Relationships Among Semisolid Food Microstructures, Rheological Behaviors, and Sensory Attributes

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1 Understanding Rheological Measurements in Terms of Sensory Perception

Rheological measurements, particularly in recent years, have become precise measurements for distinguishing and explaining the textures of food products; however, translating these measurements into a meaningful understanding of the experience of consuming a food product can often be challenging. For example, knowing that a given beverage has an apparent viscosity of 30 mPa.s does little to characterize the experience of consuming that beverage. This difficulty is exacerbated with semisolid food or time-dependent products, which display behavior characterized by properties of both fluids and solids in response to the varied conditions in the oral cavity. Despite this difficulty, much progress has been made in this area, and new experimental techniques show promise for future studies.

1.1 Conceptualizing Oral Sensations

In the oral cavity, food is exposed to an extremely varied set of conditions. It has been reported that the tongue can move at a rate of 200 mm s^{-1} (Hiiemae and Palmer 2003) and apply loads between 0.01 to 90 N (Miller and Watkin 1996). However, oral sliding speed and thus oral shear rates will vary greatly depending on the food being consumed as well as from one oral moment to the next during oral processing of any given food product. For semisolid and other non-Newtonian food products, this will therefore result in varying apparent viscosity and produce varied sensations

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across the oral cavity in response to the differences in shear forces. In response to these forces, the food itself is changing as the structure is being broken down. Imagine how much the structure of a dry cracker must be changed during oral processing from the initial bite to the point at which the bolus it becomes can be swallowed. Still further complicating a description of oral processing is the fact that our perception of attributes such as thickness or creaminess can be influenced greatly based on our olfactory, gustatory, or visual perceptions of the food. In other words, two foods that might be identical from a standpoint of purely instrumental rheological measurements, such as full-fat and low-fat yogurts, may be perceived to have very different textural properties based on sensory cues provided by the product's smell, taste, or appearance. Defining the parameters to which a food is subjected in the oral cavity has proven to be challenging, and there is still debate about which rheological parameters and testing methodologies are the most relevant to represent perceived texture attributes and the shear rates and shear stresses that occur in the mouth, respectively, during consumption of a food product (Van Vliet 2002; Malone et al. 2003; He et al. 2016).

In an attempt to compartmentalize the major forces at work during the consumption of a food product, oral processing is typically broken into three stages: initial (first bite), masticatory (during chewing), and residual (after swallowing) (Margaret et al. 1963; Guinard and Mazzucchelli 1996; Foegeding and Drake 2007). More recently, however, it has been suggested to break oral processing into six stages so as not to inhibit the development of in vitro techniques to describe the forces the food experiences during oral processing (Stokes et al. 2013). These six stages are (1) first bite, in which the food is fractured for the first time; (2) comminution, in which the food is broken down into large pieces; (3) granulation, in which the food is broken down into small pieces and mixed with saliva; (4) bolus formation, in which the food particles plus saliva are formed into a solid, relatively homogeneous mass in preparation for swallowing; (5) swallowing; and (6) residual, in which any thin films of food or food–saliva mixture left in the mouth after swallowing are sensed. During each of these six stages, the food's structure is changed significantly, therefore the food's rheological behavior will vary greatly from one stage to the next. It should be noted that these stages form a continuum rather than marked steps, and that there is a good deal of overlap from one stage to the next. Studying these stages separately, however, has the advantage of focusing on the underlying physics governing a given stage so that insights can be obtained on the specific functionality imparted by the components of food (Stokes et al. 2013).

A range of surfaces in the mouth also affect the way in which the food is exposed to the forces exerted orally. Food can be compressed between the tongue and the palate, sheared between the teeth, or pressed along the soft surfaces of the cheeks (or numerous combinations thereof). Each of these presents a specific rheological challenge in terms of finding relevant parameters to study as well as textures and geometries to use as a model. Semisolid foods are generally palated, so shear forces in the tongue–palate and tongue–teeth contacts are likely the most important to mimic when developing instrumental tests that mimic oral processing behaviors for semisolid foods. Regardless of the test used, it is agreed at the time of publication of this book that the initial stages of oral processing are dominated by rheological properties, while at the later stages, tribological properties may be better suited to characterize the relevant forces to the oral processing experience (Pradal and Stokes 2016). Therefore, a range of instrumental tests are needed to fully capture food behaviors during all stages of oral processing.

1.2 Sensory Perception of Foods

Sensory evaluation of food is an expensive and time consuming category of analysis. Since it relies on examining individuals' perceptions, the results typically show much more variation than would be observed from taking measurements from several replicates of the same food on a rheometer or texture analyzer. Additionally, while a given rheometer or texture analyzer is manufactured to a precise set of specifications and is typically sold with a guarantee of accuracy and specific limit of detection, sensory panelists are quite the opposite. Two participants in a sensory panel may have significantly different perceptions and expectations about a product's attributes due to differences in sensitivity to tastes and flavors, methods of oral processing, and personal preference and previous history with a given food. Therefore, the experimental design of a sensory study must incorporate the variability that will be experienced between individual panelists. Typically, this means that in contrast to instrumental studies where an average of three replicates is usually sufficient to give an illustration of potential variation in the data, sensory experiments usually require a much higher number of panelists to produce data which shows meaningful correlations and trends. Since sensory evaluation is a destructive technique, this requires preparing or obtaining much larger quantities of samples and adds the logistical complications of bringing a large group of panelists together at the same time to evaluate samples. For example, the minimum number of panelists for a general (untrained) consumer sensory panel is 50 based on statistical considerations; 100 panelists is considered to be the gold standard for this type of panel. Accordingly, recruiting this many panelists can take days or weeks, and setting up and running the panel can take several days and hundreds of pounds of sample. In comparison, the five or six samples evaluated in this type of panel can be evaluated instrumentally using less than a kilogram of sample in a few hours.

Additionally, the conditions under which sensory testing is performed can also significantly impact the data. Room temperature, food temperature, airflow, lighting, and panelist comfort while sitting can all affect a panelist's perception of the food products being evaluated. Even seeing another panelist's facial expression or the visual appearance of the food before evaluation can influence panelists' perceptions of the food. To negate these effects, a set of standards have been agreed upon for the rooms in which sensory evaluation tests are typically performed (ISO 8589:2007). These standards include white lighting, positive room pressure (to avoid odors from other locations entering the room), and separate evaluation booths

Table 1 Example of sensory descriptors, their definitions, and the protocol for analysis as defined by a sensory panel

	Attribute	Definition	Protocol
Mouthfeel	Initial thickness	Pressure needed to press the sample between the tongue and the palate	Put a spoonful of sample onto the tongue, gently press the tongue against the palate 3 times
	Thickness in mouth	Pressure taken to move the sample between the tongue and the palate	Put a spoonful of sample onto the tongue, move the sample in the mouth, rub the tongue for 5 times
	Stickiness on lips	Pressure to separate the sample from the lips	Use lips to take a tip of sample (avoid touching from lips), and hold there for 5 s, then separate the lips for 3 times
	Stickiness in mouth	Elasticity of the sample between the tongue and the palate	Put a spoonful of sample onto the tongue, gently press the tongue against palate and hold there for 3 s and then separate for 5 times
	Mouth coating	Amount of residue left in the oral cavity after swallowing	Put a spoonful of sample into the mouth, move around the tongue and chew the sample for 5 times and swallow
Flavor and taste	Overall flavor	Overall intensity of flavor perceived	Put a spoonful of sample into the mouth, move around the tongue and chew the sample for 5 times and swallow
	Overall sweetness	Overall intensity of sweetness of the samples	Put a spoonful of sample into the mouth, move around the tongue and chew the sample for 5 times and swallow

Table reproduced from He et al. (2016)

for each panelist. Although they can notably improve the precision of the sensory measurements, these requirements can add an additional layer of complication to the sensory evaluation of food, as they can necessitate a specialized facility.

One way to standardize the results of sensory testing is to use descriptive sensory analysis techniques, in which the sensory panel is trained to recognize certain attributes and develops a set of standardized definitions, evaluation protocols, and reference products for these attributes. During training sessions, panelists typically first develop definitions for certain attributes of interest, such as creaminess, graininess or thickness. After this lexicon is developed and evaluation practices are agreed upon, panelists will use the reference foods as calibration standards to scale how much of a given attribute a food has. Multiple practice sessions are usually needed for proper panelist calibration; calibration can be monitored through statistical testing to evaluate intra- and inter-panelist accuracy and precision. Formal sample evaluation begins after panelist calibration is considered to be sufficient to properly evaluate the products of interest. During formal evaluations, panelists generally have access to the reference products if needed for comparison to the test samples. This practice can help standardize inter-panelist data and provide more consistent results. An example sensory lexicon for thickened carbohydrate solutions is shown in Table 1 (He et al. 2016).

Although there are numerous hurdles associated with sensory analysis, it remains the so-called “gold standard” for evaluation of many foods because it is the same method by which foods will be ultimately be judged by consumers. The numerous complications associated with sensory analysis, however, indicate that it is advantageous to food manufacturers to find relevant parameters to measure instrumentally for the purposes of quality control or for initial stages of product development when may formulations need to be rapidly screened. Therefore, finding relevant instrumental parameters that are highly correlated with food textural parameters is a timely and necessary field of study.

1.3 Instrumental Evaluation of Food Properties for Comparison to Textural Attributes

The approaches to instrumentally measuring food properties or behaviors for comparison to texture attributes have historically fallen into three categories: (1) imitative techniques designed to mimic oral movements, (2) empirical methods that seek to align a given measurement with a sensory perception, and (3) fundamental measurements of mechanical and structural properties of a food, e.g. rheometry (Stokes et al. 2013). More recently, methodologies such as direct physiological analysis and tribology have been used in an attempt to get a more holistic view of oral processing. This section discusses these categories of techniques, as well as some of the more novel techniques used for developing relationships between food sensory texture attributes and instrumentally measured parameters.

1.3.1 Imitative Techniques for Food Texture Approximation

Imitative techniques consist of using an instrument that is designed to mimic in some way the deformation of a food that occurs during oral processing. An early example is the Voldokevich bite tenderometer, which squeezed food between two rounded wedges in an attempt to simulate biting with teeth (Volodkevich 1938). Recently, texture analyzers (e.g. the TAXT manufactured by Texture Technologies) have become widely adopted. These devices have a crosshead that can be raised or lowered at a range of constant speeds to a desired distance or load force and can be fitted with a variety of probes to measure crushing, penetrating, or shearing of food. The food material to be measured is placed on a platform or in a cell at the bottom of the machine’s head; semisolid foods are typically tested in some kind of cell or container that holds them in a certain shape. These instruments interface with a computer to give rapid data collection and analysis of the force–deformation or force–time curve.

The classic example of an imitative technique is the "two-bite" test, also known as Texture Profile Analysis (TPA). During this test, which is typically run on a texture analyzer, a food is compressed and released twice, mimicking the first and second bite of a food product. TPA is useful for measuring the change in structure that occurs between the first and second "bite" of a food as this information can be useful for determining how the structure behaves in response to deformation. Consider compressing a thin wafer, which would break under an applied force, as opposed to a strong gel, where the first and second "bites" would be relatively similar (assuming the gel was not compressed to the point where the structure was completely broken). It should be noted that foods should not be fractured or ruptured when performing TPA (Friedman et al. 1963).

Analysis of the data from a two-bite test is classified into several parameters: hardness, elasticity, adhesiveness, cohesiveness, brittleness, chewiness, and gumminess. These parameters can be derived from the time-force curve produced during the two-bite test (Fig. 1). The two-bite test was first described by Friedman et al. (1963). *Hardness* is measured as the height of the first peak (or chew). Hardness values can be normalized by dividing the height of the first peak by the volts input. *Cohesiveness* is a measure of the ratio of the area of the second peak to the area of the first peak (A_2/A_1 in Fig. 1). The parameter of *elasticity* is defined as the difference between the distance B for the food product being tested and the same measurement made on a completely inelastic standardized material such as clay. *Adhesiveness* is measured as the area (A_3 in Fig. 1) of the negative peak occurring between the two compression cycles; this peak represents the work necessary to pull the plunger off of the sample. *Brittleness* (or *fracturability*) is measured as the height of the first local maximum in the first peak where the sample breaks (point C in Fig. 1). *Chewiness* is expressed as the sum of hardness, cohesiveness, and elasticity. Finally, *gumminess* is the sum of hardness and cohesiveness multiplied by 100.

As mentioned in Chapter "Sensory and Oral Processing of Semisolid Foods", TPA may not be appropriate for semisolid foods. Users of TPA should carefully consider first whether TPA is an appropriate test for the semisolid food product of

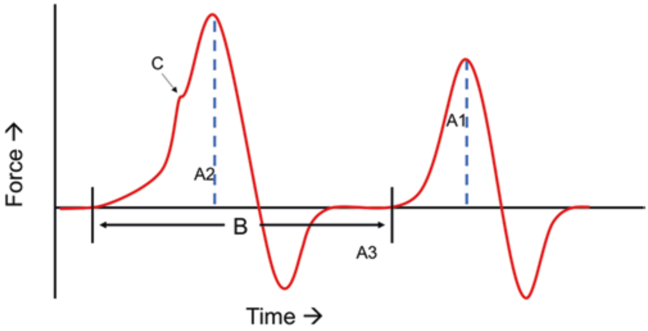

Fig. 1 A typical texturometer curve showing force vs. time. (Figure redrawn from (Martinez et al. 2004))

interest, and second, whether a given TPA parameter is appropriate for describing semisolid food behaviors. For example, firmness may be an appropriate term to describe the force needed to compress a yogurt, but yogurt can hardly be described as “chewy”. Thus, it is not appropriate to use the chewiness calculation for yogurt samples.

Early TPA measurements attempted to correlate the findings of sensory panelists with instrumental measurements and were able to do so with high correlations for food products that varied by a single attribute (Szczesniak et al. 1963). For example, the attribute of ‘chewiness’ was rated based on the time required to masticate a sample at a rate of one chew per second to the sufficient texture needed for swallowing on a seven-point scale including rye bread, gum drops, and Tootsie rolls. Later TPA testing showed good correlation among TPA parameters and first-bite sensory attributes, but fewer correlations were found among TPA parameters and chewdown or residual sensory terms (Foegeding and Drake 2007).

An advantage of imitative techniques is their adaptability, which allows them to be readily modified to be performed under certain conditions or with food products with nonhomogeneous composition or “difficult” geometries. One adaptation of this type of testing was used by Kohyama et al. (2016). They used a probe to compress a rice grain (instead of the half-inch sample height initially described by Friedman et al. (1963)) for compressive testing) to 25% of its initial height, raised the probe, recompressed the grain to 90% of its original height, and finally raised the probe again. But while the adaptability and range of imitative methods can make them extremely versatile, this feature can often hinder analysis. It is difficult to draw meaningful conclusions among experiments when different methods of analysis are used, particularly when it is not possible to convert the results to fundamental measurements (e.g. stress and strain), which is often the case. Furthermore, it can be difficult to know which parameters are relevant to sensory data. In a study examining the effect of changing the experimental parameters defined in TPA, it was found that significant differences occurred in the measured values for the same samples tested under different parameter sets (Rosenthal 2010). For example, the hardness of gels was measured to be an average 541 mN with a plunger and 880 mN with a platen. The percent deformation used in TPA is also frequently changed, ranging from 10% to 90% deformation in literature (Gupta and Sharma 2007; Birkeland and Skåra 2008), and can greatly affect the interpreted cohesiveness and hardness values (Rosenthal 2010). While variation in the percent deformation may be needed so that samples are not ruptured during the test, changes in percent deformation among studies are often due to improper use of TPA.

Another major limitation of imitative testing is that it typically only gives information about the initial sensory behaviors of the food. It is estimated that the first bite encompasses only 2–10% of the total mastication time for a food product, making it difficult to characterize the entire experience of consuming a food product using this data alone (Borne 1975). Other tests are needed to evaluate food properties and behaviors related to later mastication stages.

1.3.2 Empirical Methods

Empirical tests, by definition, measure observed characteristics of the food product. Rheological empirical tests apply a torque or deformation to a material and record the resulting changes to the material's shape (e.g. amount of deformation or resistance to movement). A wide variety of testing geometries and sample shapes can be used in empirical tests, making them quite versatile for a variety of semisolid food products. In general, the imitative tests discussed in the previous section are empirical.

A major advantage of empirical tests is that they are often inexpensive, easy to perform, and in many cases present a good solution for measuring a given attribute of a specific product when a deeper understanding of the underlying structure is not required. One example is the Bostwick consistometer, which is frequently used for measuring the consistency of products such as tomato paste and other foods that are semisolids or thick fluids. The test apparatus consists of a trough with gradations along the bottom. The product is placed into a chamber at one end of the trough that is enclosed by a spring-loaded door. The operator starts a timer when the door is opened and records how far the product has traveled down the trough after a given amount of time has elapsed. This is useful for rapidly and easily comparing between two different samples of the same product type, e.g. between different batches as part of a manufacturing facility's QC plan.

Another widely-used empirical instrument for measuring the consistency of semisolid food is the Adams consistometer (Adams and Birdsall 1946). Similar to the Bostwick consistometer, this device involves measuring how far a food spreads out in a given time period. Instead of placing the food in a trough, however, the Adams consistometer involves placing the food in a center, circular chamber. When the test is started, the walls of the center chamber are raised, allowing the material to flow out from the center in a circular pattern. A set of concentric rings with standardized diameters is used to measure the distance that the material has traveled in the given time. This provides an estimate of the consistency of the food.

Introduced in 1954, the Posthumus funnel is an empirical method that is commonly used to examine the texture of yogurt during production. It has been found to be an effective predictor of perceived thickness or viscosity. Skriver et al. 1999 found a strong correlation (r = 0.834) between the efflux time—the time required for the sample to drain out of the funnel—and the oral viscosity obtained by sensory evaluation. Both shear and elongational flow can occur as the funnel is drained by gravity, similar to the flow behaviors encountered in the oral cavity during processing (Van Vliet 2002; Janhøj et al. 2006). The similarities in flow behavior may contribute to the correlation between oral viscosity measurements and funnel data.

While empirical testing has several advantages, a major drawback of these tests is that it difficult to use empirical test data to determine underlying physicochemical properties such as particle size, surface tension, flow profiles, and viscoelastic moduli. For example, the consistency measured by a Bostwick consistometer cannot be converted to viscosity. In addition, due to the arbitrary test conditions used in empirical testing, it is often difficult to correlate the information obtained from empirical methods with other methodologies (Tunick 2000), convert the empirical data to fundamental data (e.g. converting force to stress or deformation to strain), or draw meaning beyond the immediate measurement given by the empirical method.

Nevertheless, empirical methods are frequently used in an industry setting to evaluate the quality of foods, and numerous methods have been developed for semisolid foods. These methods are often much more easily conducted than sensory tests, and the results can be correlated with sensory data. For instance, if the desired consistency of a product as given by a sensory panel can be correlated to a measurement on a given consistometer, it can be used as a helpful quality control tool. Indeed, these empirical methods are widely used in industry as a rapid check for quality control.

1.3.3 Fundamental Methods

Fundamental rheological methods measure well-defined mechanical properties of the food such as Young's modulus, shear modulus, flow profiles, and viscoelastic moduli. Unlike empirical methods for which measurements combine numerous physicochemical properties of the food and incorporate them into a single measurement (such as efflux time), fundamental properties are measured independently. Measurements of fundamental properties have the advantage of reproducibility when measured on different instruments because they are intrinsic to the foods themselves, as opposed to being the result of only being observed under a specific set of conditions such as those in an Adam's consistometer. However, fundamental measurements generally require more costly equipment, precisely controlled testing parameters, homogeneous samples, and standardized sample geometries. They may also require more time to perform and may need a trained operator to accurately and precisely perform measurements. Therefore, these tests are more commonly used in research laboratories to explore fundamental food properties to develop a deeper understanding of the connections among food microstructure, composition, mechanical behaviors, and sensory texture attributes. While they may also be used during the research and development process, fundamental tests are typically not used for food quality assessment during manufacturing.

Chapter "Rheological Testing for Semisolid Foods: Traditional Rheometry" discusses multiple fundamental tests in detail, including shear rate sweeps, stress and strain sweeps, and frequency sweeps. These are the most commonly used fundamental tests used for semisolid foods. While fundamental rheological properties have been correlated to multiple sensory terms, like empirical data, the correlations between food mechanical properties and sensory attributes evaluated in the later stages of mastication are generally poor (Richardson et al. 1989; Pons and Fiszman 1996; Liu et al. 2007; Foegeding et al. 2017).

1.3.4 Tribological Methods

Tribology represents a relatively new but promising avenue for the study of texture as it relates to oral processing. As with rheological measurements, a major challenge for the usage of tribology to study sensory perceptions is in correlating the data. One approach is to find an entrainment speed or speed range where the friction coefficient correlates with sensory texture attributes. However, the pitfalls of this are discussed in Chapter "Semisolid Food Tribology", and it is not always possible to find a speed range that has meaning during oral processing and also correlates with sensory data. Additionally, the inherently complex nature of most food structures makes it difficult to separate which aspects of the food are contributing to the various sensory and friction attributes being observed (Stokes et al. 2013).

Despite these difficulties, a shift is occurring in food research from instrumentally measuring the food properties that relate to the "first bite" sensory attributes towards a more holistic examination of how the mechanical and physicochemical properties of a food change as it is transformed during oral processing (Stokes et al. 2013). This includes the lingering oral sensations after the bolus has been swallowed. As the food changes from the so-called first bite to the final bolus, there are changes that occur in the dominant behaviors which apply to the bolus (Fig. 2) (Prakash et al. 2013). As oral processing progresses, the behaviors that dominate sensory texture perception move from rheology-dominant to tribology-dominant (Stokes et al. 2013; Foegeding et al. 2017). Sensations related to thickness, firmness, melting, and breakdown are determined when bulk properties dominate the sensory profile. As the food film on the oral surfaces thins to between 0.1 to 100 μm during bolus preparation for swallowing, a person will make determinations regarding creaminess, fattiness, smoothness, and slipperiness (Stokes et al. 2013). Sensations of astringency, roughness, afterfeel, and homogeneity are determined when only residue remains, and also derived from a perception of thin-film, or tribological, characteristics (Selway and Stokes 2013).

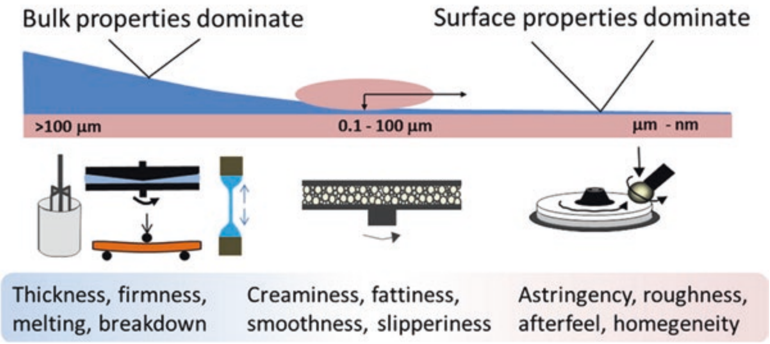

Fig. 2 Schematic diagram depicting the change in properties that are experienced as the food surface thins during oral processing. Also shown are indicators of the types of instruments that could be used to study the relevant forces during these areas of processing. (Figure reproduced from Stokes et al. 2013)

To characterize the interaction of food moving between the palate and tongue, numerous methodologies have been employed in the early twenty-first century to study friction coefficient profiles and how they can affect food sensory attributes. Reviews of these methodologies have been published by Prakash et al. 2013 and Pradal and Stokes 2016. Additional information is also presented in Chapter "Semisolid Food Tribology".

There are multiple devices that can be used to measure friction behavior of fluid and semisolid foods. One such device is the friction tester, one of the most basic tribological methods of analysis (Fig. 3). This apparatus consists of stretching a rubber band between an electric motor and a load cell. When the motor is rotating, the friction between the cylinder and the rubber band produces a force (F_1) that can be detected using the load cell. When the direction of the cylinder is reversed, the load drops to a second force, F_2. Knowing these two forces, it is possible to calculate the coefficient of friction (μ) using Eq. 1 (de Wijk and Prinz 2005):

$$\mu = \frac{1}{\pi \ln\left(\frac{F_1}{F_2}\right)} \tag{1}$$

One potential problem with this method is that it relies on the frictional forces between the food and rubber band. This is not necessarily representative of the surface interactions encountered between a tongue or palate and food (de Wijk and Prinz 2005; Prakash et al. 2013).

Several devices for studying tribology in foods have been mounted on rheometers; Chapter "Semisolid Food Tribology" provides more detail on tribological testing setups. In general, testing geometries can be made in-house or purchased from a rheometer manufacturer. These geometries include ball(s)-on-plate(s) and ring-on-plate setups (Heyer and Läuger 2009; Goh et al. 2010). The ring and plate geometry has been used to differentiate friction coefficients among cream cheeses with different fat contents (Nguyen et al. 2016), while the double-ball system has been used to study acid milk protein gels (Joyner (Melito) et al. 2014). The latter

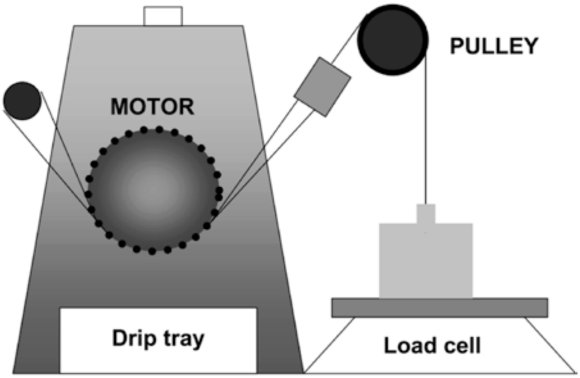

Fig. 3 Schematic representation of a friction tester. Reproduced from de Wijk and Prinz 2004

study showed promise in terms of the ability to relate instrumental friction measurements to sensory attributes. Another device that can be used for friction measurements is a texture analyzer rotated on its side so that gravity is normal to the force exerted by the texture analyzer. This device has been used to obtain friction-related information for both Newtonian and non-Newtonian fluids (Chen et al. 2014).

1.3.5 Direct Physiological Analysis

Direct physiological analysis involves the study of food texture by instrumentally measuring one or more parameters as they are occurring during oral processing. Çakir et al. (2012) investigated the effects of various textured foods on adaptation of subjects' chewing pattern by examining jaw muscle activity and kinematic measures of mastication. Self-adhering diodes were placed on subjects' chewing muscles and jaw movements were recorded using a specialized camera with 3D modeling software. In response to a reduction in the fat content of cheese, oral processing was found to adjust to consist of increased closing muscle activity, a shorter cycle duration, and an increase in the power stroke time. This unique method not only allows for data to be collected directly from oral processing (thus removing some of the difficulty between translating from instrumental to sensory analysis) but also shows different foods are subjected to different oral processing conditions based on their texture.

2 Typical Relationships Found Between Instrumental and Sensory Data

As discussed in Sect. 1, the types of data collected from sensory and instrumental evaluation of foods are quite different. Therefore it is necessary to draw correlations or develop relationships between the two data types for a proper understanding of how food rheological and sensory behaviors align. Often, it is convenient to use a simplified gel or emulsion to study how a variable can change the sensory characteristics of a food instead of a more complex food system. This has the advantage of minimizing variables as long as the model selected is still sufficiently close to the food so as to generate meaningful conclusions.

2.1 Relationships Between Rheological and Sensory Data

Semisolid food viscosity is often related to various sensory attributes such as thickness. Because many semisolid foods have shear-dependent behavior, the perceived thickness of foods determined in sensory evaluation can be used to estimate shear rates during oral processing by comparing instrumentally measured viscosity values at different shear rates to perceived thickness and determining where the data best align. This procedure was used by Wood (1968), who compared the perceived thickness of shear-thinning cream soups and Newtonian glucose syrups. When a soup and syrup were found to have similar perceived thickness, Wood theorized that the point at which the shear rates crossed on their viscosity curves would be relevant to thickness perception. This shear rate was determined to be 50 s^{-1}. The finding that complex viscosity at 50 rad s^{-1} is highly correlated with perceived thickness was corroborated by Richardson et al. (1989). Small deformation measurements of dynamic viscosity under oscillatory shear at a single frequency (50 rad s^{-1}) correlated directly with panel scores for perceived thickness of solutions without yield stress and weak gels. Panel scores for sliminess also directly correlated with instrumental values of dynamic viscosity at ~50 rad s^{-1}, irrespective of the extent of the extent of shear-thinning behavior (Richardson et al. 1989). This relationship was also found for lemon pie fillings (Hill et al. 1995).

Other studies (Shama et al. 1973) examined a range of fluid and semisolid food products including yogurt, tomato ketchup, tomato soup, and lemon curd. They found that a wide range of shear rates are involved with oral evaluation of food, extending from 10 s^{-1} to 1000 s^{-1}, with the operative shear rate depending on the flow conditions of the food. Low viscosity liquids (<0.1 Pa.s) are evaluated orally at a shear stress of approximately 10 Pa; however, for highly viscous foods, (>10 Pa.s), the viscosity is evaluated at a constant shear rate of approximately 10 s^{-1}. This finding was corroborated by Tárrega and Costell (2007), who investigated the relationship between instrumental rheological measurements and sensory measurements of seven semisolid dairy desserts and found a high correlation between their perceived oral thickness and the measured yield stress values ($r = 0.96$) and apparent viscosity values at 10 s^{-1} ($r = 0.89$). Additionally, storage modulus at 1 Hz and complex viscosity at 7.95 Hz (50 rad s^{-1}) were found to have higher correlation coefficients (0.92 for both) with the perceived oral thickness than loss modulus and complex viscosity at 1 Hz (Tárrega and Costell 2007).

More recently, tribological and rheological evaluation has been combined with microscopy to develop a better understanding of the underlying structures that lead to perceived sensory characteristics. In a study which used particle size, microstructure, rheology, tribology, and sensory evaluation to examine varying ratios of whey protein and casein in yogurt, Laiho et al. (2017) found that the gel network in yogurts with high levels of whey protein had gel microstructures comprising large whey protein–casein aggregates in addition to self-aggregated whey protein particles. In contrast, the gel network of yogurts with low levels of whey protein mostly comprised aggregates containing both whey and casein proteins. Samples with higher whey protein content had stronger protein networks due to increased crosslinking. However, under shear, both of these gel microstructures were broken down into clumps. Trained sensory panel evaluation of the yogurts showed that yogurts with high levels of whey protein had higher "lumpy in-spoon" scores for visual appearance (Laiho et al. 2017), likely because the stronger networks resisted breakdown under shear, resulting in larger lumps in the yogurt body.

In a study using custards as a model dairy semisolid food, three tribological regimes occurred in the friction profiles of the fat-containing samples: (1) fluid entrainment, characterized by a decreasing coefficient of friction; (2) gel particle entrainment, characterized by an increasing coefficient of friction; and (3) accumulation of multiple layers of material at high speeds, characterized by decreasing or constant coefficients of friction (Godoi et al. 2017). When these regimes were compared to confocal laser scanning microscopy images, it was determined that at the low speeds (0.5 mm s^{-1}) of the first regime, the ingredients were evenly dispersed. In the second regime, confocal images indicated a gel particle entrainment zone. Finally, in the third regime, an image taken at 10 mm s^{-1} showed the accumulation of multiple layers of material which favored the separation of the two rubbing surfaces (Godoi et al. 2017). This study is an excellent example of how microscopy results can be used to explain tribological phenomena. More studies like this are needed for a fuller understanding of sample behaviors during tribological testing and how those behaviors contribute to sensory textures.

2.2 Relationships Between Food Composition and Sensory Behavior

2.2.1 Fat Content

Both fat content and type of fat used in a food formulation can have a significant impact on the rheological properties and sensory attributes of the product. Fats composed of saturated fatty acids—that is, fatty acids which do not contain any double bonds between carbons in the chains—will typically have a higher melting point than fats of the same chain length which have double bonds between the carbons. This is because unsaturated fats cannot align as readily as saturated fat can due to kinks in their chains, and thus the intermolecular forces between them are weaker. This phenomenon is largely responsible for the rheological differences observed in, for example, butter (which is mostly saturated fat) and canola oil (which is predominantly unsaturated) at room temperature. Similarly, the underlying fat structure has a large effect on the texture of the finished product.

One of the most commonly examined factors of dairy products that is related to fat is creaminess. For oil-in-water emulsion systems, creaminess has been found to relate primarily to product viscosity, as well as the volume fraction of oil (Akhtar et al. 2005). Typically, creaminess is related to the amount of fat in a product; however, with the usage of fat replacers, it has been found that there are numerous factors such as viscosity, flavor, and appearance that also influence the perception of creaminess (Akhtar et al. 2005). Creaminess can also be increased by increasing the bulk viscosity of the food, using small, stable fat droplets in emulsions, adding flavors associated with creaminess such as dairy flavors, and minimizing, but not eliminating, loss of bulk viscosity during oral processing by using starches that show limited mechanical and enzymatic break-down during oral processing (De Wijk et al. 2006).

The perceived viscosity and smoothness of a sample have been found to be strong predictors of perceived creaminess (Janhøj et al. 2006; Ponne 1983):

$$creaminess = thickness^{0.54} \times smoothness^{0.84} \tag{2}$$

In emulsions, the degree of fat droplet coalescence, or the degree to which the fat droplets throughout the emulsion are able to come together to form larger droplets, has been found to relate to the level of creaminess sensation. The occurrence of coalescence in emulsions correlates with enhanced fat perception as measured by a Quantitative Descriptive Analysis panel and a lowering of the friction coefficients as measured instrumentally (Dresselhuis et al. 2008). This trend was also shown in model emulsion-filled gels. When these gels were manufactured with either bound or unbound particles, gels with bound particles were less susceptible to coalescence and had higher friction coefficients (Liu et al. 2015). Interestingly, whether the droplets were bound or unbound had a much greater impact on the sensory perception of fat than the actual solid fat content (Liu et al. 2015). This result points to the importance of free fat, not just total fat content, in sensory texture of emulsion-based foods. This importance of free versus bound fat may explain why several studies have found that fat level does not necessarily correlate with the viscosity of semisolid dairy products such as cream cheese or yogurt, but does impact friction behaviors (Selway and Stokes 2013; Nguyen et al. 2016).

2.2.2 Protein Content

Typically, when a food protein is in its native structure, the protein is folded such that the hydrophobic residues are arranged on the inside of the protein structure, with more hydrophilic moieties on the outside, allowing the protein to be soluble in water. When food proteins are denatured through heat, acid, or other means, the native structure is disrupted as the protein begins to unfold, and the hydrophobic regions of the protein may be exposed. This denaturation can result in increased aggregation and network formation due to hydrophobic association, wherein the hydrophobic regions of the proteins will associate. If the process is allowed to continue, e.g. if the food is held at a certain pH or temperature, the result is the formation of a three-dimensional gel network that is capable of entrapping fluid and small particles. At low protein concentrations (typically $<1\%$), the gel is a semisolid and often referred to as a fluid gel.

Whey proteins are commonly used to create gels in food products; gelation can be induced by changing temperature, ionic strength, pH, or a combination of these. Changing the pH as well as the salt type and concentration of a whey protein isolate gel allows precise manipulation of the gel structure, mechanical properties, and water-holding capacity even as protein concentration remains constant (Kuhn and Foegeding 1991; Stading and Hermansson 1991; Langton and Hermansson 1992;

Mcguffey and Foegeding 2001; Gwartney et al. 2004). These properties in turn have the ability to affect the sensory perceptions of the food. In Cheddar cheese, which consists of a casein protein network entrapping water, fat, and small molecules such as salts and minerals, the strength of the casein network will change over time as the network connectivity decreases. This results in a shift from the springy texture of a fresh Cheddar (<2 mo storage) to the hardened texture more characteristic of a jammed structure in an aged Cheddar (>6 mo storage) (Rogers et al. 2009).

Furthermore, the type of protein network present has the ability to change the sensory characteristics of the food. Due to their structure, whey proteins have the ability to form either stranded or particulate gels, which can result in varied textural sensations. In a study using descriptive sensory analysis to characterize stranded and particulate whey protein gels manufactured by manipulating $CaCl_2$ content, particulate gels were described by a trained sensory panel as having high values for adhesiveness, crumbliness, cohesiveness of mass, moisture release, particle size distribution, and rate of breakdown. Stranded gels, on the other hand, were characterized as having high values of moisture, slipperiness, compressibility, springiness, surface smoothness, irregular particle shape, particle size, and smoothness (Gwartney et al. 2004). Additionally, increased particles in the mouth, such as those from precipitated proteins or flocculation of dead cells, were related to astringent sensations, reduced oral lubrication, and thus increased friction (de Wijk and Prinz 2005). These results point to the need for tribological measurements of food products for a better understanding of friction-related food texture attributes.

2.2.3 Carbohydrate Content

Certain complex carbohydrates can increase the viscosity of a food. This is particularly useful in creating low-fat versions of products where simply removing the fat would affect the structure of the product, and thus the perception of its quality if no replacement ingredient is added to maintain the structure. For example, in mayonnaise, modified starch, inulin, pectin, carrageenan, microcrystalline cellulose, and microparticulated pectin gels have been investigated for this purpose, with microparticulated pectin gels and weak pectin gels determined to be acceptable replacements for fat based on sensory analysis results (Liu et al. 2007).

In addition to their ability to increase viscosity by acting as bulking agents, many polysaccharides have the ability to form crosslinks and therefore contribute to gel structure and product firmness. Moreover, as consumers seek to add nutrients such as fiber to their diet, it is becoming more relevant for producers to add fiber to food products. Fibers such as inulin can be used as a low-calorie bulking agent or as a texturizing agent to replace fat and sugar (Tungland and Meyer 2002). In dairy products, inulin has been used to replace fat while improving taste and mouthfeel (Aryana et al. 2007; Allgeyer et al. 2010; Elleuch et al. 2011; Crispín-Isidro et al. 2015). For inulin, this functionality has been attributed to its ability to form a particulate gel network and bind water molecules (Franck 2002). Addition of inulin to model fat-free dairy desserts was shown to increase both storage modulus and complex viscosity, which was correlated with increased sensory sweetness, thickness, and creaminess (Tárrega and Costell 2006). In some low fat food products, the breakdown of starch by salivary amylase resulted in reduced oral friction, possibly due to the release and subsequent migration of fat to the surface of a starch-based matrix where it can act as a lubricant (de Wijk and Prinz 2005). This breakdown can have a notable impact on sensory texture, particularly temporal sensory attributes.

2.2.4 Flavor and Aroma Perception

Gel formation typically reduces the amount of flavor that is perceived in a food because the gel structure is essentially trapping the molecules within the network. This includes the tastant molecules as well, which are also trapped and reach the tongue in reduced quantities (Stieger and Van De Velde 2013). Similarly, when comparing high- and low-viscosity foods of the same salt concentration, the high-viscosity food will be perceived as less salty since it is more difficult for the salt molecules to diffuse to the tongue (Mills et al. 2011). On the other hand, increased flavor perception was found for brittle gels. This effect is due to the rapid rate at which brittle foods form new surfaces, and therefore have more area to interact with the tongue (Hafen et al. 2012). In another study using in vitro methods, foods such as elastic gels that break down into more and smaller particles, and thus have a larger surface area, have greater flavor release than foods such as brittle gels which break apart into fewer, larger fragments, and thus have a smaller surface area for the tastant molecules to interact with the tongue (Mills et al. 2011). Furthermore, brittle gels tend to have high syneresis; the expelled serum would carry flavor and tastant molecules to the tongue more rapidly.

3 Rheological and Sensory Evaluation of Yogurt

Yogurt provides an excellent example medium to study the rheology of semisolid foods. Although yogurt is simply fermented milk, there are numerous factors that can affect the final texture of the product. These can range from the starting ingredients (Jumah et al. 2001), such as the fat content of the milk (Sandoval-Castilla et al. 2004; Xu et al. 2007), added stabilizers (Hematyar et al. 2012; Imamoglu et al. 2017), and the type of bacteria used for fermentation (Kailasapathy 2006; Yang et al. 2016), to the pasteurization and fermentation temperature and time (Parnell-Clunies et al. 1988; Dagher and Ali 2016), shear rate experienced during processing, and whether the yogurt is set or stirred (Haque et al. 2001). Furthermore, in more complicated yogurt systems, additional ingredients such as fiber, fruit, or other ingredients may be added for fortification, flavor, and/or color that will also impact the final product gel structure and thus yogurt texture (Noisuwan et al. 2009; Considine et al. 2011; Imbachí-Narváez et al. 2018).

A large part of the structure of yogurt is due to the gelation of both casein and whey proteins (Schorsch et al. 2001; Modler and Kalab 2010). Fermentation drops the pH of the yogurt base, releasing colloidal calcium phosphate from the casein micelles and allowing the casein molecules to interact to form a gel (Pyne and McGann 1960; Dalgleish et al. 1989; Ozcan et al. 2011). During heat treatment, whey proteins denature and interact with caseins, which improves the water-holding capacity of the gel (Mottar et al. 2010). Higher heat treatments cause more denaturation, and thus more texture changes. Yogurt made with both skim milk and ultrafiltered milk was found to have higher scores for thickness and graininess than yogurt made from skim milk alone, probably due to the increased denatured whey protein available to gel the system (Biliaderis et al. 1992). Similarly, Janhøj et al. 2006 asked panelists to rate the meltdown rate, defined as “the rate by which the yogurt bolus breaks down in the mouth” and found that yogurt with a high level of added protein had the highest sensory viscosities and the slowest meltdown rate. However, further addition of microparticulated protein did not increase the viscosity, indicating that there is a limit on how much protein can alter yogurt viscosity.

The rheological properties of some yogurts are due in part to the formation of exopolysaccharides produced by bacteria, which can cause a ropy texture. The specific exopolysaccharides produced can vary depending on the strain of bacteria used to ferment the product (Tunick 2000). These hold the structure together and prevent fracture and syneresis (Cerning 1995). They also generate a long, stringy texture which can result in increased perception of smoothness or sliminess, depending on the level of exopolysaccharide present.

Stirred yogurts can be differentiated by their response to deformation in the linear (LVR) and nonlinear viscoelastic regions (Crispín-Isidro et al. 2015). The length of the LVR, as well as the food’s behavior in the LVR, is related to the structural arrangement of the food, while nonlinear viscoelastic behavior is related to the food’s response when the structure is broken or severely disrupted (Harte et al. 2007). In a study examining the effect of varying levels of fat and inulin content on yogurt rheological and sensory perception, the nonlinear viscoelastic behavior was more closely related to consumer perceptions than the behavior in the LVR (Guggisberg et al. 2009). Additionally, in a study examining the effect of different gums on yogurt texture, it was found that apparent residual stress as determined by a rheometer was significantly correlated ($r > 0.9$) with perceived sensory viscosity. Additionally, yield stress was a strong predictor of initial firmness perception (Harte et al. 2007).

For more information on how yogurt microstructures impact their rheological and sensory behaviors, Chapter “The Impact of Formulation on the Rheological, Tribological, and Microstructural Properties of Acid Milk Gels” presents rheological and tribological behaviors of acid milk gels, and Chapters “Relationships Among Acid Milk Gel Sensory, Rheological, and Tribological Behaviors”, and “Using Human Whole Saliva to Better Understand the Influences of Yogurt Rheological and Tribological Behaviors on Their Sensory Texture” present an in-depth study on microstructure–function–texture relationships of acid milk gels and yogurt, respectively.

4 Looking Forward

Due to its commercial relevance, the attempt to understand how underlying structures affect the sensory perceptions of food during oral processing has become an active area of research over the past several decades. Although new instruments and testing methodologies have greatly improved our understanding of structure–function–texture relationships, researchers are still looking to develop a reliable, low-cost and easy-to-use instrument that will generate data that can not only be used to test a wide range of food products, but will also give data that is corelated to multiple sensory attributes for those foods (Nguyen et al. 2016). Due to the complexity of most food products, it is still difficult to provide meaningful predictions about sensory characteristics from instrumental data using current approaches to understanding structure–function–texture relationships. Measurements in this area face a paradox of needing to be sophisticated enough to replicate the extremely complex conditions that occur in oral processing, yet simple enough that experimentation and data analysis can be performed as easily and quickly as possible. Combined with the need to produce fundamental data for proper replication of results, this makes developing approaches to evaluating food structure–function–texture relationships quite difficult. However, progress is being made on these approaches, particularly through multidisciplinary collaborations. As the fundamental understanding of the relationships among food microstructure, functional properties, and sensory textures continues to develop, it is highly likely that major breakthroughs in analysis protocols will emerge, further enhancing the understanding of the behaviors of complex foods.

References

Adams, M., & Birdsall, E. (1946). New consistometer measures corn consistency. *Food Industries, 18*, 844.

Akhtar, M., Stenzel, J., Murray, B. S., & Dickinson, E. (2005). Factors affecting the perception of creaminess of oil-in-water emulsions. In *Food hydrocolloids* (pp. 521–526).

Allgeyer, L. C., Miller, M. J., & Lee, S. Y. (2010). Drivers of liking for yogurt drinks with prebiotics and probiotics. *Journal of Food Science, 75*. https://doi.org/10.1111/j.1750-3841.2010.01579.x.

Aryana, K. J., Plauche, S., Rao, R. M., et al. (2007). Fat-free plain yogurt manufactured with inulins of various chain lengths and Lactobacillus acidophilus. *Journal of Food Science, 72*, 79–84. https://doi.org/10.1111/j.1750-3841.2007.00302.x.

Biliaderis, C. G., Khan, M. M., & Blank, G. (1992). Rheological and sensory properties of yogurt from skim milk and ultrafiitered retentates. *International Dairy Journal, 2*, 311.

Birkeland, S., & Skåra, T. (2008). Cold smoking of Atlantic salmon (Salmo salar) fillets with smoke condensate - an alternative processing technology for the production of smoked salmon. *Journal of Food Science, 73*. https://doi.org/10.1111/j.1750-3841.2008.00850.x.

Borne, M. (1975). Is rheology enough for food texture measurement? *Journal of Texture Studies, 6*, 259–262. https://doi.org/10.1016/j.yexmp.2014.03.001.

Çakir, E., Koç, H., Vinyard, C. J., et al. (2012). Evaluation of texture changes due to compositional differences using oral processing. *Journal of Texture Studies, 43*, 257–267. https://doi.org/10.1111/j.1745-4603.2011.00335.x.

Cerning, J. (1995). Production of exopolysaccharides by lactic acid bacteria and dairy propionibacteria. *Le Lait, 75*, 463–472. https://doi.org/10.1016/0023-7302(96)80129-1.

Chen, J., Liu, Z., & Prakash, S. (2014). Lubrication studies of fluid food using a simple experimental set up. *Food Hydrocolloids, 42*, 100–105. https://doi.org/10.1016/j.foodhyd.2014.01.003.

Considine, T., Noisuwan, A., Hemar, Y., et al. (2011). Rheological investigations of the interactions between starch and milk proteins in model dairy systems: A review. *Food Hydrocolloids, 25*, 2008–2017. https://doi.org/10.1016/J.FOODHYD.2010.09.023.

Crispín-Isidro, G., Lobato-Calleros, C., Espinosa-Andrews, H., et al. (2015). Effect of inulin and agave fructans addition on the rheological, microstructural and sensory properties of reduced-fat stirred yogurt. *LWT- Food Science and Technology, 62*, 438–444. https://doi.org/10.1016/j.lwt.2014.06.042.

Dagher, S., & Ali, A. (2016). Effect of pasteurization, centrifugation and additives on quality of concentrated yogurt (Labneh). *Journal of Food Protection, 48*, 300–302. https://doi.org/10.4315/0362-028x-48.4.300.

Dalgleish, D. G., Law, A. J. R., BAUMY, J. J., et al. (1989). pH-induced dissociation of bovine casein micelles. II. Mineral solubilization and its relation to casein release. *The Journal of Dairy Research, 56*, 727. https://doi.org/10.1017/S0022029900029290.

de Wijk, R. A., & Prinz, J. F. (2004). The role of friction in perceived oral texture. https://doi.org/10.1016/j.foodqual.2004.03.002

de Wijk, R. A., & Prinz, J. F. (2005). The role of friction in perceived oral texture. *Food Quality and Preference, 16*(2), 121–129. https://doi.org/10.1016/j.foodqual.2004.03.002.

de Wijk, R. A., Terpstra, M. E. J., Janssen, A. M., & Prinz, J. F. (2006). Perceived creaminess of semi-solid foods. *Trends Food Science Technology, 17*, 412–422. https://doi.org/10.1016/j.tifs.2006.02.005

Dresselhuis, D. M., De Hoog, E. H. A., Stuart, M. A. C., et al. (2008). The occurrence of in-mouth coalescence of emulsion droplets in relation to perception of fat. *Food Hydrocolloids, 22*, 1170–1183. https://doi.org/10.1016/j.foodhyd.2007.06.013.

Elleuch, M., Bedigian, D., Roiseux, O., et al. (2011). Dietary fibre and fibre-rich by-products of food processing: Characterisation, technological functionality and commercial applications: A review. *Food Chemistry, 124*, 411–421. https://doi.org/10.1016/j.foodchem.2010.06.077.

Foegeding, E. A., & Drake, M. A. (2007). Invited review: Sensory and mechanical properties of cheese texture. *Journal of Dairy Science, 90*, 1611–1624. https://doi.org/10.3168/jds.2006-703.

Foegeding, E. A., Stieger, M., & van de Velde, F. (2017). Moving from molecules, to structure, to texture perception. *Food Hydrocolloids, 68*, 31–42. https://doi.org/10.1016/j.foodhyd.2016.11.009.

Franck, A. (2002). Technological functionality of inulin and oligofructose. *The British Journal of Nutrition, 87*, 287–291. https://doi.org/10.1079/BJNBJN/2002550.

Friedman, H. H., Whitney, J. E., & Szczesniak, A. S. (1963). The texturometer - a new instrument for objective texture measurement. *Journal of Food Science, 28*, 390–396. https://doi.org/10.1111/j.1365-2621.1963.tb00216.x.

Godoi, F. C., Bhandari, B. R., & Prakash, S. (2017). Tribo-rheology and sensory analysis of a dairy semi-solid. *Food Hydrocolloids, 70*, 240–250. https://doi.org/10.1016/j.foodhyd.2017.04.011.

Goh, S. M., Versluis, P., Appelqvist, I. A. M., & Bialek, L. (2010). Tribological measurements of foods using a rheometer. *Food Research International, 43*, 183–186. https://doi.org/10.1016/j.foodres.2009.09.024.

Guggisberg, D., Cuthbert-Steven, J., Piccinali, P., et al. (2009). Rheological, microstructural and sensory characterization of low-fat and whole milk set yoghurt as influenced by inulin addition. *International Dairy Journal, 19*, 107–115. https://doi.org/10.1016/j.idairyj.2008.07.009.

Guinard, J.-X., & Mazzucchelli, R. (1996). The sensory perception of texture and mouthfeel. *Trends in Food Science and Technology, 7*, 213–219.

Gupta, R. K., & Sharma, A. (2007). Textural profile analysis of sunflower-sesame kernel confection (Chikki). *Journal of Texture Studies, 38*, 153–165. https://doi.org/10.1111/j.1745-4603.2007.00091.x.

Gwartney, E. A., Larick, D. K., & Foegeding, E. A. (2004). Sensory texture and mechanical properties of stranded and particulate. *Journal of Food Science volume, 69*, 333–339. https://doi.org/10.1111/j.1365-2621.2004.tb09945.x.

Hafen, C. A., Allen, J. P., Mikami, A. Y., et al. (2012). The pivotal role of adolescent autonomy in secondary school classrooms. *Journal of Youth and Adolescence, 41*, 245–255. https://doi.org/10.1016/j.foodhyd.2012.05.003.

Haque, A., Richardson, R. K., & Morris, E. R. (2001). Effect of fermentation temperature on the rheology of set and stirred yogurt. *Food Hydrocolloids, 15*, 593.

Harte, F., Clark, S., & Barbosa-Cánovas, G. V. (2007). Yield stress for initial firmness determination on yogurt. *Journal of Food Engineering, 80*, 990–995. https://doi.org/10.1016/j.jfoodeng.2006.06.027.

He, Q., Hort, J., & Wolf, B. (2016). Predicting sensory perceptions of thickened solutions based on rheological analysis. *Food Hydrocolloids, 61*, 221–232. https://doi.org/10.1016/j.foodhyd.2016.05.010.

Hematyar, N., Samarin, A. M., Poorazarang, H., & Hossein Elhamirad, A. (2012). Effect of gums on yogurt characteristics. *World Applied Sciences Journal, 20*, 661–665. https://doi.org/10.5829/idosi.wasj.2012.20.05.2353.

Heyer, P., & Läuger, J. (2009). Correlation between friction and flow of lubricating greases in a new tribometer device. *Lubrication Science, 21*, 253–268. https://doi.org/10.1002/ls.88.

Hiiemae, K. M., & Palmer, J. B. (2003). T ongue M ovements in F eeding and S peech. *Critical Reviews in Oral Biology and Medicine, 14*, 413–429. https://doi.org/10.1177/154411130301400604.

Hill, M. A., Mitchell, J. R., & Sherman, P. A. (1995). The relationship between the rheological and sensory properties of a lemon pie filling. *Journal of Texture Studies, 26*, 457–470. https://doi.org/10.1111/j.1745-4603.1995.tb00983.x.

Imamoglu, H., Coggins, P. C., & Rowe. (2017). Influence of storage time and starches on texture attributes of conventional milk yogurt using response surface methodology. *International Food Research Journal, 24*, 1721.

Imbachí-Narváez, P. C., Sepúlveda-Valencia, J. U., & Rodríguez-Sandoval, E. (2018). Effect of modified cassava starch on the rheological and quality properties of a dairy beverage prepared with sweet whey. *Food Science and Technology, 39*, 134–142. https://doi.org/10.1590/1678-457x.28017.

ISO. (2007). International Standard 8589. Sensory analysis. General guidance for the design of test rooms. Ref. No. ISO 8589:2007. International Organization for Standardization, Geneva, Switzerland.

Janhøj, T., Petersen, C. B., Frøst, M. B., & Ipsen, R. (2006). Sensory and rheological characterization of low-fat stirred yogurt. *Journal of Texture Studies, 37*, 276–299. https://doi.org/10.1111/j.1745-4603.2006.00052.x.

Joyner (Melito), H. S., Pernell, C. W., & Daubert, C. R. (2014). Impact of formulation and saliva on acid milk gel friction behavior. *Journal of Food Science, 79*, E867–E880. https://doi.org/10.1111/1750-3841.12439.

Jumah, R. Y., Shaker, R. R., & Abu-Jdayil, B. (2001). Effect of milk source on the rheological properties of yogurt during the gelation process. *International Journal of Dairy Technology, 54*, 89–93. https://doi.org/10.1046/j.1364-727x.2001.00012.x.

Kailasapathy, K. (2006). Survival of free and encapsulated probiotic bacteria and their effect on the sensory properties of yoghurt. *LWT- Food Science and Technology, 39*, 1221–1227. https://doi.org/10.1016/J.LWT.2005.07.013.

Kohyama, K., Sodhi, N. S., Suzuki, K., & Sasaki, T. (2016). Texture evaluation of cooked rice prepared from Japanese cultivars using two-bite instrumental test and electromyography. *Journal of Texture Studies, 47*, 188–198. https://doi.org/10.1111/jtxs.12172.

Kuhn, P. R., & Foegeding, E. A. (1991). Mineral salt effects on whey protein gelation∗. *Journal of Agricultural and Food Chemistry, 39*, 1013.

Laiho, S., Williams, R. P. W., Poelman, A., et al. (2017). Effect of whey protein phase volume on the tribology, rheology and sensory properties of fat-free stirred yoghurts. *Food Hydrocolloids, 67*, 166–177. https://doi.org/10.1016/j.foodhyd.2017.01.017.

Langton, M., & Hermansson, A.-M. (1992). Fine-stranded and particulate gels of β-lactoglobulin and whey protein at varying pH. *Food Hydrocolloids, 5*, 523–539. https://doi.org/10.1016/S0268-005X(09)80122-7.

Liu, H., Xu, X. M., & Guo, S. D. (2007). Rheological, texture and sensory properties of low-fat mayonnaise with different fat mimetics. *LWT- Food Science and Technology, 40*, 946–954. https://doi.org/10.1016/j.lwt.2006.11.007.

Liu, K., Stieger, M., van der Linden, E., & van de Velde, F. (2015). Fat droplet characteristics affect rheological, tribological and sensory properties of food gels. *Food Hydrocolloids, 44*, 244–259. https://doi.org/10.1016/j.foodhyd.2014.09.034.

Malone, M. E., Appelqvist, I. A. M., & Norton, I. T. (2003). Oral behaviour of food hydrocolloids and emulsions. Part 1. Lubrication and deposition considerations. In *Food hydrocolloids* (pp. 763–773).

Margaret, A. B., Elaine, Z. S., & John, A. C. (1963). Texture profile method. *Journal of Food Science, 28*, 404–409.

Martinez, O., Salmerón, J., Guillén, M. D., & Casas, C. (2004). Texture profile analysis of meat products treated with commercial liquid smoke flavourings. *Food Control, 15*, 457–461. https://doi.org/10.1016/S0956-7135(03)00130-0

Mcguffey, M. K., & Foegeding, E. A. (2001). Electrostatic effects on physical properties of particulate whey protein isolate gels. *Journal of Texture Studies, 32*, 285–305. https://doi.org/10.1111/j.1745-4603.2001.tb01049.x.

Miller, J. L., & Watkin, K. L. (1996). The influence of bolus volume and viscosity on anterior lingual force during the oral stage of swallowing. *Dysphagia, 11*, 117–124. https://doi.org/10.1007/BF00417901.

Mills, T., Spyropoulos, F., Norton, I. T., & Bakalis, S. (2011). Development of an in-vitro mouth model to quantify salt release from gels. *Food Hydrocolloids, 25*, 107–113. https://doi.org/10.1016/j.foodhyd.2010.06.001.

Modler, H. W., & Kalab, M. (2010). Microstructure of yogurt stabilized with milk proteins. *Journal of Dairy Science, 66*, 430–437. https://doi.org/10.3168/jds.s0022-0302(83)81810-4.

Mottar, J., Bassier, A., Joniau, M., & Baert, J. (2010). Effect of heat-induced association of whey proteins and casein micelles on yogurt texture. *Journal of Dairy Science, 72*, 2247–2256. https://doi.org/10.3168/jds.s0022-0302(89)79355-3.

Nguyen, P. T. M., Bhandari, B., & Prakash, S. (2016). Tribological method to measure lubricating properties of dairy products. *Journal of Food Engineering, 168*, 27–34. https://doi.org/10.1016/j.jfoodeng.2015.07.011.

Noisuwan, A., Hemar, Y., Wilkinson, B., & Bronlund, J. E. (2009). Dynamic rheological and microstructural properties of normal and waxy rice starch gels containing milk protein ingredients. *Starch/Staerke, 61*, 214–227. https://doi.org/10.1002/star.200800049.

Ozcan, T., Horne, D., & Lucey, J. A. (2011). Effect of increasing the colloidal calcium phosphate of milk on the texture and microstructure of yogurt. *Journal of Dairy Science, 94*, 5278–5288. https://doi.org/10.3168/JDS.2010-3932.

Parnell-Clunies, E., Kakuda, Y., Deman, J. M., & Cazzola, F. (1988). Gelation profiles of yogurt as affected by heat treatment of milk. *Journal of Dairy Science, 71*, 582.

Ponne, C. (1983). BibliotheekTU Delft predicting the texture of liquid and melting semi-solid foods. *Journal of Food Science, 48*, 1221–1225.

Pons, M., & Fiszman, S. M. (1996). Instrumental texture profile analysis with particular reference to gelled systems. *Journal of Texture Studies, 27*, 597–624. https://doi.org/10.1111/j.1745-4603.1996.tb00996.x.

Pradal, C., & Stokes, J. R. (2016). Oral tribology: Bridging the gap between physical measurements and sensory experience. *Current Opinion in Food Science, 9*, 34–41.

Prakash, S., Tan, D. D. Y., & Chen, J. (2013). Applications of tribology in studying food oral processing and texture perception. *Food Research International, 54*, 1627–1635.

Pyne, G. T., & McGann, T. C. A. (1960). The colloidal phosphate of milk: II. Influence of citrate. *The Journal of Dairy Research, 27*, 9–17. https://doi.org/10.1017/S0022029900010074.

Richardson, R. K., Morris, E. R., Ross-Murphy, S. B., et al. (1989). Characterization of the perceived texture of thickened systems by dynamic viscosity measurements. *Topics in Catalysis, 3*, 175–191. https://doi.org/10.1016/S0268-005X(89)80002-5.

Rogers, N. R., Drake, M. A., Daubert, C. R., et al. (2009). The effect of aging on low-fat, reduced-fat, and full-fat Cheddar cheese texture. *Journal of Dairy Science, 92*, 4756–4772. https://doi.org/10.3168/jds.2009-2156.

Rosenthal, A. J. (2010). Texture profile analysis - how important are the parameters? *Journal of Texture Studies, 41*, 672–684. https://doi.org/10.1111/j.1745-4603.2010.00248.x.

Sandoval-Castilla, O., Lobato-Calleros, C., Aguirre-Mandujano, E., & Vernon-Carter, E. J. (2004). Microstructure and texture of yogurt as influenced by fat replacers. *International Dairy Journal, 14*, 151–159. https://doi.org/10.1016/S0958-6946(03)00166-3.

Schorsch, C., Wilkins, D. K., Jones, M. G., & Norton, I. T. (2001). Gelation of casein-whey mixtures: Effects of heating whey proteins alone or in the presence of casein micelles. *The Journal of Dairy Research, 68*, 471–481. https://doi.org/10.1017/S0022029901004915.

Selway, N., & Stokes, J. R. (2013). Insights into the dynamics of oral lubrication and mouthfeel using soft tribology: Differentiating semi-fluid foods with similar rheology. *Food Research International, 54*, 423–431. https://doi.org/10.1016/j.foodres.2013.07.044.

Shama, F., Parkinson, C., & Sherman, P. (1973). Identification of stimuli controlling the sensory evaluation of viscosity I. non-oral methods. *Journal of Texture Studies, 4*, 102–110. https://doi.org/10.1111/j.1745-4603.1973.tb00656.x.

Skriver, A., Holstborg, J., & Qvist, K. B. (1999). Relation between sesnory texture analysis and rheological properties of stirred yoghurt. *The Journal of Dairy Research, 66*, 609–618.

Stading, M., & Hermansson, A.-M. (1991). Large deformation properties of β-lactoglobulin gel structures. *Food Hydrocolloids, 5*, 339–352. https://doi.org/10.1016/S0268-005X(09)80046-5.

Stieger, M., & Van De Velde, F. (2013). Microstructure, texture and oral processing: New ways to reduce sugar and salt in foods. *Current Opinion in Colloid & Interface Science*. https://doi.org/10.1016/j.cocis.2013.04.007.

Stokes, J. R., Boehm, M. W., & Baier, S. K. (2013). Oral processing, texture and mouthfeel: From rheology to tribology and beyond. *Current Opinion in Colloid & Interface Science, 18*, 349–359.

Szczesniak, A., Brandt, M., & Freidman, H. (1963). Development of standard rating scales for mechanical parameters and correlation between the objective and sensory texture measurements. *Food Technology, 22*, 50–54.

Tárrega, A., & Costell, E. (2006). Effect of inulin addition on rheological and sensory properties of fat-free starch-based dairy desserts. *International Dairy Journal, 16*, 1104–1112. https://doi.org/10.1016/j.idairyj.2005.09.002.

Tárrega, A., & Costell, E. (2007). Colour and consistency of semi-solid dairy desserts: Instrumental and sensory measurements. *Journal of Food Engineering, 78*, 655–661. https://doi.org/10.1016/j.jfoodeng.2005.11.003.

Tungland, B. C., & Meyer, D. (2002). Nondigestible oligo- and polysaccharides (dietary fiber): Their physiology and role in human health and food. *Comprehensive Reviews in Food Science and Food Safety, 1*, 90–109. https://doi.org/10.1111/j.1541-4337.2002.tb00009.x.

Tunick, M. H. (2000). Rheology of dairy foods that gel, stretch, and fracture. *Journal of Dairy Science, 83*, 1892–1898. https://doi.org/10.3168/jds.S0022-0302(00)75062-4.

Van Vliet, T. (2002). On the relation between texture perception and fundamental mechanical parameters for liquids and time dependent solids. *Food Quality and Preference, 13*, 227–236. https://doi.org/10.1016/S0950-3293(01)00044-1.

Volodkevich, N. N. (1938). Apparatus for meassurements of chewing resistance or tenderness of foodstuffs. *Journal of Food Science, 3*, 221–225. https://doi.org/10.1111/j.1365-2621.1938.tb17056.x.

Wood, F. W. (1968). Psychophysical studies on the consistency of liquid foods. *Soc Chem Ind Monogr Rheol Texture Food Stuffs*, 40–49.

Xu, Z.-M., Emmanouelidou, D. G., Raphaelides, S. N., & Antoniou, K. D. (2007). Effects of heating temperature and fat content on the structure development of set yogurt. *Journal of Food Engineering*. https://doi.org/10.1016/j.jfoodeng.2007.08.021.

Yang, Z., Yu, P., Zhang, Y., et al. (2016). Improvement of the texture of yogurt by use of exopolysaccharide producing lactic acid bacteria. *BioMed Research International, 2016*, 1–6. https://doi.org/10.1155/2016/7945675.