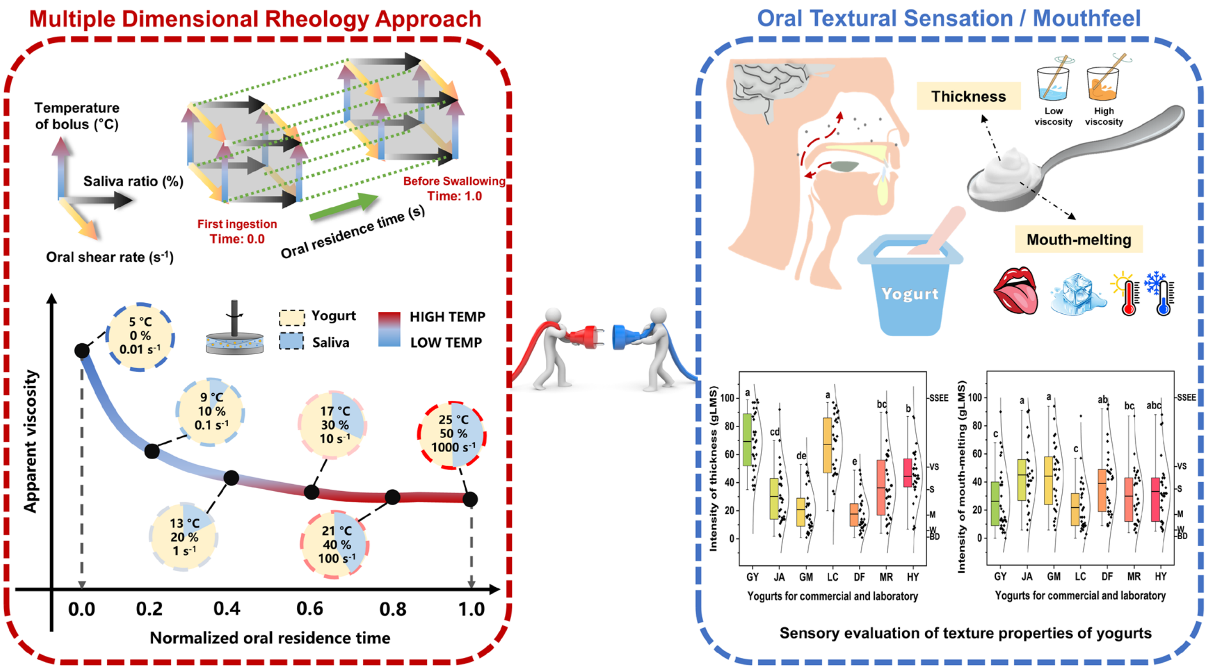
Abstract

The rheological approach has been widely applied to investigate the flow behavior of fluid food for the understanding as well as prediction of oral textural sensation of such products. However, due to multiple dimensional contributions involved in food texture sensation and the highly dynamic nature of oral processing, the conventional rheological measurements can hardly be precise for the prediction of the textural sensation and mouthfeel. Here, we propose a very different rheology approach, which synchronizes four major dimensions/variables in one set of rheological measurements: the oral residence time, the bolus temperature, the saliva ratio, and the oral shear rate. Results indicated that the multiple dimensional rheology approach improved the predictive accuracy of the in-mouth thickness of low-temperature yogurt and provided a new measure for quantifying the mouth-melting of yogurt. It appeared that rheology measurement at a temperature of 13 °C, a saliva ratio of 20 %, and a shear rate of 1 s^{-1} gave the most reliable prediction of in-mouth thickness of yogurt. This novel approach gives a much-improved accuracy of texture prediction but with a much-reduced number of rheology tests. We believe that, even though this experimental approach was initially designed for low-temperature yogurt drinks, it is fully applicable to the texture and mouthfeel prediction of many other food products.

Keywords: Multiple dimensional rheology; Yogurt texture; Mouthfeel; Viscosity; Thickness; Mouth-melting; Food oral processing

Graphical abstract



Highlights

- A novel rheological approach that synchronizes oral residence time, bolus temperature, saliva ratio, and oral shear rate in one set of rheological measurements.
- Optimal conditions for rheology prediction of the in-mouth thickness of yogurt were identified as: bolus temperature (13 °C), saliva ratio (20 %), and oral shear rate (1 s^{-1}).
- The method provides a new feasible approach for *in vitro* prediction and quantification of mouth-melting.
- Real and dynamic oral temperature of low-temperature yogurt from ingestion to before swallowing was measured.

1. Introduction

Food texture and mouthfeel are crucial sensory perceptions to the acceptance and liking of many products and have been shown to influence consumer's choices (Koehler et al., 2024; Stokes et al., 2013; Stribiţcaia et al., 2020). Food rheology, which studies the flow behavior of foods, has been seen as valuable in providing insights into the sensory properties of food. However, accurate prediction of sensory perception using rheological tests remains challenging due to the complex multidimensionality of textural sensation and the dynamic nature of oral processing. Conventional rheological tests can only test one single variable at a time and struggle to simulate the intricate processes that occur in the mouth (Deblais et al., 2021; Koç et al., 2013; Lillford, 2000; Mowlavi et al., 2016; Ong et al., 2018; Thomazo et al., 2019). As a result, there is a need to reconsider the multiple dimensions/variables that impact oral textural sensation and their integration in rheological analysis in order to gain a more comprehensive understanding of food texture perception.

Yogurt is one of the oldest and most popular fermented milk products in the world (Clark et al., 2019). The product is produced by coagulation of milk proteins through lactic acid fermentation using thermophilic Lactobacillus bulgaricus and Streptococcus thermophilus (Savaiano & Hutkins, 2020) and is usually consumed at fridge temperature (around 4 °C). Rheology has been most commonly used for the assessment of yogurt texture and has been successful in many cases. For example, a yogurt product with a higher apparent viscosity, whether dairy or plant-based (Conti-Silva et al., 2018; Greis et al., 2022; Mehta et al., 2023), as well as set or stirred (Harte et al., 2007; Nguyen et al., 2017; Sonne et al., 2014), generally indicate a higher perceived thickness in the mouth. However, complicated microstructure created by multiple level particle aggregation (protein particles as well as oil/fat droplets) gives the yogurt a much richer texture sensation than thickness. Of a wide range of textural terms used for yogurt products, mouth-melting is a typical and unique textural sensation during oral consumption of yogurt. Even though our understanding of mouth-melting is still limited, it is generally believed that its sensation could be related to the changing rate of the reduction of perceived thickness. Predicting the mouth-melting of yogurt through its rheological behavior may be a potential methods (Alting et al., 2009).

Challenges to the rheological approach for oral textural prediction of yogurt is the involvement of multiple dimensions/variables during oral processing. The changing temperature, the incorporation of saliva, and the varying rate of deformation will all play a role, either independently or more likely in an integrated manner, in influencing oral texture sensation. Single rheology measurement is simply unable to simulate actual oral conditions and the complex and dynamic interactions that influence textural sensation (Aktar, 2022; Makame & Nolden, 2024). For example, in the case of low-temperature yogurt, oral processing involves continuous incorporation of saliva and dynamic changes in temperature (Huc et al., 2016; Mosca & Chen, 2017). Obviously, the common practice of setting up rheological measurements at a specified saliva ratio and/or temperature deviates measurements from the actual oral conditions during eating. Another challenge that is not easily replicated by rheometers is the uncertainty of the actual shear/deformation rates inside the oral cavity during oral processing and swallowing (Lv et al., 2017). The apparent viscosity at a shear rate of 50 s^{-1} is commonly used to represent perceived thickness/viscosity (Rao & Lopes da Silva, 2007), but scientific evidence is not sufficient for this selection (Ong et al., 2018). The oral cavity experiences a wide range of shear rates (predicted to be close to zero to more than 1000 s^{-1}), depending on the mechanical properties of the food (Houska et al., 1998; Shama & Sherman, 1973). The relevance of shear rate at various stages of oral processing needs to be further clarified. There is no doubt that these dimensions and variables (e.g., bolus temperature, saliva ratio, and oral shear rate, etc.) must be taken seriously because they are not only key for measuring the rheological properties of food but also significant factors impacting textural sensation and mouthfeel.

Based on these considerations, we have developed a novel rheological approach in this work for fast and reliable texture prediction of yogurt products by synchronizing multiple variables in one single set of measurements. Variables of synchronization include the oral residence time, the bolus temperature, the saliva ratio, and the oral shear rate. The reliability of the multiple dimensional rheology approach was approved by: a) a much-improved correlation between the measured apparent viscosity and perceived sensory thickness; and (b) the established relationship between sensory perceived mouth-melting and the rate of viscosity changes during oral processing. We believe that the multiple dimensional rheology proposed in this work provides a novel approach to bridging the gap between rheological measurements of foods and the sensory experience of consumers.

2. Materials and methods

2.1. Yogurt and their mixtures with the artificial saliva

In this study, we examined a total of six commercial yogurt products and one laboratory-made yogurt. Among these, five were dairy-based and two were plant-based yogurts. The detailed composition and physicochemical properties of all yogurts are presented in **Table 1**. The commercial dairy yogurts (sample code: GY, JA, GM, and LC) were chosen to represent different types of yogurts (Greek-style and stirred), varying fat contents (ranging from 0 % to 6.9 %), and the differentiated sensory features, which represent the diversity of dairy yogurts on the market. As the global market reflects an increasing consumption of dairy alternatives, plant-based yogurts with soy or almond as the main ingredients were included in this study (sample code: DF and MR). Additionally, a laboratory-made yogurt (sample code: HY) was also included to serve as a model system. The preparation for the laboratory-made yogurt was provided in **Supplementary Fig. 1**. All commercial products were purchased online and were analyzed before their best before date.

Artificial saliva was prepared based on a previously reported protocol (Karthik et al., 2019). In addition to necessary inorganic substances, mucin from porcine stomach type II and α-amylase were also used in order to achieve a viscosity similar to that of human saliva, along with other potential properties.

2.2. Sensory evaluations of in-mouth thickness and mouth-melting

2.2.1. Participants and ethics approval

A total of 30 participants (19 females and 11 males; mean age = 24.3 ± 1.4 years) with previous experience in sensory evaluation were recruited from the School of Food Science and Biotechnology at Zhejiang Gongshang University. The participants were instructed not to eat or drink anything (except water) for at least an hour before the experiment. They reported not being hungry or full, not having any olfactory or gustatory deficits, and not having any health problems. Participants confirmed their willingness to consume yogurt at the time of recruitment. All participants provided written informed consent prior to beginning the experiment, and relevant training was conducted to meet the requirements and familiarize themselves with the procedure. The research protocol was approved by the *Experimental Ethics Committee of Zhejiang Gongshang University* (No. 2023030104).

2.2.2. Preparation of samples for sensory evaluations

Yogurt samples used for sensory evaluation were the same as described in **Section 2.1**. It is worth noting that all yogurts were prepared in advance and stored in the refrigerator (4 °C) with covered lids until the start of each sensory session. Samples, each with a total sample weight of approximately 12 g, were placed in randomly coded plastic cups marked with a three-digit number. A plastic spoon was provided to each participant to ensure the same ingestion size (3.8 ± 0.1 g) in sensory evaluation. The choice of about 3.8 g of yogurt (one-time intake) was based on the results of pre-experiments, because this sample size can avoid both perceptual fatigues caused by too large a sample and the inability to fully perceive the texture attributes due to too small a sample.

2.2.3. Procedure for sensory evaluations

Before the experiment, participants did not know whether dairy yogurt or plant-based yogurt was to be evaluated. Participants were asked to wear a blindfold during the sensory evaluation to avoid potential influences due to the visual appearance of the yogurt samples. Samples were coded by arbitrary numbers (three digits) and were presented in random order. The samples were presented one at a time to minimize the comparison between the samples.

Participants had the option of evaluating the sample multiple times, but only one sensory attribute could be evaluated at a time. Sensory attributes assessed by the participants were in-mouth thickness and mouth-melting that were defined as follows (Pascua et al., 2013): (i) thickness is defined as the perceived resistance perceived when compressing the sample between the tongue and the hard palate; (ii) mouth-melting is defined as the perceived rate at which the sample dissolves or melts in the mouth.

Compusense (Guelph, ON, Canada) was used to collect ratings on a generalized labeled magnitude scale (gLMS). The scale ranged from 0 to 100, with “No sensation” marked at 0, “Barely detectable” marked at 1.4, “Weak” marked at 6, “Moderate” marked at 17, “Strong” marked at 35, “Very strong” marked at 51, and “Strongest sensation ever experienced” marked at 100. To minimize fatigue and carryover effect, participants were asked to rest for 5 min between each sample and were instructed to clean their mouths with water of room-temperature during this rest period.

2.3. Rheological measurement of yogurts

Rheological tests, either the apparent viscosity of yogurts or their mixtures of artificial saliva, were performed using the Discovery HR-2 shear rheometer (TA, USA), equipped with a cone-plate geometry with a 40 mm diameter cone and a 2.017 °. Flow sweep tests were conducted to examine the relationship between shear rates and apparent viscosity of samples, with shear rates ranging from 0.01 to 1000 s^{-1}. Temperature was controlled by using a Peltier technique.

Before the measurement, sample of yogurt/saliva mixture was left for rest for 3 min to ensure fully recover of microstructure and excess yogurt sample was carefully removed from the edge. A specifically designed cover was applied to prevent moisture evaporation of the yogurt. All samples were measured for at least 3 times to ensure reproducibility and average values were taken.

2.4. *In situ* measurement of the temperature of yogurt bolus

A K-type thermocouple temperature sensor (TCM_UA, Dagasensor, China) was used to conduct real-time measurements on 10 participants (5 males and 5 females) and record the temperature changes of the low-temperature yogurt during oral consumption (**Fig. 1A**). The sampling frequency and temperature resolution of the sensor were 15 Hz and 0.01 °C respectively. Three yogurts with different apparent viscosity: high (LC), medium (JA), and low (GM) were selected (**Section 2.1** and **Supplementary Fig. 2**) for oral temperature measurement to obtain representative data of bolus temperature inside the oral cavity (results are shown in **Fig. 1B**).

Before the experiment, participants were required to refrain from eating for 30 min to ensure that their oral temperature was closer to its equilibrium state. In addition, all yogurt samples were placed in a refrigerator at 4 °C until the start of the experiment. During the experiment, the temperature sensor was first placed in the yogurt sample for 5 s to record the temperature and this temperature was used as the initial temperature of the yogurt, or the first ingestion temperature. Then, about 3.8 ± 0.1 g of yogurt sample was quickly placed into the mouth, and the temperature sensor was positioned in the middle of the participant's tongue and inside the yogurt bolus. This process lasted for 10 s, and the temperature change of the yogurt bolus was recorded in real-time. The temperature at 10 s was identified as the temperature in the mouth before the yogurt bolus was about to reach the swallowing point. The selection of 10 s was based on the oral residence time of yogurt determined in this study (**Section 3.1.1**). Furthermore, the average oral temperature (mouth without yogurts) of the participants was recorded as a control group. To be consistent with the experimental group, the temperature sensor in the control group was initially placed in 4 °C water for 5 s as the initial temperature.

It is important to note that participants were asked to consume yogurt in a way that was as familiar and natural as possible during the experiment. This was done to increase the exposure of oral tissue to ambient temperature and convective airflow, simulating the dynamic changes of the oral cavity during eating (Erickson, 1980). Additionally, the participants rinsed their mouths with room-temperature water between each sample and ensured they rested for 3 to 5 min to allow the oral temperature to return to normal.

2.5. Statistical analysis

The SPSS 26.0 (SPSS Inc., Chicago, Illinois, USA) was used for statistical analysis of experimental data. Pearson correlation analysis was used to test the correlation between different indicators. To determine significant differences in the intensity of thickness or mouth-melting, ANOVA (Duncan) was used. The goodness of fit (R^2) was determined using simple linear regression. When calculating the fitting slope of the apparent viscosity, it's important to standardize it: the original apparent viscosity was converted using a logarithmic function and then scaled to obtain a dimensionless value (standardized apparent viscosity).

3. Results

3.1. Construction of a multiple dimensional rheology approach and optimized ranges of variables during oral processing

For oral texture sensation, we intend to believe that oral shear rate, saliva incorporation, and bolus temperature are the three most important dimensions (or the most important determining factor). The three factors are of course time-dependent, i.e. they vary as a function of oral processing. The concept of these multiple dimensions is shown in **Fig. 2A**, where three independent variables vary as a function of oral residence time. In applying rheology analysis for the prediction of oral texture sensation, it will be therefore critically important to know the dynamic conditions for rheological measurement. In this study and specifically for oral processing of yogurts, the ranges for these variables were specified as follows: oral residence time (0 to 10 s), bolus temperature (5 to 25 °C), saliva ratio (0 to 50 %), and oral shear rate (0.01 to 1000 s^{-1}). The reasons for these conditions are given below:

3.1.1. Oral residence time (0 to 10 s):

The oral residence time is defined as the time from the first ingestion until the completion of swallowing (Chen & Lolivret, 2011). It should be noted that in this study, the oral residence time excludes the time of swallowing; but refers only to the time before the point of swallowing. As indicated by a previous study, real oral residence time could vary significantly among individuals, but mostly around 2.5 s for viscous fluid foods (Chen & Lolivret, 2011). However, it has also been noticed that the actual oral residence time of yogurt during sensory evaluation generally increased by 2 to 3 times compared with that of daily eating habits (Aguayo-Mendoza et al., 2020). Therefore, for the convenience of experimental setup, a universal oral residence time of 10 s was selected for the oral processing of yogurt and will be used as an overall guidance for rheological measurements.

3.1.2. Temperature of bolus (5 to 25 °C):

The importance of temperature change during food oral processing is often overlooked in sensory analysis as well as in instrumental measurement. In order to determine the temperature variation of a low-temperature yogurt during an eating process, a thermocouple temperature sensor was used to measure *in situ* real-time temperature of the yogurt from first ingestion to before swallowing (**Fig. 1A**). Considering that differences in viscosity can impact the rate of heat transfer, three yogurt products with high (LC), medium (JA), and low (GM) apparent viscosity were examined (**Supplementary Fig. 2**). Additionally, the oral temperature (mouth without yogurts) was also measured for participants and was used as a reference.

It was observed that low-temperature yogurt experienced significant temperature changes during oral processing for all 10 participants (**Fig. 1B**). The average temperature of the yogurts increased by almost 20 °C in about 10 s, rising from about 5 °C when ingested to about 25 °C before being swallowed. In the initial 4 s of consumption, the high-viscosity yogurt (LC) heated up slowly, while the low-viscosity yogurt (GM) heated up much quicker, and the medium-viscosity yogurt (JA) was in between. Additionally, temperature changes were more pronounced during this stage but gradually leveled off as the oral residence time increased. As a comparison, the average oral temperature of the control group rose rapidly from about 5 °C to 34 °C within 2 s and remained constant as the oral residence time increased.

It is obvious that the temperature of the yogurt bolus is a function of oral resident time but also varies across yogurt samples due to different heat transfer coefficients for different yogurt products. For the convenience of the experimental setup, we choose to have a whole temperature change of 5-25 °C evenly distributed across the oral resident time.

3.1.3. Ratio of saliva (0 to 50 %):

Given the dynamic nature of oral processing and saliva secretion, it is challenging to determine the amount of saliva in a yogurt bolus during eating. This complication becomes more so when considering that the stimulus of food ingredients, salivary flow rate, and chewing frequency vary significantly among consumers (Chen, 2009; Navazesh & Kumar, 2008; Pedersen et al., 2018). A number of efforts have been made in trying to collect yogurt bolus for saliva ratio determination. However, the approach was found to be practically not feasible because of the unknown amount of initial saliva present in the oral cavity and because of the very imprecise cutting-off point for bolus spitting/collection. In this study, we give a saliva ratio of 0 % at ingestion (time zero) and assume that a yogurt bolus contains about half of the saliva when it is swallowed, i.e. a saliva ratio of 50 % in yogurt bolus at the point of swallowing (**Fig. 2B**). This ratio was obtained simply by the estimation. We assume that an initial saliva covering oral surfaces is around 2.5 g and secretion of saliva during oral processing can reach as high as 1.2 g according to literature prediction of stimulated saliva (Humphrey & Williamson, 2001). This makes the final saliva ratio in yogurt bolus around 50 %. It is also worth noting that the low acidity of the yogurt product could potentially stimulate saliva secretion (Murugesh et al., 2015).

3.1.4. Oral shear rate (0.01 to 1000 s-1):

Shear rate refers to the speed of deformation. During oral processing, the real shear rate of food varies significantly, depending on the individual's oral physiology, the type of food, the dimension (or more specifically the thickness) of the food, the stage of oral processing, etc. Shama and Sherman have already indicated a few decades ago that the oral shear rate may range from close to zero to over 1000 s^{-1} (Shama & Sherman, 1973). However, no literature evidence is available to give the exact value of shear rate at various stages of yogurt consumption and no research has confirmed which shear rate is most relevant to sensory perception. Therefore, yogurt samples were tested over a shear rate range of 0.01 and 1000 s^{-1} using a shear rheometer. Apparent shear viscosity was recorded as a function of shear rate.

We speculate that the real oral shear rate should gradually increase during oral processing, from a very low value to a much higher value at the point of swallowing, due to the fact that food is spread out and becoming a thinner layer during oral processing (Stokes et al., 2013). Therefore, we specifically assign 0.01 and 1000 s^{-1} as the starting shear rate and the ending shear rate for oral processing of yogurt. The selection of these figures was based on two considerations. Firstly, a very low shear rate (< 0.01 s^{-1}) means very limited deformation and could mean very little to sensory perception. A magnitude of 10^3 s^{-1} is the estimated shear rate for a low-viscosity liquid food (Shama & Sherman, 1973). As an approximation, we assume that there are six magnitudes of change in oral shear rate during the oral processing of yogurt, following a logarithmic pattern.

Based on the above discussion, we obtain varying values for all three dimensions as a function of the normalized oral residence time. These values are given in **Fig. 2B** and are nicely illustrated in **Fig. 2C** and **2D**.

3.2. Multiple dimensional rheology approach for prediction of oral textural sensation

3.2.1. In-mouth thickness prediction based on apparent viscosity measurement

The positive correlation between the apparent viscosity and the perceived intensity of thickness has been confirmed in previous studies for various fluid food samples (Deblais et al., 2021; He et al., 2016). In this work, the sensory intensity of thickness for seven different types of yogurts has been assessed and results are shown in **Fig. 3A**. The results showed that there were significant differences in the perceived thickness among the yogurts. The two Greek-style yogurts (GY and LC) were thicker than other stirred yogurts, while the two plant-based yogurts (DF and MR) were more or less in a similar range to the perceived thickness of other dairy yogurts.

In parallel to sensory analysis, flow behavior and apparent viscosity of these yogurt samples as well as their mixture with artificial saliva have also been measured in a systematic manner according to the principle of multiple dimensional rheology approach discussed above. Relationships between the measured apparent viscosity at different stages of oral processing and the perceived thickness reported by the participants are given in **Fig. 3B**. Our findings indicated that different combinations of temperature, saliva ratio, and shear rate impacted the correlation coefficient (r) and the goodness of fit (R^2) between the apparent viscosity and the intensity of thickness. We observed an inverted U-shaped curve, where the correlation coefficient (r = 0.93, $p < 0.01$) and goodness of fit ($R^2 = 0.86$) reached their highest values at a temperature of 13 °C, saliva ratio of 20 %, and shear rate of 1 s^{-1}. This suggests that under these specific rheological measurement conditions, the apparent viscosity can accurately reflect the perceived thickness. Additionally, we used shear rate as a control variable (**Supplementary Fig. 3**) and found that the average correlation coefficient (r = 0.90) remained high across all shear rates (0.01 - 1000 s^{-1}) when the temperature was 13 °C and the saliva ratio was 20 %. These results suggest that oral sensation at around the middle stage of oral processing could play a dominant role in overall sensation of yogurt texture. Above results also give strong evidence supporting the reliability of multiple dimensional rheology results across a wide range of shear rates. With this approach, sensory texture prediction does not require a whole range of rheological tests for all variables, but selected measurements at the key conditions (13 °C, 20 % saliva, and 1 s^{-1}) can well predict oral texture sensation.

Another interesting observation is that multiple dimensional rheology can also give a clear differentiation between dairy yogurt and plant-based yogurt (**Fig. 3C**). It was observed that both plant-based yogurts (DF and MR) showed a significant "convergence of apparent viscosity" at the later stage of oral processing (indicated by arrows), indicating a consistent viscosity of the yogurt at higher shear rates unaffected by other variables like bolus temperature and saliva ratio. In contrast, this phenomenon was not observed in any of the dairy yogurts (**Fig. 3C** and **Supplementary Fig. 4**). Even though MR (plant-based yogurt) and LC (dairy yogurt) have a similar initial apparent viscosity (around 1400 Pa·s at 0.01 s^{-1}), MR's apparent viscosity still exhibited a convergent trend at the later stages of oral processing, whereas LC behaved in a very different manner. This difference may be linked to the composition and structure of plant-based yogurt (Dhakal et al., 2023).

3.2.2. Multiple dimensional rheology approach for sensory prediction of mouth-melting

Mouth-melting is a unique texture feature for many dairy products, significantly influencing consumer preferences for a product (Guichard et al., 2018). The sensory definition of mouth-melting is widely accepted as how quickly a sample dissolves/melts inside the mouth (**Section 2.2.3**). Therefore, sensory mouth-melting should have a close link with two very significant rheological features: the thickness and the changing rate of the thickness.

The sensory intensity of mouth-melting was first evaluated for the seven yogurt products and results are shown in (**Fig. 4A**). Significant differences were observed in the mouth-melting among these samples. The Greek-style yogurts (GY and LC) had lower mouth-melting values than other stirred yogurts, probably implying that they dissolve or melt more slowly inside the mouth during oral processing. This result seems to be opposite to the changing trend of perceived thickness. The correlation analysis between the perceived intensity of thickness and the perceived intensity of mouth-melting (**Fig. 4B**) showed a significant negative correlation ($r = -0.17$, $p < 0.05$), suggesting that the higher the in-mouth thickness of the yogurt, the slower its melting rate.

The dynamics of viscosity changing for the yogurt samples have also been analyzed, by plotting the apparent viscosity as a function of oral residence time. Since the initial viscosity varies significantly among yogurt samples and oral residence time varies significantly among subjects, it was therefore decided to standardize and normalize both variables, and results are plotted in **Fig. 4C**. In this way, a clear pattern emerges for the rate of viscosity change for all tested samples, reflected by the slope of the curves. Among them, the largest absolute slope value was observed for yogurt GM (approximately 261), while the smallest absolute slope value was observed for yogurt LC (approximately 166). By plotting the sensory intensity of mouth-melting against the dimensionless slope obtained in **Fig. 4C**, we observe a significant negative correlation between the sensory perception and rheological measurement for the mouth-melting (r = -0.73, $p < 0.05$) (**Fig. 4D**). This result confirms our speculation that a faster apparent viscosity changes corresponds to a stronger sensory perception of mouth-melting for yogurt products. We intend to believe that the current approach should also be applicable for sensory prediction of many other fluid and soft solid products, such as ice cream, creams, chocolates, gels, salad dressing, or even soup-type drinkable products.

3.3. Comparison of conventional rheology and multiple dimensional rheology

It must be noted that the rheological approach has been widely applied in predicting sensory thickness and other sensory attributes of yogurts and many other food products. However, the conventional approach normally adopts flow behavior tests conducted at a controlled temperature over a whole range of shear rates and selects apparent viscosity at a specific shear rate (usually 50 s^{-1}) for comparison. For low-temperature yogurt, tests were often conducted at its storage temperature of 5 °C (or the ingestion temperature) or close to its swallowing temperature (25 °C) yogurt (Kumari et al., 2023; Sözeri Atik et al., 2023). Such an approach has also been conducted here and results are shown in **Fig. 5A**. Strong positive relationships are clearly observable between perceived thickness and measured apparent viscosity, with a correlation coefficient of 0.86 and 0.84 at 5 and 25 °C respectively ($p < 0.05$).

However, the multiple dimensional rheology approach seems to give a much better prediction compared to the conventional approach (**Fig. 5B**). One can see that a highly significant positive correlation between the apparent viscosity and perceived thickness of yogurt with a correlation coefficient of 0.9253 and a *p*-value of 0.0028 ($p < 0.01$). The corresponding optimal rheological measurement conditions at this point were: temperature of 13 °C, saliva ratio of 20 %, and shear rate of 1 s^{-1}. These results demonstrate that, while the conventional rheology approach could still be useful in predicting the sensory texture of dairy products, the multiple dimensional rheology approach gives a great advantage in improving prediction accuracy. By integrating four variables in one single approach, the multiple dimensional rheology approach is also much more efficient by significantly reducing the number of tests.

4. Further discussion

Over the past few decades, many researchers have been delving into the potential relationship between objective instrumental data and subjective sensory analysis (Chauvin et al., 2010; Saleh & Lee, 2023; Skarlatos et al., 2020; Sonne et al., 2014; Yilmaz-Ersan & Topcuoglu, 2022). However, this is not an easy task. The challenge comes from the fact that oral textural sensation and mouthfeel of low-temperature yogurt or other foods are significantly impacted by the dynamic interactions between multiple dimensions/variables, such as the bolus temperature, the saliva ratio, the oral shear rate, and the oral residence time, from the first ingestion to before swallowing, but conventional rheology approach can only deal with one or two variables at a time and therefore fails to reflect the dynamic nature of oral texture sensation (Culler, 2019).

In this study, the four main dimensions/variables that impact mouthfeel were synchronized for the first time in a single rheological measurement. This allowed us to dynamically track the changes in apparent viscosity of low-temperature yogurt from the first ingestion to before swallowing (**Fig. 2D**). The optimized rheological measurement conditions for predicting in-mouth thickness were found as follows: bolus temperature (13 °C), saliva ratio (20 %), and shear rate (1 s^{-1}) (**Fig. 3B**). The multiple dimensional rheology approach significantly improved the predictive accuracy of perceived thickness compared with conventional rheological tests (**Fig. 5**). The correlation coefficient increased from 0.85 to 0.93 ($p < 0.01$). To further verify the reliability of the multiple dimensional rheology approach in more complex and variable oral environments, tests have also been conducted with shear rate as a control variable (**Supplementary Fig. 3**). The results show that the optimal measurement conditions still have a strong and effective prediction ability for in-mouth thickness in all shear rate ranges (0.01 - 1000 s^{-1}), with an average correlation coefficient r of more than 0.90. Additionally, the multiple dimensional rheology approach established a significant correlation between the slope and the mouth-melting by fitting apparent viscosity (r = -0.73, $p < 0.05$), offering a feasible method for *in vitro* prediction and quantification of mouth-melting (**Fig. 4**).

One of the challenges in establishing the multiple dimensional rheology approach was determining the range of variables during food oral processing. Specifically, temperature sensation contributes to human enjoyment of foods and beverages, but the changes in bolus temperature during eating are often simplified or even overlooked (Lemon, 2021). In this study, we used a K-type thermocouple temperature sensor to measure the temperature changes of yogurt bolus from first ingestion to before swallowing (**Fig. 1B**). This measurement has a significant advantage, as the small temperature probe (consisting of two metal wires of about 1 cm in length) will not affect the normal oral behavior/eating habit of the participants. Furthermore, it allows for continuous monitoring of the temperature inside the yogurt bolus during dynamic oral processing, as opposed to using an infrared thermometer to measure temperature only at specific oral residence times or targeting the tongue surface (Engelen et al., 2003; Lv et al., 2019). It is no surprise that temperature rises fast in the early stages of oral processing and gradually reaches the "equilibrium" temperature before being swallowed. It is also not surprising that the rate of bolus temperature increase is affected by the thickness of food. Thicker food appears to have lower thermal conductivity and slower heat transfer during oral processing, possibly due to poorer mixing with saliva (Bikos et al., 2022).

Multiple dimensional rheology approach provides new evidence for understanding the relative importance of textural sensation at different stages of oral processing. Our results suggest that sensory perception of the thickness of yogurt close to the middle stage of eating (normalized time 0.4) plays the most significant role in our overall thickness perception, while thickness sensation at just ingestion and close to swallowing appear to have little influence (**Fig. 3B**). The correlation between the perceived thickness and the apparent viscosity of the yogurt changes along the oral processing time - at first, the correlation increases, but then it decreases sharply towards the late stage of oral processing. This may again prove the hypothesis of the rheology and tribology transition during oral processing (Chen & Stokes, 2012). It has been shown that the texture of food in the early stages of oral processing is mainly affected by its bulk properties (rheology), while in the later stages, it's influenced by the film properties (tribology) of the food bolus (Stokes et al., 2013). This suggests that tribology may have a more significant impact in the later stages of eating, which leads to a sharp decrease in the correlation between the measured apparent viscosity and the perceived intensity of thickness.

There are some potential limitations of this study that deserve further exploration. Firstly, although the selection of yogurt samples in this study has been carefully considered for their diversity, the sample size was still small (n = 7), which may impact the general applicability of the results. Secondly, the current approach treats variables/dimensions on a linear scale, which may not accurately represent actual oral/eating conditions. For example, saliva flow rate shows a trend of rapid increase and then gradual decrease with chewing time (Dawes, 2008), which indicates that the ratio of saliva in food may increase fast initially and then remains little changed during the late stage of oral processing, rather than following a linear pattern. Thirdly, the temperature of yogurt bolus varies among yogurt products because of their difference in viscosity. However, only one generalized temperature profile was taken for the multiple dimensional rheology approach. Additionally, one cannot deny that, in addition to the four main dimensions/variables (i.e. the oral residence time, the bolus temperature, the saliva ratio, and the oral shear rate), there could be other unknown variables that impact oral sensation of yogurt texture. Examples of such variables include saliva composition, oral volume, tongue pressure, and sample size, etc., all of which require further investigation.

5. Conclusion

In recent years, rheological techniques have become essential tools for interpreting as well as predicting the oral textural sensation of food products. However, translating rheological measurements into meaningful interpretations of consumers' perceptions still poses many challenges. By acknowledging the fact that oral textural sensation is dynamic and influenced by multiple factors, this work proposes a novel approach by synchronizing four dominating factors into one single rheology test: the oral residence time, the bolus temperature, the saliva ratio, and the oral shear rate. By investigating the apparent viscosity and its changing rate of low-temperature yogurts, the multiple dimensional rheology approach not only significantly improved the accuracy of predicting in-mouth thickness perception, but also gave an effective prediction of mouth-melting. The optimal conditions of variables for this multiple dimensional rheology approach for yogurts were found to be: bolus temperature (13 °C), saliva ratio (20 %), and oral shear rate (1 s^{-1}). Despite some limitations still need further investigation, we believe that this approach could be widely applicable to predicting the oral textural sensation of many other fluid and soft solid food products.

CRediT authorship contribution statement

Tian Ma: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jianshe Chen:** Writing – review & editing, Supervision, Methodology, Conceptualization, Funding acquisition.

Declaration of competing interest

The work was conducted independently at Zhejiang Gongshang University for the purpose of scientific understanding and all authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the findings reported in this paper.

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Data availability

Data will be made available on request.

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Figure Captions

Fig. 1 The determination of bolus temperature of low-temperature yogurt during oral processing. (A) Schematic diagram of *in situ* real-time recording of the dynamic temperature of yogurt bolus. A K-type thermocouple temperature sensor was used to measure the temperature changes from first ingestion to just before swallowing. **(B)** Results of dynamic temperature changes of low-temperature yogurt during the oral processing for 10 participants. Yogurts with three different apparent viscosities - high (LC), medium (JA), and low (GM) - were used as representative samples and the average oral temperature (without yogurts) was used as the control group.

Fig. 2 Illustrations of the multiple dimensional rheology approach. (A) Schematic diagram of the synchronization of four main dimensions/variables for rheological measurements: oral residence time, bolus temperature, saliva ratio, and oral shear rate. **(B)** The combination of multiple dimensional rheological variables obtained by normalizing time and linear mapping of multiple variables. **(C)** Preparation of samples and procedure for multiple dimensional rheology. **(D)** Results of multiple dimensional rheology of seven yogurts: changes in apparent viscosity of the yogurt bolus from first ingestion to before swallowing as a function of oral residence time, bolus temperature, saliva ratio, and oral shear rate.

Fig. 3 Optimal conditions for measuring in-mouth thickness based on apparent viscosity. (A) Assessment of 30 participants on the intensity of thickness for seven yogurts, categorized as follows: dairy-based yogurts: GY, JA, GM, LC, and HY; plant-based yogurts: DF and MR. BD: barely detectable (1.4), W: weak (6), M: moderate (17), S: strong (35), VS: very strong (51), SSEE: strongest sensation ever experienced (100). The horizontal line represents the average value, and the right side of the box displays all data points along with their corresponding Normal distribution curves. Letters (a - e) indicate significant differences among samples ($p < 0.05$). **(B)** Analysis of the correlation and goodness of fit between measured apparent viscosity and perceived intensity of thickness. P-values: * $p < 0.05$; ** $p <$

0.01. **(C)** Exploration of multiple dimensional rheology as a potential approach for differentiating between dairy and plant-based yogurts: The apparent viscosity of plant-based yogurts (DF and MR) showed a "convergence" at the later stages of oral processing, indicating a consistent viscosity at higher shear rates unaffected by other variables like bolus temperature and saliva ratio. The convergence of the apparent viscosities of the yogurts is marked by arrows.

Fig. 4 Multiple dimensional rheology approach for the prediction of mouth-melting sensation. (A) Assessment of 30 participants on the intensity of mouth-melting for seven yogurts, categorized as follows: dairy-based yogurts: GY, JA, GM, LC, and HY; plant-based yogurts: DF and MR. BD: barely detectable (1.4), W: weak (6), M: moderate (17), S: strong (35), VS: very strong (51), SSEE: strongest sensation ever experienced (100). The horizontal line represents the average value, and the right side of the box displays all data points along with their corresponding Normal distribution curves. Letters (a - c) indicate significant differences among samples ($p < 0.05$). **(B)** Correlation analysis between perceived intensity of thickness and perceived intensity of mouth-melting. The Pearson correlation coefficient (r) ranges from -1 to 1; * indicates a significance level of $p < 0.05$. **(C)** Linear fitting of apparent viscosity obtained by multiple dimensional rheology approach and the corresponding slope values. Letters (a - c) indicate significant differences among samples ($p < 0.05$). **(D)** Correlation between the slope of apparent viscosity obtained by multiple dimensional rheology approach and the perceived intensity of mouth-melting.

Fig. 5 Comparison between conventional rheology approach and multiple dimensional rheology approach. (A) Correlation results between apparent viscosity (50 s^{-1}) and in-mouth thickness of yogurt at 5 °C and 25 °C in conventional rheology test. **(B)** Correlation results between measured apparent viscosity and perceived intensity of thickness in multiple dimensional rheology approach. The corresponding optimal rheological measurement conditions are: the bolus temperature at 13 °C, the saliva ratio at 20 %, and the shear rate at 1 s^{-1}.