Sensory and Oral Processing of Semisolid Foods

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1 Food Texture: Solids, Semisolids and Liquids

Food texture comprises a highly complicated set of sensory attributes perceived by consumers during food consumption. It determines the way food is handled during the eating process and plays a critical role in influencing consumers' eating experience as well as their preference for a given food product. There have been many definitions of food texture, but the most-accepted definition is probably the one proposed by Szczesniak, one of the pioneers of food texture research. Szczesniak defined food texture as the "sensory manifestation of the structure of food and the manner in which this structure reacts to the forces applied during handling and, in particular, during consumption" (Szczesniak 1963). This definition includes mechanical, tactile, visual, and auditory perception of the texture perceived by the assessors. Table 1 summarizes common textural features of semisolid and solid foods and their corresponding physical parameters and sensory terminologies. While most of the sensory parameters are applicable to semisolid foods, some textural attributes such as "crumbly", "crunchy", and "brittle" are mostly used for brittle solid foods. However, some highly elastic semisolid foods (e.g. soft gelatin gels) may also show brittleness, or sharp fracture upon compression, because these foods normally fracture rather than flow under applied stress or strain.

Fluid foods tend to use notably different texture terminology largely because of their different mechanisms of oral manipulation and texture sensation compared to semisolid and solid foods. Fluid foods flow and spread readily inside the mouth.

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Table 1 Textural characterization of semisolids and solids

Sample characteristics	Primary parameters	Secondary parameters	Popular terminology
Mechanical characteristics	Firmness		Soft, hard, film
		Brittleness	Crumbly, crunchy, brittle
		Chewiness	Tender, chewy, tough
	Cohesiveness		Short, mealy, pasty
	Viscosity	Gumminess	Thin, viscous, gummy
	Springiness		Plastic, elastic
	Adhesiveness		Sticky, tacky, gooey
Geometrical characteristics	Particle size and shape		Gritty, grainy, coarse
	Particle orientation		Fibrous, cellular, crystalline
Other characteristics	Moisture content		Dry, moist, wet, watery
	Fat content	Oiliness Greasiness	Oily Greasy

Szczesniak and Kleyn (1963)

They do not require teeth for mastication; tongue compression and pushing is what normally needed for the consumption of a fluid food (Aktar et al. 2015). Table 2 summarizes sensory terminology for fluids as has been previously developed by Szczesniak (1979). From the table, flowability and spreadability are probably the two most important associated rheological and mechanical properties. These parameters are also important for semisolid foods that are manipulated using mainly the tongue and soft palate, such as yogurt, custard, pudding, sour cream, and peanut butter. In fact, many studies on semisolid food texture develop a descriptive sensory lexicon for the foods of interest that combines selected texture attributes from both solid and fluid foods, such as viscosity, smoothness, mouthcoat, firmness, grittiness, and graininess. The use of this type of lexicon is illustrated in Chapters "The Impact of Formulation on the Rheological, Tribological, and Microstructural Properties of Acid Milk Gels" and "Relationships Among Acid Milk Gel Sensory, Rheological, and Tribological Behaviors", which include the results of a descriptive sensory analysis study on stirred acid milk gels and yogurts, respectively.

In general, viscoelasticity is probably the core rheological property that impacts the majority of texture features of semisolid foods. Therefore, there had been considerable effort to link semisolid food rheological behaviors with their sensory texture attributes. Recently, the thin-layer and lubrication properties have also been recognized as highly important for the oral sensory perception of fluid foods (Chen and Stokes 2012). Accordingly, the use of oral tribology (lubrication behaviour of food) together with fluid rheology and sensory studies has become an important approach for texture interpretation of fluid as well as some semisolid foods. Chapters "Relationships Among Semisolid Food Microstructures, Rheological Behaviors, and Sensory Attributes", "The Impact of Formulation on the Rheological, Tribological, and Microstructural Properties of Acid Milk Gels" and "Relationships Among Acid Milk Gel Sensory, Rheological, and Tribological Behaviors" provide

Table 2 Classification of textural properties for liquid foods (Szczesniak 1979)

Category	Popular terminology
Viscosity-related	Thin, thick, viscous
Feeling on soft tissue surfaces	Smooth, pulpy, creamy
Carbonation-related	Bubbly, tingly, foamy
Body-related	Heavy, watery, light
Chemical effects	Astringent, sharp
Oral coating	Mouth coating, clinging, fatty, oily
Resistance to tongue movement	Slimy, syrupy, pasty
Afterfeel (mouth)	Sticky
Afterfeel (physiological)	Clean, drying, lingering, cleansing
Temperature-related	Cold, hot
Wetness-related	Wet, dry

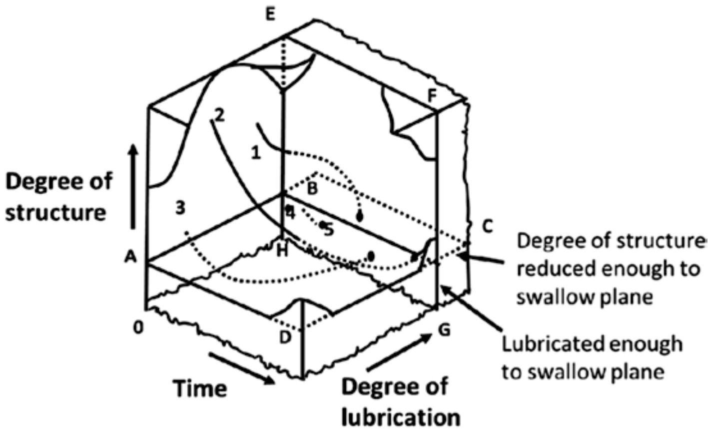

Fig. 1 Illustration of the three-degree food breakdown model for solid and semisolid food during mastication produced by Hutchings and Lillford (1988)

a series of studies on acid milk gels and yogurts that take this approach towards understand semisolid food texture behaviors in terms of their rheological and tribological properties.

As introduced by Hutchings & Lillford (1988) in the late 1980s, texture perception is a dynamic phenomenon due to the continuous processing of food and the changes in its properties during the eating process. Thus, foods with different microstructures and compositions can have notably different breakdown pathways. Furthermore, a minimum level of lubrication is essential for food bolus formation and swallowing (Fig. 1). In this model, the degree of structure, degree of lubrication, and oral processing time are considered to be the primary controlling factors of oral processing of semisolid and solid foods. This model gives a superb description of the dynamic nature of food oral breakdown in terms of particle size change and saliva secretion and incorporation. It is still widely in use to provide insight into how altering the microstructure or composition of food alters the required extent of oral movements and duration of oral processing before swallowing.

2 Oral Processing: Food Deconstruction in the Mouth

Oral processing is a relatively new area of research in food science. It quickly gained popularity in the early twenty-first century because it opened up great possibilities for manipulating food design to create controlled patterns of oral breakdown and desirable mouthfeel. The area of oral processing research includes food physics, oral physiology, sensory psychology, and neural science. While extensive studies have been conducted on food physics and oral physiological responses, research on sensory mechanisms and related neural activities is relatively limited. Work in these areas is needed because there are an enormous array of different texture sensation mechanisms at different stages of oral processing, starting at pre-mastication when the food is brought to the mouth, during mastication and bolus formation, and after bolus swallowing (Fig. 2).

Encouragingly, the growing body of research in food oral processing has led to the development of new techniques to study bolus swallowing using relevant sensory approaches in healthy and dysphagic adults. Bolus swallowing is a fast-growing research area, in particular in countries where elderly populations are steadily increasing. These populations have a higher incidence of dysphagia and other swallowing disorders that make oral processing of many foods difficult. Understanding

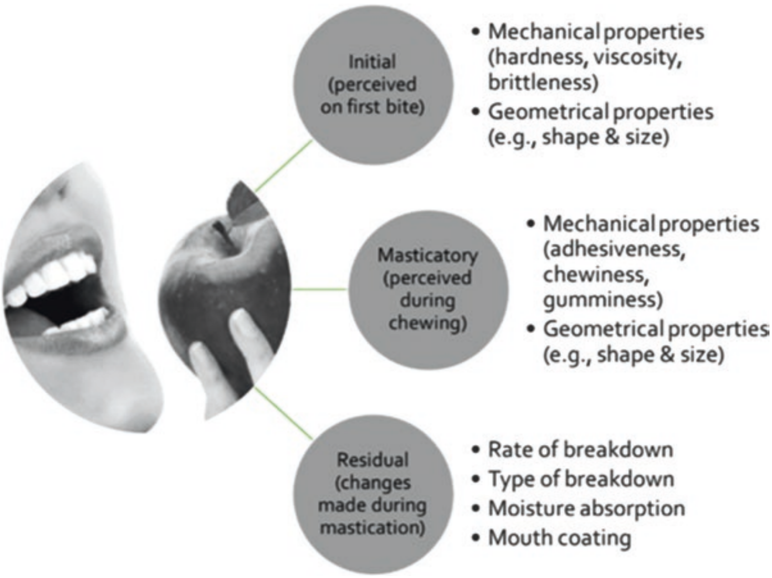

Fig. 2 Structural changes and texture sensation from original product to after bolus swallowing

the divergence from normal oral processing behavior can promote a better understanding of oral processing as a whole, as well as strategies to manipulate food textures to increase their ease of oral processing. Several studies have described the relationship between food (or food bolus) properties and oral processing behavior (Chen 2015; Foegeding et al. 2015). These studies revealed that healthy human individuals are fully capable of adapting oral movements and oral forces for food structure transformation according to the dynamic changes in food and food bolus properties during oral processing. Chewing behavior at an early stage of oral processing is influenced mainly by the composition and bulk rheological properties of the food, while the later stages of oral processing, including swallowing, are influenced mainly by the flow behaviour of the bolus and the interfacial properties (Çakır et al. 2012; Devezeaux de Lavergne et al. 2015; Koç et al. 2013, 2014; Witt and Stokes 2015).

During oral processing, however, the main challenge to food property assessment is the accessibility of the food in real time as it is chewed or palated and converted into a bolus. So far no technique is available for direct testing or imaging what happens to the food inside the mouth during an eating process. Indirect assessment by collecting bolus samples at various stages of oral processing is currently the main approach for understanding the dynamic changes to food properties and rheological behavior. The mechanical properties of the expectorated food bolus can then be determined using a texture analyzer (Devezeaux de Lavergne 2015) or a rheometer (Ishihara et al. 2011), while the particle size distribution can be determined using sieving techniques (Peyron et al. 2004), laser light diffraction (Hoebler et al. 2009), or image analysis (Hoebler et al. 2009).

Particle size distribution, saliva content, and rheological properties of the bolus at the point of swallowing have been investigated by many research groups (Engelen et al. 2005; Loret et al. 2011; Yven et al. 2010). Although these studies provide a good understanding of the final bolus properties, the evolution of bolus properties throughout mastication remains poorly understood. Peyron et al. (2011) conducted a study that analyzed the physical and sensorial properties of boluses collected at different stages of oral processing using texture profile analysis (TPA) and temporal dominance of sensations (TDS). This approach provides a way to elucidate the evolving kinetics of the food bolus as well as changes to its mechanical (textural) properties. This approach has been applied in other studies to examine food destruction during oral processing. Despite the achievements discussed above, the relationship among material properties, human texture perception, and bolus formation dynamics have yet to be thoroughly investigated and understood (Lillford 2011).

Swallowing, a simple but extraordinary task, is triggered when a food bolus reaches its "defined" state (Chen 2009). But although this view is well-supported, there is a lack of solid evidence to demonstrate what general criteria for bolus properties exist for bolus swallowing. Two very different aspects must be considered when considering bolus swallowing: human physiology and the food (bolus) properties. The crucial role of bolus physical properties has been highlighted for various foods in experiments correlating food rheological behavior to ease of swallowing (Alsanei and Chen 2014). One of the most important principles of bolus swallowing is the relationship between bolus flow properties and the swallowing capability of a given individual (Laguna and Chen 2016). There has been much effort to understand the impact of human oral physiology on differences in oral processing and bolus swallowing. This understanding will make it possible to account for inter-individual differences in swallowing and other oral processing studies.

2.1 Oral Behaviour of Semisolid Foods

Semisolid foods refer to food materials that are easily deformable and require a relatively small oral effort for oral processing and consumption (either between the teeth for size reduction and/or between the tongue and palate for compressing and deformation). During oral processing, a semisolid food absorbs the applied force until reaching its yield point, after which significant deformation and breaking will take place. For semisolid foods, the force required to reach this yield point is relatively low and can generally be achieved by palating. Therefore, most semisolid foods are palated rather than chewed. The extent and rate of semisolid food oral deformation depend primarily on its rheological properties, offering a unique textural experience to the consumers.

Semisolid foods are considered to be the most commonly consumed among all food types. An extensive range of semisolid foods are available either as processed (e.g. purees, sauces, and yogurt) or naturally available (e.g. eggs and some fruits). The texture of such foods is determined by their structure. The textural features of semisolid foods can be manipulated by controlling the size, shape, and physicochemical properties of the particle and droplets; the interfacial characteristics; and the rheological properties of the continuous phase or the gelled matrix.

Oral residence time is an important element influencing eating and sensory experience. Compared to fluid foods, such as liquid beverages, semisolid foods usually have a much longer oral residence time due to the need to form a bolus. This longer residence time offers extended sensory exposure. Even though semisolid foods usually cannot give a sharp burst of aroma and flavor release like a solid food because of the sudden increase of surface area when a solid food fractures, they offer a lasting aroma and flavor release due to its gradual mixing and kneading with saliva (e.g. cream cheese, yogurt).

Certain structural features of semisolid foods can contribute to flavor release and textural changes during oral processing. For example, the emulsion gel is a major type of semisolid food in which lipid droplets are embedded into a gel matrix either as active fillers, which interact with the matrix, or inactive fillers, which are entrapped by the matrix but do not interact with it (Chen and Dickinson 1999). The mechanical properties of gelled emulsions have been well-characterized and related to mouthfeel (Sala et al. 2007). The unique sensory feature of emulsion gel systems is the release of lipid droplets during consumption, which will not only lead to an enhanced lipid sensation on the oral surfaces but also alter the lubrication behavior in the oral cavity. In the case of droplets that are strongly associated with the gel matrix (active fillers), the release rate is determined by the melting of the gel matrix during oral processing. The release rate of unbound lipid droplets (inactive fillers) appears to depend on the size of the fragments of the shear-disrupted gel matrix.

It is important to identify the structural and physicochemical properties underlying the different sensory properties to obtain more insight into the way in which humans perceive sensory properties. Until recently, much of the research on the physicochemical properties underlying sensory perception has focused on taste and aroma (odor) characteristics. Research on the origins of texture and mouthfeel has been limited to properties such as hardness and brittleness of solid foods and perceived thickness of fluid foods. Semisolid foods, however, have a much wider possible range of texture variation; therefore, semisolid foods can be prepared with many different textures via technical manipulations of food structure design. Of all possible semisolid textural attributes, thickness, consistency, melting, smoothness, roughness, creaminess, and stickiness are probably the most relevant to semisolid food texture perception (Engelen and de Wijk 2012). The following sections will explore the underlying physical mechanisms of these textural attributes and their impacts on the oral processing and sensory perception.

2.1.1 Temporal Attribute Sensations During Oral Processing

The physical properties of semisolid foods continuously change during oral processing, which makes oral processing—and sensory perception—a dynamic process. The textural attributes that are sensed during oral processing of semisolid foods have been examined and cataloged in chronological order by de Wijk, Janssen, & Prinz (2011). Some attributes can be sensed as soon as the food is placed in the mouth, including warmness/coldness, thickness, and firmness. Sensation of other attributes may require longer oral processing time. Smoothness and creaminess are typical examples of such sensory features (de Wijk et al. 2003, 2011). van Aken et al. (2007) studied the temporal nature of certain sensory attributes in more detail and noted the chronological order of warmness/coldness, thickness, heterogeneity, creaminess, and smoothness. Thermal sensations were perceived at the first contact between the food and the outer skin of the oral cavity. Thickness sensations were sensed by the flow behavior of the food in the mouth with the help of compression forces applied by the tongue against the palate. On the other hand, heterogeneity was found to be sensed according to flow characteristics and particles after oral flow has taken place (i.e. after thickness is sensed). The sensation of creaminess normally occurred after other sensory attributes were sensed, and usually after the formation of a viscous coating on the tongue surface, more so after swallowing. Finally, smoothness sensation was perceived as the absence of small particles after the food was mixed with saliva and diluted. While this study provided insight into the order in which texture attributes may be perceived, it should be noted that the chronological order of oral sensations may vary for different food systems because of the differences in mechanical and textural characteristics of the food. Moreover, there may be individual differences in temporal oral textures due to variations in oral physiological behavior.

2.1.2 Effect of Surface and Bulk Properties on Oral Texture Sensation

The sensation of all textural attributes is directly related to oral movements. In addition, de Wijk et al. (2006) indicated that sensory attributes are linked with the surface properties of the food bolus. Therefore, the interaction capability of the food with oral tissues plays an important role in texture sensation. Furthermore, sensation of bulk attributes requires only a short amount of time but more intense oral movements, while surface attributes require longer oral processing time but less intense oral movements (de Wijk et al. 2011). This echoes the findings of van Aken et al. (2007) discussed in the previous section. For example, thickness is related to viscosity, a bulk property, and is rapidly perceived. Smoothness, on the other hand, is a surface property which takes significantly longer to perceive.

Another main factor of semisolid food texture sensation is the continuation of oral movements after bolus swallowing. This is often termed as after-feel, a sensation closely linked to mouth coating. Mouth coating is a thin layer of food–saliva mixture that covers the oral surfaces (Buettner et al. 2002). The amount and in some cases the thickness of the coating can be linked with different attributes, such as greasy, oily, creamy, and lubricating properties. The amount and thickness, as well as other properties of the oral coating, depend largely on the composition of the thin layer and the oral processing time (de Wijk et al. 2009). While it is important to understand the relationship between coating composition and sensory perception, there is not much information available in the literature at the time of publication of this book.

2.2 Tongue Movements and the Role of Saliva During Semisolid Food Oral Processing

Tongue movement plays a dominant role in the oral processing of semisolid foods. The tongue performs compression and shear by pressing the food against the hard palate while moving the food particles in lateral directions (Nicosia and Robbins 2001; van Vliet 2002). While oral deformation is predominantly shear, elements of extensional deformation have also been recognized as important, in particular during bolus swallowing (Chen and Lolivret 2011). However, the exact pattern of forces and velocities caused by oral movements is still largely unknown. In a pioneering study, Shama and Sherman (1973) showed that a wide range of shear rates could occur within the oral cavity (from below 1 s^{-1} to over 1000 s^{-1}), depending on the mechanical nature of the food. Once a bolus is swallowed, there is no longer bulk deformation but thin-layer lubrication within the oral cavity. In this case, tribology is believed to be the dominating mechanism for oral texture sensation rather than rheology. Here, oral shear and shear rates are still important, but this is because they play a role in thin-film (friction) behavior and thus friction-related sensations.

Saliva is another important factor contributing to the structural and textural alteration of semisolid foods during oral processing. The role of saliva in oral processing is multifaceted, but one of the most important roles of saliva in relation to eating and sensory perception is oral lubrication. The rate and composition of saliva secretion can be significantly influenced by food stimuli, and this may subsequently influence sensory perception, particularly the mouthfeel and afterfeel of food consumption. The tribological properties of saliva have been studied extensively, taking into consideration the various influencing factors such as the load, presence of surfactants, substrate roughness, composition, aging, and rheological behaviors (Macakova et al. 2011; Bongaerts et al. 2007; Stokes et al. 2013). These findings illustrated that the hydrophilic character of the adsorbed salivary film allows reduction of friction in the boundary regime; however, this effect is reduced at lower normal loads compared to high loads. Higher normal loads cause a gradual loss in lubrication capability (Macakova et al. 2011). In general, key factors affecting the lubrication behavior of saliva include applied load, entrainment speed, and surface roughness (Bongaerts et al. 2007). Increased surface roughness increases the friction for human saliva, where centrifugation and aging of the saliva alter the characteristic shear-thinning behavior and elasticity of the saliva, which can also impact friction behaviors (Bongaerts et al. 2007).

Surface wetting, mixing, and buffering are the main functions of saliva during food oral processing. These processes occur simultaneously with changes to the food's physicochemical properties and the formation of the food bolus. Another process occurring during food consumption is enzymatic degradation, in which salivary enzymes interact with food components and lead to the breakdown of specific molecules. For example, α-amylase exists abundantly in human saliva. This enzyme will interact with the starch-based components of the food and break them down to small sugar molecules, usually leading to a significant reduction of oral viscosity or consistency and a slightly sweet taste. The functions and impact of saliva interactions during food oral processing have been summarized by Mosca and Chen (2017) (Fig. 3).

Despite the evident role of saliva in bolus formation and its effect on bolus consistency, the incorporation of saliva in instrumental tests that measure real-time changes to food mechanical behaviors for sensory prediction has so far not been possible in any commercial device. Therefore, researchers must be careful when linking instrumental results with human sensory perception: certain sensory perceptions, such as astringency, may be highly dependent on temporal food–saliva interactions, but instrumental measurements do not capture these changes.

2.3 Mechanoreceptors as Sensors for Textural Attributes

All tactile sensations are perceived through various mechanoreceptors distributed under tongue surface and oral tissues. Mechanoreceptors are placed on the epidermis and dermis layers of the skin and are classified based on their functions as temporal, spatial, or frequency receptors (Klatzky et al. 2003). Temporal mechanoreceptors are activated by the continuous stimulation of the skin and have two different groups: slow-adapting and rapid-adapting. Slow-adapting receptors

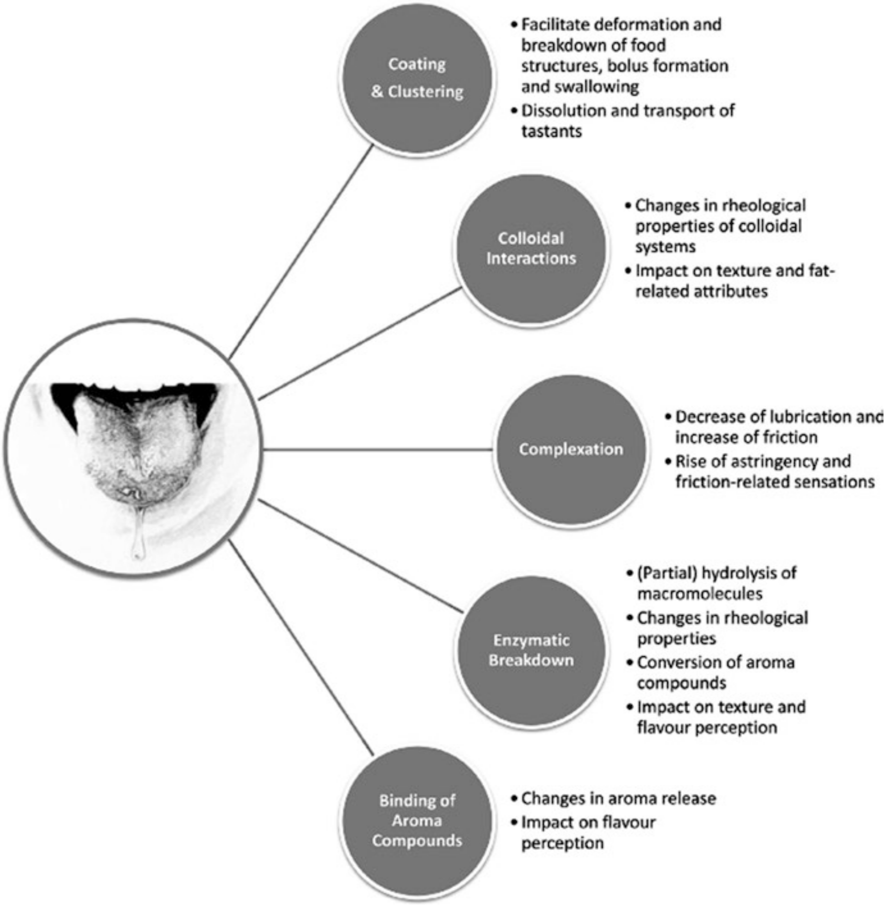

Fig. 3 Food–saliva interactions and impacts on eating and sensory perception. (Adapted from Mosca and Chen 2017)

continuously trigger the senses during stimulation. In contrast, rapid-adapting receptors fire only at the onset and offset of continuous stimulation (Tseng et al. 2009). In the oral cavity, around 35% of the mechanoreceptors have been found to be slow-adapting, which suggests that the oral cavity is more capable of detecting stimulus alteration during an eating process as compared to continuous sensing of a particular stimulus (Bukowska et al. 2010). Spatial mechanoreceptors are used to sense surface-dependent sensory attributes, such as graininess, roughness, smoothness, or lubricating effects, as well as stretching sensations or vibrations (Johnson 2001). Lastly, frequency mechanoreceptors determine the capability to sense the speed of stimulation on the skin during a particular vibration stimulus (Klatzky et al. 2003).

The mechanoreceptors located on the tongue and other oral skin surfaces show no morphological differences, but their density varies at different locations (Capra 1995; Trulsson and Johansson 2002). The hard and soft palates, tongue, and gums are considered to be the predominant locations for texture sensation through mechanoreceptors. On the other hand, mechanoreceptors under the periodontal membrane are responsible for precise detection of the force needed for fracturing both semisolid or solid foods between the opposing teeth (Boyar and Kilcast 1986). The receptors in the muscles and tendons in the jaw are responsible for regulating the speed of jaw movement (Gordon and Ghez 1991). Therefore, the dominant and active receptors for texture sensation are actually dependent on food type. For instance, texture sensation of solid foods would involve mechanoreceptors at all three locations, whereas texture sensation of semisolid foods would involve the hard and soft palates, tongue, and gums because manipulation of semisolid foods relies primarily on tongue movement (Kutter et al. 2011). However, one should keep in mind that the mechanoreceptors, regardless of their location, can work in a synergistic way for optimized sensation. Szczesniak (2002) also indicated that mechanoreceptors and tissues work together to perceive texture-related sensations. Signals from multiple receptors are instantly carried to the central nervous system by the trigeminal nerves for integrated sensory interpretation. While significant progress on understanding the role of mechanoreceptors in food texture perception has been made in the last several decades, further study is needed to more fully develop an overall picture of how mechanoreceptors.

3 Assessment of Food Texture Properties

3.1 Instrumental Assessment

The rheological behaviour of semisolid foods depends to a large extent on the constituents and microstructure of the food. As discussed in Chapters "Overview: Semisolid Foods" and "Rheological Testing for Semisolid Foods: Traditional Rheometry", viscosity is the most commonly used rheological measurement of fluid and semisolid food flow behavior. Viscosity is a measure of the resistance of a material to flow and is related to the amount of force, often expressed as stress, needed to deform the sample at a certain deformation rate. The viscosity profile of foods or viscosity at selected shear rates (e.g. 10 or 50 s^{-1}) are often related to various sensory attributes, such as thickness and mouthcoating. The viscoelastic properties of semisolid foods can also be measured for comparison to sensory behaviors. More detail on viscosity and viscoelastic measurements for semisolid foods is presented in Chapter "Rheological Testing for Semisolid Foods: Traditional Rheometry". Rheological measurements are widely used due to their consistent and objective nature, as well as the economical and time advantages compared to sensory evaluations. On the other hand, rheometry is an imperfect mimic of oral conditions;

therefore, it will not give a comprehensive image without a coordinating, well-designed sensory test.

While measuring the rheological behaviors of foods, especially when the aim is to understand oral processing mechanisms, it is crucial to include saliva in the instrumental tests. The chemical interactions of the saliva with the food causes a dramatic change in the food's texture attributes, which is reflected in alterations of the oral perception (Stokes 2012). Saliva is expected to cause structural changes to the bolus structure as well as dilution. Therefore, instrumental assessment requires mimicking the process of saliva addition to the food during oral processing. More importantly, salivary amylase will also contribute to the structural break-down of the starchy components and therefore "thickness" or "viscosity" will be the primarily affected texture attributes (de Wijk et al. 2006). However, integrating saliva into the experimental design is still considered to be too comlicated to be practival and the developed methods usually do not correspond with the natural mechanism of eating.

Tribometry has gained increased interest in recent years; these tests determine the friction behaviors of foods. Combining rheological and tribological tests can provide stronger insight into the determining mechanisms of oral sensation of food texture parameters than either alone. More details about semisolid food tribology is provided in Chapter "Semisolid Food Tribology".

3.1.1 Back Extrusion

The back extrusion test, an empirical test, uses a relatively simple testing geometry and method that allows for the generation of high forces for the characterization of the flow behavior of thick paste materials. In the back extrusion test, a cylindrical probe is pushed into a sample, then removed at a constant crosshead velocity. The force on the probe as it is moved is recorded. This test can be performed on food products in their original containers, allowing testing of the original, undisturbed food microstructures. However, care must be taken to perform the test using the same geometry, testing parameters, and amount of sample. Additionally, if the sample is transferred into a different container for testing, care must be taken to minimize the damage to the sample structure and not press-pack the sample into the container (i.e. increase the sample density). Furthermore, there may be issues with test accuracy for highly adhesive samples, as a vacuum can build up under the probe as it is extracted, causing measurement artifacts.

Steffe and Osorio (1987) and Osorio and Steffe (1991) tested particles or fibers suspensions in back extrusion. Using the methods described for power law fluids, they were able to use back extrusion to determine the flow behavior index and consistency coefficient for these materials. Similarly, appropriate testing speeds can be used to calculate the flow behavior index of boluses at different extents of mastication and at the point of a swallow. The kinetics of bolus formation can then be determined in a semi-quantitative manner.

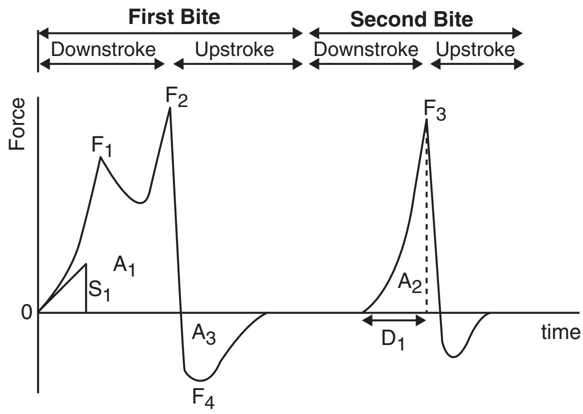

Fig. 4 Force-displacement curve from a TPA test. F_1: Fracturability, F_2: Hardness (firmness), A_2/A_1: Cohesiveness, A_3: Adhesiveness, D_1: Springiness, Gumminess: Hardness × cohesiveness, Chewiness: Hardness × cohesiveness × springiness, and S_1: Elastic modulus

3.1.2 Texture Profile Analysis (TPA)

Texture Profile Analysis (TPA) is probably the most commonly mentioned method in the literature for texture assessment of semisolid food, although it does not directly mention food texure. The method was first proposed more than a half-century ago by Friedman et al. (1963), in which the researchers used a Texturometer to perform a double compression test to obtain a set of textural features for gel-type foods. The key feature of the method is the double compression which mimics the first two bites of an eating process. The method was further promoted by Bourne some years later (Bourne 1978), who developed a systematic approach for the test conditions and texture explanation (see Fig. 4).

While the TPA method has been a landmark achievement of food texture studies and has been proved useful in many industrial applications, misuse of the method and confusion of the interpretation of its parameters are very common. Cases of TPA misuse have been discussed in detail by Bourne and Smewing (1996). Despite the fact that an expanded description of TPA analysis was later given by Bourne himself in his well-known food texture book published in 2002 (Bourne 2002), confusion of TPA analysis and data interpretation is still seen in the literature (Nishinari et al. 2013). Moreover, Corradini and Peleg (2010) have raised concerns on the scientific solidity of the defined textural parameters of TPA method. Users of TPA should carefully consider the limitations of the technique and avoid over-stretching data interpretation from the method.

3.2 Sensory Evaluation

Sensory evaluation is an inseparable part of oral processing investigations. It is a crucial element for market success of the food product and consumer satisfaction. Ideally, reliable and robust instrumental assessment should correlate well to sensory evaluation, showing agreement between the two different test modalities and providing a more comprehensive explanation of food transformation during oral processing. Instrumental analyses have already been shown to be reliable, yet they are still incapable of precisely mimicking the varying oral conditions during oral processing as well as the sensory differences between individual assessors. Therefore, it is difficult for instrumental tests to induce the changes to food physicochemical properties that occur during oral processing.

Unlike instrumental assessments, sensory evaluations are still far from being economical in terms of time and expenditure. Additionally, cultural and personal differences between individuals are likely to affect the results which aim to get a description from the assessor either on numerical scales or verbal (Boyar and Kilcast 1986). Nevertheless, it is possible to overcome some of these challenges by careful design of sensory experiments, incorporation of instrumental testing to screen samples for sensory evaluation (i.e. evaluating a reduced sample set) and training panelists to minimize differences in individual sensitivity and preference.

Techniques for sensory evaluation have undergone significant development and are accepted as essesstial procedures in industry for the assessment of for taste modalities. However, we still have limited findings on textural and rheological observations in terms of sensory assessments and relation with the instrumental tests (Aktar et al. 2015, 2017). During sensory assessments, researchers generally focus on the basic 5 human senses related to the type of modality. In texture assessments of semisolid foods, the sensory experience initiates with the visual senses prior to tactile contact. After visual observation of the texture, the assessor evaluates the sample by using a tool (cutlery), picking up the food with their hands, or directly by tongue and palate depending on cultural eating habits and the type of food. It is important to note that, due to the dynamic nature of oral processing, the sample is expected to undergo catastrophic structural changes, which results in a change in the texture as well as taste and aroma (van Vliet 1999). Additionally, saliva integration into the sample initiates with the first bite, which causes modifications of the food's temperature, pH, texture, and flavor, as well as the specific perception mechanisms of these. Because food texture is dynamic and evaluated from the first sight of the food to post-swallowing, sensory evaluation of texture should measure texture at various points during consumption of the food product for a full picture of texture perception.

4 Summary

Because sensory attributes originate from the microstructure and mechanical properties of food products, texture and mouthfeel of semisolid foods exhibit a huge range of variation (Nishinari and Fang 2018). This offers food manufacturers great possibility for designing food products with desirable texture and mouthfeel that suit consumers' diverse requirements. Material properties, saliva incorporation, and human oral physiology are the three most dominant factors for the sensation and perception of food texture. Despite the usefulness of instrumental methods for food texture characterization for either quality control or prediction of consumer perception, to a certain extent, instrumental characterization only reveals the material properties of the food but not the true sensory properties. When studying food texture and relating food texture to instrumental measurements of food mechanical properties, the dynamic changes to food properties due to saliva mixing and interactions, and the variation of oral physiology among human individuals must be taken into consideration. Future food texture studies should focus more on the understanding of how the changes to food microstructure and mechanical behaviors impact texture perception during oral processing.

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