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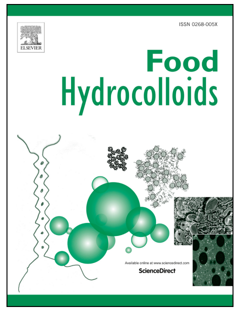

Instrumental Food Texture Evaluation in Relation to Human Perception

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Instrumental Food Texture Evaluation in Relation to Human Perception

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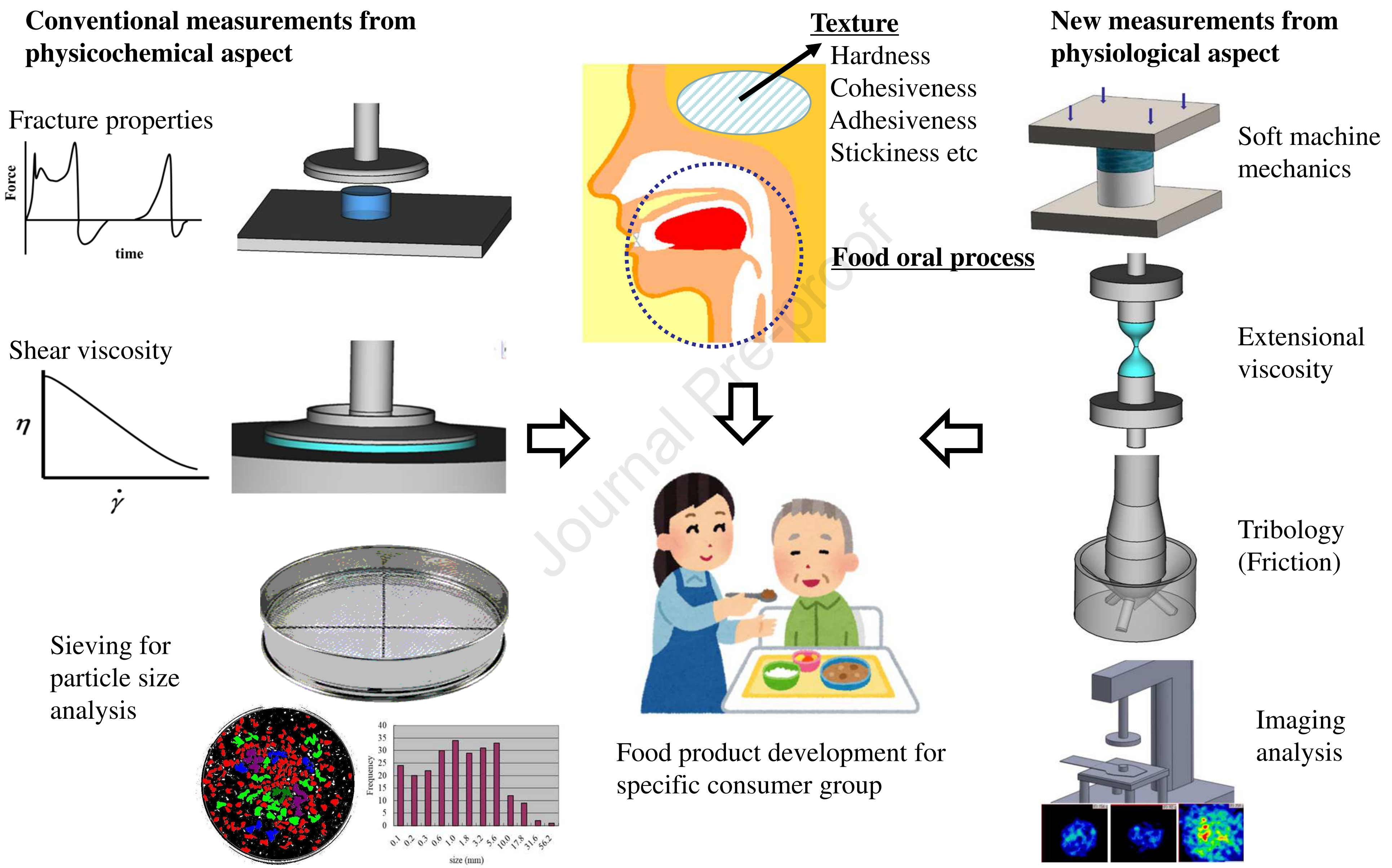

Conventional measurements from physicochemical aspect
Fracture properties
Force
time
Shear viscosity
Sieving for particle size analysis
Frequency
size (mm)
Texture
Hardness
Cohesiveness
Adhesiveness
Stickiness etc
Food oral process
Food product development for specific consumer group
New measurements from physiological aspect
Soft machine mechanics
Extensional viscosity
Tribology (Friction)
Imaging analysis

Instrumental Food Texture Evaluation in Relation to Human Perception

San-Ei Gen F.F.I., Inc.
Takahiro Funami and Makoto Nakauma

Abstract

This article reviews the relationship between food texture or mouthfeel which human perceives and objective properties of foods which instruments measure. Instrumental measurements overviewed cover 3 domains of physicochemical properties which govern food texture, including mechanical, geometrical, and moisture- and fat-related surface properties. Research questions in this review consist of research subjects, tests in focus to reach to the research subjects, and new findings from the tests compared to counter tests (i.e., conventional method), through which facilitation of literature search by readers is intended. Tests in focus correspond to instrumental measurements which take mechanics of food oral processing in human into account, and texture estimation and prediction through correlation with mechanical property is featured. This is followed by imaging analysis for evaluation of geometrical property and tribology measurement for evaluation of moisture- and fat-related surface property for detailed description of texture from different and comprehensive approaches. Most pieces of research presented in this review are concerned with texture evaluation using polysaccharide emulsions, gels, and solutions as a model food, including the authors' works, referring to great contribution of colloid technology to progress of texture study.

1. Introduction

Foods should provide people with happiness and satisfaction, and increased palatability or eating enjoyment must be an eternal mission for food manufactures in product development. Food palatability is determined by human perception such as texture, flavor, appearance, sound, and temperature through five senses, and texture and flavor are said to be two major essential elements (Kohyama, 2005). Of these elements, importance of texture is emphasized not only from food palatability but also from eating safety in recent super-aged society which all the world is facing with to a degree. Eating safety is often related to swallowing difficulty, which is equal to dysphagia problem.

Texture is a whole body of mechanical, geometrical, and thermal properties of foods perceived by human during a series of oral processing, including chewing and swallowing, and corresponds to sensory characteristics via oral and oropharyngeal organs and tissues, including teeth, tongue, hard and soft palate, and throat etc. Although texture cannot be measured instrumentally but only by human, a common approach in food science is to evaluate relationships between texture perception by human and structural, rheological, and mechanical properties of foods by instruments. Instrumental measurements of 'texture-related properties' with certain quantitativeness and reproducibility have been required for this purpose.

Texture cannot be presented by any single attribute or characteristic but by a combination of multiple ones (Szczesniak, 1975). A lot of researchers in different places have tried to establish terminology and procedure for objective and reproducible texture evaluation applicable to wide range of foods. In this pathway, it has been proposed (Szczesniak, 1963a, b) that textural properties of foods should be classified into 3 domains including mechanical, geometric, and moisture- and fat-related surface properties.

In accordance with this classification, research questions in this review consist of research subjects, tests in focus to reach to the research subjects, and new findings from the tests compared to counter tests (i.e. conventional method), intended to facilitate literature search by readers depending on type of foods; solid and semi-solid/liquid foods. Tests in focus correspond to instrumental measurements which take mechanics of human food oral processing into account, and texture estimation and prediction through correlation with mechanical property is featured. This is presented by soft machine mechanics compared to TPA for characterization of solid foods in chewing and extensional viscosity/dynamic viscoelasticity measurements compared to shear viscosity measurement for characterization of liquid foods in swallowing, progressed as complementary or even to overcome conventional drawbacks for obtaining of new findings. Imaging analysis for evaluation of geometrical property and tribology measurement for evaluation of moisture- and fat-related surface property are then featured for detailed description of texture from different and comprehensive approaches. Important role of hydrocolloids in texture study is also presented in this article, ascribing to easiness of mechanical control or essential ingredients themselves in processed foods. In this context, most pieces of research presented in this review are concerned with texture evaluation using polysaccharide emulsions, gels, and solutions as a model food, including the authors' works, referring to great contribution of colloid technology to progress of texture study.

1. Mechanical properties of foods and human perception during food oral processing

1.1 Size reduction of solid foods

1.1.1 Background and conventional technology

Five primary parameters have been proposed to present mechanical property of foods including 'hardness', 'cohesiveness', 'viscosity', 'springiness', and 'adhesiveness' (Szczesniak, 1963a, b). According to definition, 'hardness' corresponds to the stress required to deform a food to a certain deformation. Similarly, 'cohesiveness' presents mechanical intensity of internal bonding within the food structure, and 'viscosity' the resistance against flow. Also, 'springiness' is defined as the time required for deformation recovery of a food upon unloading, and 'adhesiveness' as the amount of work required to overcome the adhesion force generated between surfaces of a food and substances with which the food comes into contact. Despite some discrepancies against scientifically validated terms in physics, these terms are clear in definition and are recognized as presenting food texture.

The simplest method for objective texture measurement should be uniaxial compression test to define mechanical property of solid foods in bulk. Uniaxial compression is to detect changes in stress and strain when a sample is compressed vertically without lateral pressure, and Texture Profile

Analysis (TPA) has been widely used so far in texture study in line with this concept. In the original TPA procedure developed by a research group of General Foods (Friedman, Whitney, & Szczesniak, 1963; Szczesniak, 1963), a food sample shaped to a certain dimension and shape is compressed twice in a reciprocation manner at a constant speed using a plunger. Movement of plunger is semicircular, simulating human jaw action during chewing. TPA is, therefore, a large deformation test. The original procedure is modified by Bourne by using uniaxial compression machine, expanding usage of TPA. Surface area of plunger should be equal to or larger than that of the food sample, and relative deformation is usually recommended to be 90% or more (Bourne, 2002b). The load (stress) -time (strain) curve obtained in this way is called TPA curve, from which the primary parameters, including 'hardness', 'fracturability' (or 'brittleness'), 'springiness', 'cohesiveness', and 'adhesiveness' and the secondary parameters including 'gumminess' and 'chewiness' as a product of these primary parameters are obtained (Bourne, 2002b). A typical TPA curve and the definition/calculation for each parameter are presented (Fig. 1). Although TPA is frequently used by food researchers as it enables simultaneous measurement of multiple texture-related mechanical parameters, inconsistency with human perception would be the case for texture evaluation.

For example, low TPA "cohesiveness" has been indicted even for cohesive foods such as chewing gum, which do not undergo complete fracture and fragmentation due to its internal binding (Pons and Fiszman, 1996). As far as the authors know, there have been few reports that perceived "adhesiveness" can be measured correctly by TPA, except for the case of cooked rice grains (Matsuo, Takaya, Miwa, Moritaka, & Nishinari, 2002). A factor explaining discrepancy between TPA and human perception in texture may lie in difference in material and movement of geometry on uniaxial compression apparatus from those of food oral processing in human. Human oral cavity has complex structure constituting of many organs and tissues, including teeth, gums, tongue, hard and soft palates etc., and constituents other than teeth and hard palate are soft materials of viscoelastic properties.

1.1.2 Soft machine mechanics

For solid foods with soft texture, bolus is formed by squeezing between the tongue and the hard palate without chewing. Human changes strategy of bolus formation depending on food texture via perception of hardness as a principal attribute. Instrumental measurements usually use hard geometries, and size reduction or decomposition of foods by squeezing cannot be fully recreated in this way. This can result in clear difference in fracture properties between foods decomposed by squeezing and those decomposed by chewing. This discrepancy can be caused by deformation of the tongue in food oral processing, which is not considered in a conventional hard machine. *In vitro* texture evaluation system using simulated or artificial tongue made of soft material on a uniaxial compression machine has been established to reproduce oral conditions of squeezing (Ishihara et al., 2013, 2014; Kohyama, Ishihara, Nakauma, & Funami, 2019).

Load is applied to food sample tested (agar gel in this case) through compression between a soft material simulating the tongue and a metal probe simulating the hard palate (Fig. 2) (Ishihara et al., 2013). When deformation of food sample is larger than that of simulated tongue, the sample is fractured, whereas the sample is not fractured when deformation of the sample is equal to or smaller than that of simulated tongue. When apparent elastic modulus of simulated tongue is ca. 5.5 x 10^4 Pa, whether or not food sample is fractured corresponds to oral strategy for size reduction in human; squeezing or chewing. It is also suggested that human may detect a difference in deformation between food and the tongue in relatively small strain region (i.e., ca. 10% strain) for determination of oral strategy for size reduction. *In vitro* texture evaluation system is believed to be effective particularly in developing foods for people with chewing and/or swallowing difficulty.

In vitro texture evaluation system presented in Fig. 2 has been validated using gellan gum gels as test sample (Ishihara et al., 2014). It is shown that modification of some operation conditions should be necessary in some cases in relation to physiological modulation of tongue-palate compression by food texture. This modulation can occur during consumption of highly deformable gels and is recreated instrumentally by decreasing tongue-palate compression speed and increasing the maximum deformation (i.e. decrease in the clearance) or by incorporating tongue excitation and shear loading by the tongue. The first factor is realized by decreasing crosshead speed (from 10 to 5 mm/s) in relation to the stress relaxation, a phenomenon of energy dissipation enhanced at lower deformation speed (Luyten & van Vliet, 1995). The second factor is realized by increasing the Young's modulus of simulated tongue (from ca. 55 to ca. 110 kPa). Slope of time course curve for tongue pressure during the first size reduction is almost independent of physical properties (texturally brittle or deformable) or consistency (soft or hard) of polysaccharide gels (Hori et al., 2015). Based on this finding, it is reasonable to think that decrease in tongue-palate compression speed should give rise to increased tongue pressure. Actually, lowering crosshead speed and/or increasing Young's modulus of simulated tongue is certainly effective for texture evaluation of highly deformable samples. Incorporation of shear force and increasing the maximum deformation should be mechanical challenges. Usage of simulated tongue of larger size should be another option since surface contact area between food and the tongue may be larger in consuming highly deformable gels. As definition of 'highly deformable', its boundary should be at ca. 60%-70% as the initial fracture strain (Ishihara et al., 2014). Human can decide oral strategy for size reduction by sensing dynamically difference in strain between food and the tongue during oral processing (Kohyama, 2015). Fracture strain has been emphasized as a dominant mechanical parameter for decision of oral strategy for size reduction (Arai & Yamada, 1993), and this is the same as determination of the biting speed (Mioche & Peyron, 1995).

1.2 Swallowing of semi-solid or liquid foods

1.2.1 Background and conventional technology

Fundamental methods commonly used for measurement of rheological properties of semi-solid/liquid foods are steady flow and dynamic (oscillation) tests to know viscous and viscoelastic behavior of sample tested, respectively. For these measurements, a rotational strain-control rheometer is often used by using a geometry of concentric cylinder, parallel plate, or cone-plate, selection of which depends on nature and applicable amount of sample tested. National Dysphagia Diet (NDD) (2002) defines four levels of viscosity intensity, including thin (0-50 mPas), nectar-like (51-350 mPas), honey-like (351-1750 mPas), and pudding-like (> 1750 mPas) based on viscosity measurement using a rotational rheometer at a shear rate of 50 s^{-1} at 25 °C. Recent studies have indicated that ‘physiological’ shear rate during swallowing is likely to be influenced by bolus viscosity and that a single shear rate is unlikely to cover overall viscosity range (Ong, Steele, & Duizer, 2018). Based on characteristic shear rate, which corresponds to a crossover shear rate between non-Newtonian and Newtonian fluids showing equivalent deformation rate of bolus during swallowing (Zhu, Mizunuma, & Michiwaki, 2014), ‘physiological’ share rates are estimated to be 120 and 990 s^{-1} in the mesopharyngeal and hypopharyngeal in healthy adults, respectively, independent of viscosity (Mizunuma, Sonomura, & Shimokasa, 2020). As clearly, these shear rates are higher than 50 s^{-1} adopted by NDD.

Most liquid foods show shear-thinning, which can be described by Power Law Model (Cho & Yoo, 2015; Talens, Castells, Verdú, Barat, & Grau, 2021). Yield stress, a stress at which flow begins (Bourne, 2002a), is another important rheological parameter for management of dysphagia foods as it presents degrees of internal binding force and structural order (Moelants et al., 2013). Yield stress is determined by fitting steady flow curve (shear stress/rate curve) with Bingham, Casson, or Herschel-Bulkley model or by the maximum elastic stress (i.e., dynamic storage modulus G' multiplied by strain) as a result of replotting as a function of strain (Walls, Caines, Sanchez, & Khan, 2003). Structural fluids lead to one coherent bolus formation and swallowing ease and is quantified by yield stress (Nakauma, Ishihara, Funami, & Nishinari, 2011). Yield stress thus can work as as a rheological criterion for bolus cohesiveness and perceived swallowing ease (Nakauma et al., 2011). In a study on correlation between mechanical properties and swallowing ease of paste-like foods thickened with starch, xanthan gum, or sodium carboxymethyl cellulose (CMC-Na), addition of CMC-Na strengthens mechanical interaction between particles, resulting in the highest yield stress and showing suitability to dysphagia foods (Abu Zarim, Zainul Abidin, & Ariffin, 2018). Formation of cohesive bolus should be essential to minimize its disintegration during oral processing and to provide sense of swallowing ease with liquid and semi-solid foods.

Some studies have evidenced that extensional flow property should be important equal to shear flow property for texture evaluation of semi-liquid/liquid foods during oral processing (Debruijne, Hendrickx, Alderliesten, & Delooff, 1993; van Vliet, 2002; Koliandris et al., 2011). Viscoelastic fluids can clearly exhibit different flow properties between shear and extension deformations. For food ingredients, a macromolecule with relatively rigid conformation such as xanthan gum shows differences in flow behavior by deformation mode. As extensional flow occurs not only in food manufacturing process such as extrusion but also in food oral processing such as swallowing, it is presumed that extensional viscosity should have effects on food texture. However, due to limitation of instruments which can easily and precisely measure extensional viscosity, less studies have been carried out compared to shear viscosity.

1.2.2 Extension rheology

Tensile separation behavior has been analyzed using commercially available fluid food products, confirming that the maximum tensile force and work till the maximum force both highly correlate to stickiness perceived using fingers (not in oral) (Chen et al., 2008). Although their method is similar to that for TPA adhesiveness, importance lies in optimization of experimental set-up, including instrumental operation conditions and selection of mechanical parameters to discuss correlation with perception. Pressure drop and cavitation due to rapid extensional flow can be critical for stickiness perception. Using the same experimental set-up, perceived swallowing difficulty highly correlate to the maximum stretching force and the work of stretching for fluid foods (Chen & Lolivret, 2011). Thus, food bolus difficult to deform upon extension (i.e., with low stretch-ability) and larger in extensional viscosity tend to show longer oral residual time until swallowing and perception of more difficult to swallow.

For more preciseness, a novel device using real-time optical detection has been proposed (Bazilevsky et al., 1990). On this device, a small amount of liquid sample sandwiched between two plates is stretched rapidly by pulling the upper plate away from the lower plate at a certain speed, applying extensional deformation to the sample for formation of liquid filament. The filament is shrunk by capillary force, in which the surface tension works as shear stress and reduces the surface area of the filament. Temporal change in diameter at the midpoint of the filament (i.e., D_{mid}) is monitored with a laser-type micrometer, from which extensional viscosity can be calculated (Fig. 3). This type of instrument has contributed to the progress of research on extensional viscosity for foods or food ingredients.

As a representative study using polysaccharide solutions as a model liquid food, human discrimination thresholds in perceiving extensional viscosity compared to shear viscosity has been investigated (Lv et al., 2017). Results indicate that ability to discriminate extensional viscosity is higher than that to discriminate shear viscosity, confirming that extensional viscosity is critical for textural characterization of liquid foods. Correlation between texture of solutions thickened by xanthan gum and several rheological parameters has been studied (He et al., 2016), confirming that perceived thickness, stickiness, and mouth coating show higher correlation with extensional viscosity than shear viscosity and that accuracy of prediction can be increased by incorporating extensional viscosity as one of independent explanatory variables. It is also reported that perceived mouthfeel correlates well to shear viscosity at low shear rates (< 100 s^{-1}), whereas perceived thickness correlates well to dynamic complex viscosity at 100 rad/s, confirming that some textural attributes should be evaluated by regression model incorporating multiple rheological parameters.

1.2.3 Dynamic viscoelasticity measurements

Rheological measurements in linear stress-strain region may provide useful information on texture evaluation rather than measurements under a large deformation condition in some cases. As a representative, correlation between dynamic viscoelasticity and perceived swallowing ease (swallowability) will be presented in this section. People with impaired swallowing function or dysphagia patients are often fed with thickened liquids or jellies and puddings. This is because bolus from these foods is said to transfer at relatively slow speed through the pharyngeal phase while swallowing. Although subjects are healthy volunteers, studies by Tashiro et al. (2010) outlines the relationship between dynamic viscoelasticity of sol-like foods and bolus transfer velocity through the pharyngeal phase measured with ultrasound pulse Doppler method (Tashiro, Hasegawa, Kohyama, Kumagai, & Kumagai, 2010).

From to the frequency dependence of dynamic viscoelasticity, mechanical spectra for polysaccharide solutions tested correspond to solution (for CMC-Na), structured solution (for xanthan gum), and concentrated solution of chain polymer (for guar gum). Despite thickeners showing different mechanical spectra, the maximum velocity of bolus transfer in the pharyngeal phase correlates to complex viscosity and steady shear viscosity. Angular frequency of 25 rad/s shows higher correlation than 2.5 rad/s for complex viscosity, whereas shear rate of 25 s^{-1} shows higher correlation than 2.5 s^{-1} for steady shear viscosity (Fig. 4) (Tashiro et al., 2010). As a conclusion, to obtain equivalent level of the maximum velocity as yogurt (i.e., 0.2 m/s), which is known practically as hardly generates misleading of food bolus, dynamic viscosity η', complex viscosity η^*, and steady shear viscosity η require 0.4-1.4 Pa·s at 25 rad/s, 0.9-4.2 Pa·s at 25 rad/s, and 0.5-1.8 Pa·s at 25 s^{-1} in this order. These can work as an objective indicator for perceived swallowing ease (or swallowing difficulty) and should be useful for development of dysphagia foods.

In relation to swallowing ease, acoustic analysis of swallowing sound has been investigated as a different approach using polysaccharide solutions from xanthan gum and locust bean gum as a model liquid food and young healthy adults panel (Nakauma et al., 2011). Acoustic analysis is used for diagnostic purpose in biomedical field (Lazareck & Moussavi, 2004) but seldom in texture study. Representative acoustic profile is illustrated in the case of swallowing water (Fig. 5), where the profile is divided into three parts, each of which is assigned to closure of the epiglottis (t_1), flow of food bolus (t_2), and opening of the epiglottis (t_3) in order of occurrence (Hamlet, Patterson, Fleming, & Jones, 1992). Relationship between duration of each oral event and texture perception during swallowing is a target for investigation.

Duration of t_2 for xanthan gum solutions decreases with increasing its concentration despite viscosity increase (ca. 60% decrease when viscosity is increased from 0.001 to 1.61 Pas at 10 s^{-1}). Whereas duration of t_2 for locust bean gum solutions is much less concentration-dependent (ca. 15% decrease when viscosity is increased from 0.001 to 1.53 Pas at 10 s^{-1}) and is consistently larger than that for xanthan gum solutions when compared at equivalent shear viscosity (Fig. 6). From sensory evaluation on a visual analogue scale, 0.6% xanthan is scored the highest (av. score 80.2) in perceived swallowing ease, whereas 0.75% locust is scored the lowest (av. score 21.3). Duration of t_2 correlates well to perceived swallowing ease and to perceived cohesiveness. It is postulated that xanthan gum solutions can flow as one coherent bolus through the pharyngeal phase with smaller variation of flow velocity than locust bean gum solutions, leading to a greater sensation of swallowing ease. Structured solution is a rheological requirement for increased perceived swallowing ease. This rheological nature can be quantified by yield stress of ca. 7.0-9.0 Pa in combination with steady shear viscosity of ca. 0.9-1.2 Pas at 10 s^{-1}.

2. Geometrical properties of foods and human perception during food oral processing

2.1 Background and conventional technology

Research target of imaging analysis has been exclusively solid foods, and no research on semi-solid or even liquid foods is found. Food in bulk structure is broken down into particulates during oral processing, followed by bolus formation through mixture with saliva prior to swallowing. Therefore, it is expected that geometrical properties of particulates in bolus should influence greatly food texture. Geometric properties of particulates include size and shape after fracture, and the size can be evaluated by mechanical sieving or image analysis. Sieving is particulate separation of different mesh sizes through a single or multiple sieve(s). By sieving of expectorated bolus at different stages of food oral processing, its dynamic changes can be determined through average particle size and size distribution as a merkmal. Bolus particulates from fibrous or heterogeneous foods are highly variable in their size and shape (Eberhard et al., 2012; Olthoff, van der Bilt, Bosman, & Kleizen, 1984). Since bolus particulates generally bear irregular shapes, and particulate characteristics depend on assumption of simulation model used (i.e., assuming spherical, cubic, ellipsoid etc.), highly accurate information can be obtained by imaging analysis in general. Effects of de-structuring process on texture perception have been investigated using hydrocolloid gels by imaging analysis.

2.2 Imaging analysis of bolus and computer simulation of bolus formation for solid foods

Attempts have been made for texture evaluation by measuring size and shape of particulates in food bolus. Temporal changes in the particle size distribution of food bolus have been investigated while chewing two types of polysaccharide gels; gellan gum single gel and gellan/psyllium seed gum mixture gel as a model of viscoelastic foods (Ishihara, Nakauma, Funami, Odake, & Nishinari, 2011). Instrumental compression of the gels is performed with shear in a reciprocating manner to mimic human jaw action in the presence or absence of artificial (simulated) saliva (Fig. 7) to obtain model bolus. A food color from red cabbage extract in emulsion is used to help visualization, and model bolus dyed with the food color and dehydrated and immobilized onto a filter paper is scanned by a color image scanner, followed by image processing using a software based on a certain HSI (hue, saturation, and intensity) value threshold. Results indicate higher structural homogeneity of model bolus from the mixture gel compared to that from the gellan single gel. For each gel sample, cumulative particulate size distribution of model bolus can be reduced logarithmically with a normal curve regardless of the addition level of saliva. Mean particulate size of model bolus from the mixture gel is generally larger than that for gellan single gels when compared at equivalent gel hardness (i.e., 1000 and 4000 Pa) and is less influenced by the addition level of saliva (Fig. 8). Based on the particulate size distribution of model bolus, coefficients of skewness and kurtosis for the composite gels tend to be larger than those for gellan single gels when compared at equivalent gel hardness (Fig. 8). Here, skewness indicates degree of asymmetry of the distribution around its mean. Positive (negative) values indicate that the distribution has an asymmetrical tail extending out toward more positive (negative) direction. The larger the absolute value, the more asymmetric the distribution is. Kurtosis designates the relative sharpness of the distribution relative to normal distribution. The larger the value, the sharper the distribution is. Different study indicates that food bolus from agar gels of relatively small fracture strain contains more small particulates, leading to greater perception of graininess and graininess, whereas the bolus from gelatin gels of relatively large fracture strain contains less small particulates, leading to greater perception of creaminess in combination with effect of its melting behavior in the mouth (Devezeaux de Lavergne et al., 2016). It has been also indicated that gels of high fracture stress require increased masticatory muscle activity in chewing, leading to greater perception of hardness and graininess.

Progress in image processing has upgraded technology for food bolus analysis. Some characteristics obtained by imaging analysis, including gray-level histograms, histogram of shape area, and gray level co-occurrence matrix, have been calculated using double layered gels consisting of agar and gelatin colored in either white or black as a feeding sample (Tournier et al., 2017) (Fig. 9), confirming high correlation with gel texture. It has been also indicated that agar layer dominates bolus properties, whereas the presence of gelatin should have impacts on dynamics of gel breakdown.

Textural attributes of gelled foods, including smoothness, elasticity (i.e., springiness), stickiness, and granularity, are greatly influenced by both mechanical and geometric characteristics before and after fracture. Therefore, a method which can simultaneously evaluate both characteristics is required. Usage of multipoint pressure sensor sheet should be one of the approaches, and in this context, temporal and spatial changes in pressure distribution have been detected during compression of cracker (as a representative of solid foods) on the sensor sheet of 44 × 44 mm size and with a spatial resolution of 1 mm (Kohyama, Nishi, & Suzuki, 1997). Usage of this sensor sheet expands to viscoelastic foods such as bread and agar gel (Kohyama, Sasaki, & Dan, 2003; Dan, Okuhara, & Kohyama, 2004), and a method for estimating food structure from pressure distribution data has been developed (Dan, Azuma, & Kohyama, 2007). As advanced, food texture can be estimated by characterizing concentration level distribution images, which is transformed from pressure distribution data during compression of test sample on this sensor sheet using gels from polysaccharides (gellan, xanthan, guar, carrageenen, locust bean etc.) and gelatin (Fig. 10) (Shibata, Ikegami, Nakao, Ishihara, Nakauma, & Higashimori, 2016). As underlying principle, human perceives changes in shape and contact force simultaneously on the tongue, and based on these inputs, texture is evaluated while chewing.

Optimization of this artificial vision system enables accurate prediction of texture using commercially available puddings and jellies (Nakauma, Ikegami, Funami, Shibata, & Higashimori, 2021). Furthermore, mechanical learning through Convolutional Neural Network elevated accuracy of the system (Shibata, Ikegami, Nakauma, & Higashimori, 2017). A series of these imaging analyses has evidenced that food texture associated with geometrical property relates to structure of relatively large size (e.g., in 1 mm order) as it is evaluated by optical imaging with no need of microscopic magnification and by a device like sensor sheet with relatively low spatial resolution. These findings emphasize the necessity of observation on temporal and spatial changes of particulates in food bolus for texture study.

Texture attributes, including granularity, meltiness, creaminess of gels perceived at later part of oral processing, are presented by dynamic changes in fluidity and geometric property of food bolus (Devezeaux de Lavergne, van Delft, van de Velde, van Boekel, & Stieger, 2015a), and to describe these textural attributes, combined usage of sensory evaluations based on quantitative descriptive analysis (QDA), temporal dominance of sensation (TDS), and progressive profiling would be recommended (Devezeaux de Lavergne, van Delft, van de Velde, van Boekel, & Stieger, 2015b). Food texture should be evaluated as series of oral processing beginning from the first bite to swallowing via bolus formation, and understanding on the relationship between texture perception and dynamics of structure changes during food oral processing should be a rational approach to food product design (Foegeding, Stieger, & van de Velde, 2017). Since food structure plays the key role on overall breakdown pattern and sensory perception, method proposed by Shibata et al. is valid as a comprehensive texture evaluation.

3. Moisture- and fat-related surface properties of foods and human perception during food oral processing

3.1 Background and conventional technology

Although moisture- and fat-related texture is a complicated sensation and difficult to present, various attempts have been made so far. It is considered that human perceptions, including thickness, smoothness, and slipperiness, and judgment of swallowing initiation should be largely due to bulk and surface properties of food bolus. Therefore, tribological approach for measurement of friction and lubrication between food and human tissue or organ during food oral processing is rational. Surface properties of foods can be evaluated by imaging techniques. For example, atomic force microscopy (AFM) has been used to image surface properties of materials, including food or food ingredients (Majd et al., 2014; Wan et al., 2020; Xu et al., 2020). AFM visualizes that epigallocatechin gallate aggregates salivary proteins to inhibit formation of mucosal pellicle structures that contribute to salivary lubrication, presuming that this should be the cause of astringency sensation of tannins (Ployon et al., 2018). Small-angle X-ray scattering (SAXS) is also known as a method for assessing surface properties of materials. In food areas, lipid crystals (Pink, Townsend, Peyronel, Co, & Marangoni, 2017), protein aggregation (de Kruif, Huppertz, Urban, & Petukhov, 2012), surface structure of starch granules (Blazek & Gilbert, 2011), and fibrous molecular structures of alginate (Schuster, Wallin, Klose, Gold, & Ström, 2017) and curdlan (Maki, Furusawa, Dobashi, Sugimoto, & Wakabayashi, 2017) have been evaluated by SAXS in relation to surface properties. Actually, friction coefficient of polyacrylamide hydrogels has been demonstrated to negatively correlate with mesh size of gel structure (Urueña et al., 2015), and this finding may be applicable to hydrogels from food polysaccharides. However, since these imaging techniques can evaluate a limited area of food surface in a stationary state, it can be difficult to evaluate changes in overall surface properties during dynamics of human feeding such as chewing. Therefore, sufficient information may not be obtained by these imaging techniques on correlation with texture.

3.2 Tribology for lubrication

3.2.1 Instrumental development for tribology measurement

Geometry using soft materials has been developed for recreation of friction behavior between food and soft oral surface during oral processing. Hardness and surface roughness of the tongue can be critical in oral tribology, and these attributes should be considered in establishing experimental equipment and its operation condition. Efforts have been made to better recreate human oral physiology by using tongue tissue from animals or polymer surfaces to mimic wetness and deformability of human tongue (Dresselhuis, de Hoog, Cohen Stuart, & van Aken, 2008; Carpenter et al., 2019), and in line with these efforts, polydimethylsiloxane and frosted glass were proposed to human tongue and palate alternatives, respectively (Bongaerts et al., 2007). Based on this knowledge, Anton Paar (Gratz, Austria) has upgraded a modular rheometer by introducing a geometry consisting of glass balls as a plunger and PDMS pins and plates as flooring (Fig. 11) for tribology measurement, and this has contributed greatly to the progress of food lubrication study (Baier et al., 2009; Biegler et al., 2016; Carvalho-da-Silva et al., 2013; Kieserling, Schalow, & Drusch 2018; Kim, Wolf, & Baier, 2015; Krzeminski, Wohlhüter, Heyer, Utz, & Hinrichs, 2012; Pondicherry, Rummel, & Laeuger, 2018; Sonne, Busch-Stockfisch, Weiss, & Hinrichs, 2014).

It has been found using this instrument that perceived creaminess of emulsified foods highly correlates to friction coefficient (Chen & Stokes, 2012). Subsequent studies have contributed to evaluation of perceived richness and fattiness of foods containing fats and oils, microgels, or both (Stokes, Boehm, & Baier, 2013; Liu, Stieger, van der Linden, & van de Velde, 2015; Godoi, Bhandari, & Prakash, 2017; Laiho, Williams, Poelman, Appelqvist, & Logan, 2017). Relationship between texture and friction coefficient has been investigated at entrainment speed of 50 mm/s, which is within the mixed lubrication regime in the Stribeck curve for microgel samples from the mixture of carrageenan and either of locust bean gum, sodium alginate, or calcium alginate, and using PDMS wetted with saliva as a substrate, and correlation is found between friction coefficient and pasty or slippery perception, while not with smoothness perception due to inhomogeneity of samples tested (Krop et al., 2019).

3.2.2 Tribology for solid food bolus

Although main target for tribology measurement should be liquid or semi-solid foods, investigation on texture of solid foods such as apples has also been performed (Kim et al., 2020). Four texture attributes of apples, including crisp, juicy, mealy, and melt rate, correlate with friction coefficient detected in liner reciprocating motion of probe, while do not with friction coefficient detected in rotational mode of probe at fixed rotation rate. It is concluded that correlation with texture perception should be higher when friction coefficient is determined through dynamic movement closer to that of human tongue compared to through steady movement. Perceived creaminess and fattiness of soft solid foods such as cream cheese correlate with lubrication behavior in low entrainment speeds (e.g., 1-100 mm/s) (Malone, Appelqvist, & Norton, 2003a), where friction coefficient for full-fat type is apparently smaller than that for either low-fat or non-fat type (Laguna, Farrell, Bryant, Morina, & Sarkar, 2017). Reduction in friction coefficient is also seen in cream cheese with increased perceived cohesiveness, thickness, and smoothness by addition of β-glucan and phytosterols (Ningtyas, Bhandari, Bansal, & Prakash, 2019). For O/W emulsions, correlation between friction coefficient and perceived fattiness has been investigated using samples of equivalent shear viscosity at 50 s^{-1} (Malone et al., 2003 a), showing that lubrication behavior can change by emulsifier used and particle size and distribution of oil droplets in the emulsions.

3.2.3 Tribology for liquid food bolus

Using aqueous guar gum solutions, friction coefficient of test sample between substances (i.e., steel ball and elastomer with rough surface) and relationship with human perceptions have been investigated (Malone et al., 2003 a). Friction coefficient at the entrainment speed of ca. 100 mm/s shows the highest correlation with perceived thickness, and this entrainment speed lies in the mixed lubrication regime in the Stribeck curve. From this result, it is considered that perceived thickness should be governed by effects from both friction and viscosity. In addition, study on soft tribology for dysphagia thickeners has shown that beverage thickened by gum-based formulation is better in lubrication capacity than that thickened by starch-based one, resulting in low perceived stickiness (as a unfavorable attribute) and in high swallowing ease (as a favorable attribute) (Vieira et al., 2020). Furthermore, a negative correlation is confirmed between friction coefficient and perceived smoothness, stickiness, or coating for acidified milk beverages stabilized with pectin or CMC-Na as a single ingredient or in combination with guar gum, locust bean gum, and gellan gum (Liu, Pedersen, Knarreborg, Ipsen, & Bredie, 2020). Positive correlation between friction coefficient and sensory attributes such as sour taste and citrus and buttermilk flavors has been also reported by the same research group. This effect can be explained by polysaccharide concentration as it correlates negatively with friction coefficient.

In discussing the relationship between tribological behavior and texture, attention should be paid in selection of measurement conditions such as entrainment speed (corresponding to tongue movement speed) and normal force (corresponding to tongue compressive force). Interaction with saliva should be also considered. Decrease in friction coefficient for highly viscous fluids such as polysaccharide solutions can be explained by two mechanisms. One is the function of polysaccharide polymer layer to mechanically prevent tongue-palate contact, and the other is function of polysaccharide thickening to suppress turbulence in the contact area (Malone et al., 2003a). Therefore, at high entrainment rates, effect of the polysaccharide source on lubrication properties is negligible when fluid viscosity is high enough to suppress turbulence. This mechanism can also be applied to hydrocolloids added to solid foods such as cream cheese described above (Ningtyas et al., 2019). Saliva is a good lubricant with friction coefficient on smooth surfaces of 10^{-2} order, forming lubricating and wear-resistant film on oral surface by combination of relatively high molecular-weight glycoprotein mucin and low molecular-weight protein (Pradal & Stokes, 2016). Generally, saliva is effective of reducing friction between surfaces, which is explained in principle by interaction between the surface and mucin. Mucin has amphipathic properties with both hydrophobic and hydrophilic regions and is thought to govern barrier properties of salivary membrane (Pradal et al., 2016). Salivary membrane has heterogeneous structure in which hydrophilic region of mucin (in extended form) forms a lubricating layer and hydrophobic region is adsorbed on the surface as an anchor layer (Macakova, Yakubov, Plunkett, & Stokes, 2011). Osmotic pressure of the lubricating layer containing mucin and other small molecular proteins increases by deformation upon loading. As a result, a force opposite to the load is generated, and effective load and thus friction coefficient decrease (Klein, 1996). It has also been reported that solvent ions change polymer conformation such as polysaccharides, reducing interaction between these polymers and surface and thus friction (Macakova et al., 2011).

Astringency, one of the main quality factors of red wine, black tea, and some fruit products, can also be friction-associated perception composed of dryness and puckering feeling. Using a mixture of human whole saliva and typical astringent compounds such as tannins, mechanism of astringency perception was investigated in relation to the lubrication behavior (Brossard et al., 2016). A correlation was found between the friction coefficient at a relatively low entrainment speed; 0.075 mm/s and human astringency perception. Astringency can be perceived through mechanical stimulation and thus be determined by tribology. Recently, several subsequent tribological studies have provided various insights into astringency-related textural attributes including dryness, puckering feeling, and roughness (Pires, Pastrana, Fuciños, Abreu, & Oliveira, 2020; Shewan, Pradal, & Stokes, 2019).

Conclusion

Literatures cited in this review is summarized in Table 1, providing an overview of key finding from and novelty of each study. Texture is the key for food product development, and it is no exaggeration to say that those who have the best knowledge on texture can only lead innovative development. In industry, instrumental quantification of textural attributes should be important, enabling to share guide for texture design of products on an objective scale. The authors wish that this article would provide food manufactures with insight into novel product development, contributing to improved QOL (Quality of Life) and ADL (Activities of Daily Living) for human.

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Figure captions

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Fig. 2 Instrumental simulation of squeezing between the tongue and the palate by human.

Fig. 3 Instrumental set-up for extensional viscosity measurements

Fig. 4 Relationship between the maximum velocity of bolus transfer through the pharyngeal phase and steady shear viscosity η or complex viscosity η^*

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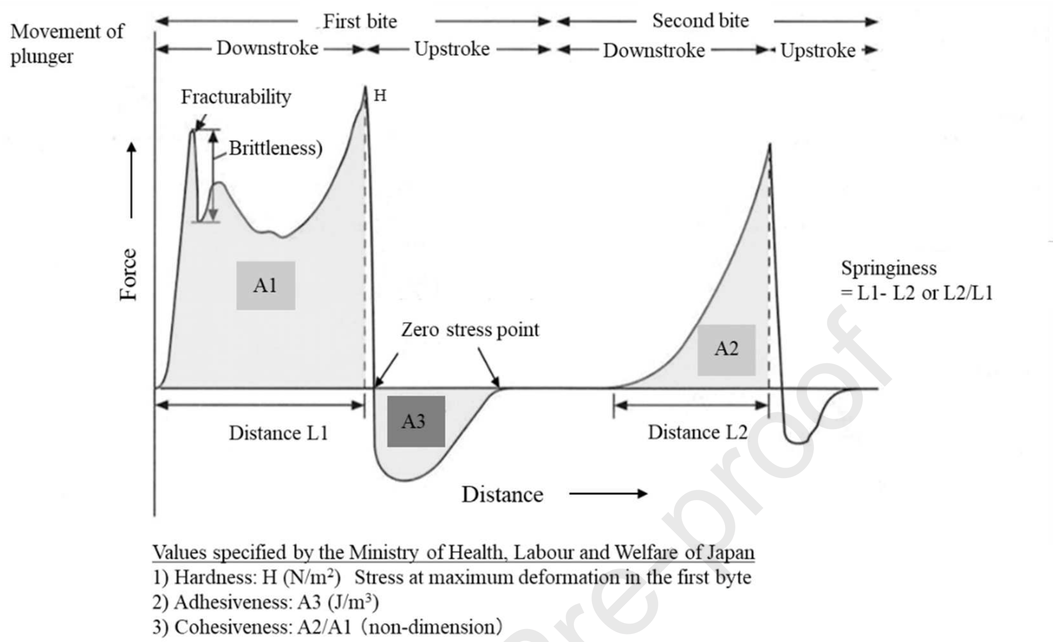
Table 1 List of influential literatures cited in this article

Section	Sub section	Citation	Test sample source	Key finding and novelty
1. Mechanical properties of foods and human perception during food oral processing	Size reduction of solid foods: Soft machine mechanics	Ishihara et al. (2013) from Journal of Texture Studies	Agar gels	Modulus of simulated tongue suitable as alternative to human test is approx. 55 kPa for texture assessment of soft foods which do not require chewing for size reduction.
		Ishihara et al. (2014) from Journal of Texture Studies	High- and low-acylated gellan gum gels	Fracture probability of gel samples corresponds to the ratio of subjects who decide to use tongue-palate compression instead of chewing for size reduction when the modulus and size of simulated tongue is optimized.
		Kohyama, K. (2015) from Journal of Texture Studies, 46, 138-151.	High- and low-acylated gellan gum gels	Human can decide oral strategy for size reduction by sensing dynamically difference in strain between food and the tongue during oral processing.
		Hori et al. (2015) from Food Hydrocolloids	Low-acylated gellan gum and psyllium seed gum gels	Slope of time course curve for tongue pressure during the first size reduction is almost independent of physical properties or consistency of polysaccharide gels.
		Kohyama et al. (2019) from Foods	High- and low-acylated gellan gum gels	Fracture profile of foods on soft machine developed shows similar results to human behavior.
	Swallowing of semi-solid or liquid foods: Extension rheology	Chen & Lolivret (2011) from Food Hydrocolloids	Eighteen commercial products (orange juice, fluid yogurt, fruit purée, ketchup etc.)	The maximum stretching force and the work of stretching show higher correlation to perceived swallowing ease compared to apparent viscosity.
		Lv et al. (2017) from Journal of Texture Studies	Solutions of guar gum and sodium carboxymethyl cellulose (CMC)	Ability to discriminate extensional viscosity is higher than that to discriminate shear viscosity.
		He et al. (2016) from Food Hydrocolloids	Solutions of xanthan gum	Perceived thickness, stickiness, and mouth coating have higher correlation to extensional viscosity than shear viscosity.
	Swallowing of semi-solid or liquid foods: Dynamic viscoelasticity measurements	Tashiro et al. (2010) from Bioscience, biotechnology, and biochemistry	Solutions of CMC, xanthan gum, and guar gum	The maximum velocity of fluid bolus correlates well to dynamic viscosity $\eta'$and complex viscosity η^*, especially those measured at angular frequency of 20–30 rad/s and above.
		Nakauma et al. (2011) from Food Hydrocolloids	Solutions of xanthan gum and locust bean gum (LBG)	Yield stress can present perceived cohesiveness of bolus, serving as a measure of swallowing ease.
2. Geometrical properties of foods and human perception during food oral processing	Imaging analysis of bolus and computer simulation of bolus formation for solid foods	Ishihara et al. (2011) from Food Hydrocolloids	Low-acylated gellan gum and psyllium seed gum gels	Mean particulate size of model bolus low-acylated gellan gum/psyllium seed gum composite gel is generally larger than that for low-acylated gellan single gel when compared at equivalent gel hardness and is less influenced by the addition level of saliva.
		Devezeaux de Lavergne et al. (2016) from Food Hydrocolloids	Emulsion-filled agar and gelatin gels	Food bolus from relatively smaller fracture strain contains more small particulates, leading to greater perception of graininess and graininess, whereas the bolus of relatively larger fracture strain contains less small particulates, leading to greater perception of creaminess.
		Tournier et al. (2017) from Food Hydrocolloids	Agar and gelatin gels	Characteristics from imaging analysis correlate to some textural attributes.
		Shibata et al. (2016) from 2016 IEEE/SICE International Symposium on System Integration (SII)	Gels from 12 types of gelling hydrocolloids	Perceived smoothness, elasticity (i.e. springiness), stickiness, and granularity are evaluated on stress distribution map from imaging analysis.
		Shibata et al. (2017) from Robotics	Gels from 12 types of gelling hydrocolloids	Perceived smoothness, elasticity (i.e. springiness), stickiness, and granularity are evaluated on stress distribution map through Convolutional Neural Network.
		Nakauma et al. (2021) from J. Jpn. Soc. Food Sci. Technol.	Gels from 12 types of gelling hydrocolloids & jellies and puddings commercially available	Discussion by Shibata et al. (2016) is validated using commercial gel-type food products along with optimization of prediction formula.
		Devezeaux de Lavergne et al. (2015) from Food Hydrocolloids	Emulsion-filled agar and gelatin gels	Gels perceived as creamy reveal high bolus flowability, whereas gels perceived as grainy form boli containg large number of fragmented particulates.
		Foegeding et al. (2017) from Food Hydrocolloids	Whey protein and polysaccharide (low-acylated gellan gum, LBG, carrageenan, and pectin) gels	Texture perception of emulsion gels is dynamic and entails a transition from rheology-dominant processes to tribology dominant processes.
3. Moisture- and fat-related surface properties of foods and human perception during food oral processing	Tribology for lubrication: Instrumental development for tribology measurement	Carpenter et al. (2019) from Food Hydrocolloids	Saliva (with protein)	Saliva proteins form lubricous boundary film, deduced by high correlation between friction coeffcient and amount of the proteins present at PDSM and silica surfaces.
		Carvalho-da-Silva et al. (2013) from Food & Function	Milk chocolates	Difference in perceived mouth-coating between two samples can be presented by that in friction coefficient at an entrainment speed of ~0.2 mm/s.
		Kieserling et al. (2018) from Biotribology	Sunflower oil and yoghurt	Water content in a food system has a substantial influence on tribological parameters.
		Kim et al. (2015) from Tribology International	Glycerol	PDMS surface properties affect consistency of tribological responses.
		Krzeminski et al. (2012) from International Dairy Journal	Sunflower oil, full-fat and low-fat yoghurt	Difference is found in friction coefficient at an entrainment speed of 1 mm/s between yoghurts with different fat contents, which is strongly influenced by surface roughness of tribosystem.
		Pondicherry et al. (2018) from Biosurface and Biotribology	Chocolate spread and cheese sauce	Extended Stribeck curves present directly correlations between frictional behavior and mouthfeel-dominated sensory attributes.
		Sonne et al. (2014) from LWT - Food Science and Technology	Yogurt	Perceived in-mouth viscosity and creaminess are presented by combination of multiple mechanical and geometric parameters, including those from tribology.
		Stokes et al. (2013) from Current Opinion in Colloid & Interface Science	Solutions of polysaccharides (locust bean gum, gellan gum, xanthan gum, carrageenan, pectin)	Oral breakdown is captured through a multi-scale approach including tribology in consideration of saliva effects.
		Liu et al. (2015) from Food Hydrocolloids	Emulsion gels containing solid fat, and WPI or tween as emulsifier.	Increased solid fat content does not have influences on fat-related perceptions although it leads to lower friction coefficient.
		Godoi et al. (2017) from Food Hydrocolloids	Custard with starch, kappa-carrageenan and fat	Addition of kappa-carrageenan does not have influences on perceived oiliness or creaminess although it leads to lower friction coefficient.
		Laiho et al. (2017) from Food Hydrocolloids	Yoghurt	Textural perceptions (gelatinous, thickness, adhesiveness, creaminess, smoothness etc.) of yoghurt are presented by either of bolus size, shape, friction coefficient, or viscosity.
		Krop et al. (2019) from Food Hydrocolloids	Hydrogels with carrageenan, locust bean gum, sodium alginate, calcium alginate	Perceived pastiness and slipperiness correlate to friction coefficient of bolus at an entrainment speed of 50 mm/s .
	Tribology for lubrication: Tribology for solid food bolus	Kim et al. (2020) from Food Quality and Preference	Ten apple varieties	Four texture attributes of apples (i.e., crisp, juicy, mealy, and melt rate), correlate with friction coefficient detected in liner reciprocating motion of probe.
		Laguna et al. (2017) from Food and Function	Commercial dairy products (milk, yoghurt and cream cheese)	Perceived creaminess and fattiness of soft solid foods such as cream cheese correlate with lubrication behavior, where friction coefficient for full-fat type is apparently smaller than that for either low-fat or non-fat type.
		Ningtyas et al. (2019) from Food Research International	Cream cheese with beta-glucan and phytosterols	Reduction in friction coefficient is seen in cream cheese with increased perceived cohesiveness, thickness, and smoothness by addition of β-glucan and phytosterols.
		Vieira et al. (2020) from Current Research in Food Science	Beverages thickened by gum- or starch-based formulation	Beverage thickened by gum-based formulation is better in lubrication capacity than starch-based one, resulting in low perceived stickiness and in high swallowing ease.
		Liu et al. (2020) from Food Science & Nutrition	Acidified protein drinks stabilized by CMC or pectin with other polysaccharides (high-acylated guar gum, LBG, or gellan gum)	A negative correlation is confirmed between friction coefficient and perceived smoothness, stickiness, or coating for acidified milk beverages stabilized with pectin or CMC as a single ingredient or in combination with guar gum, LBG, and high-acylated gellan gum.

Tribology for lubrication: Tribology for liquid food bolus	Pradal et al (2016) from	Human saliva	Mucin has amphipathic properties with both hydrophobic and hydrophilic regions and is thought to govern barrier properties of salivary membrane.
	Brossard et al. (2016) from Journal of Texture Studies	Red wines	Perceived astringency correlates to friction coefficient at an entrainment speed of 0.075 mm/s.
	Pires et al. (2020) from Foods	Polyphenols	Oral astringency is presented by combination of multiple factors, including pH, viscosity, temperature, not simply by saliva lubrication alone.
	Shewan et al. (2019) from Journal of Texture Studies	Epigallocatechin gallate, epicatechin gallate and epicatechin	Astringency is a complex sensation which does not solely depend on changes in lubrication of salivary film.



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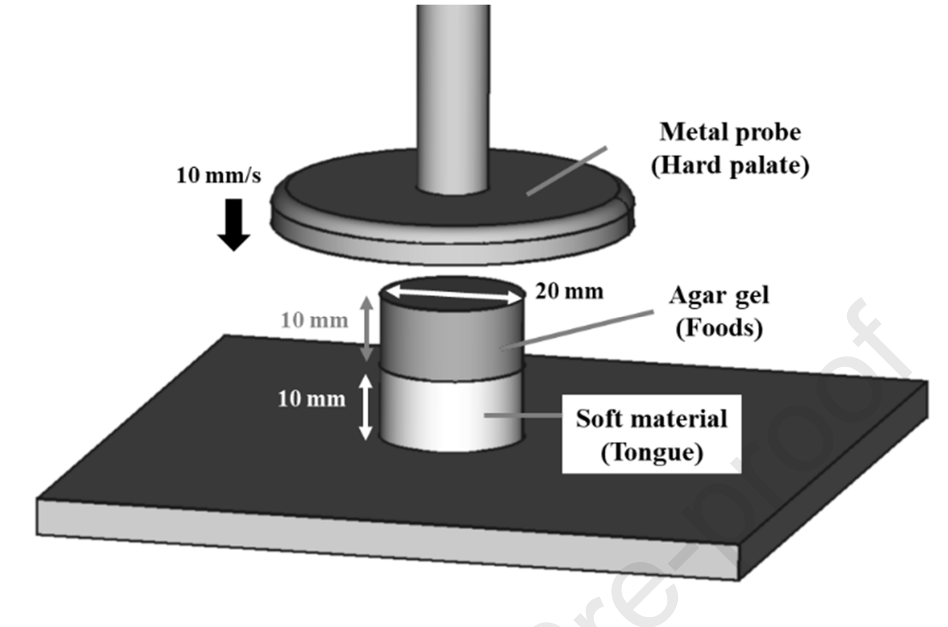

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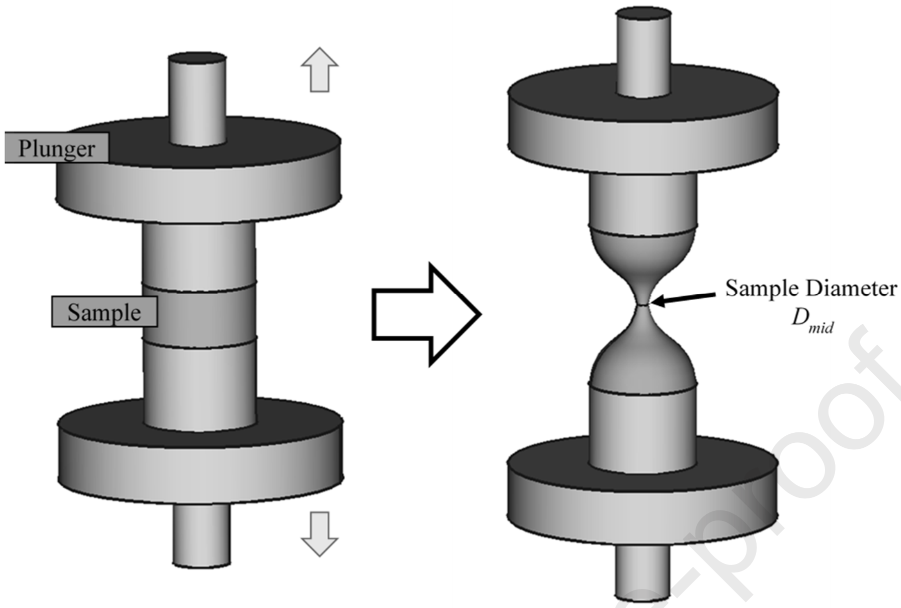

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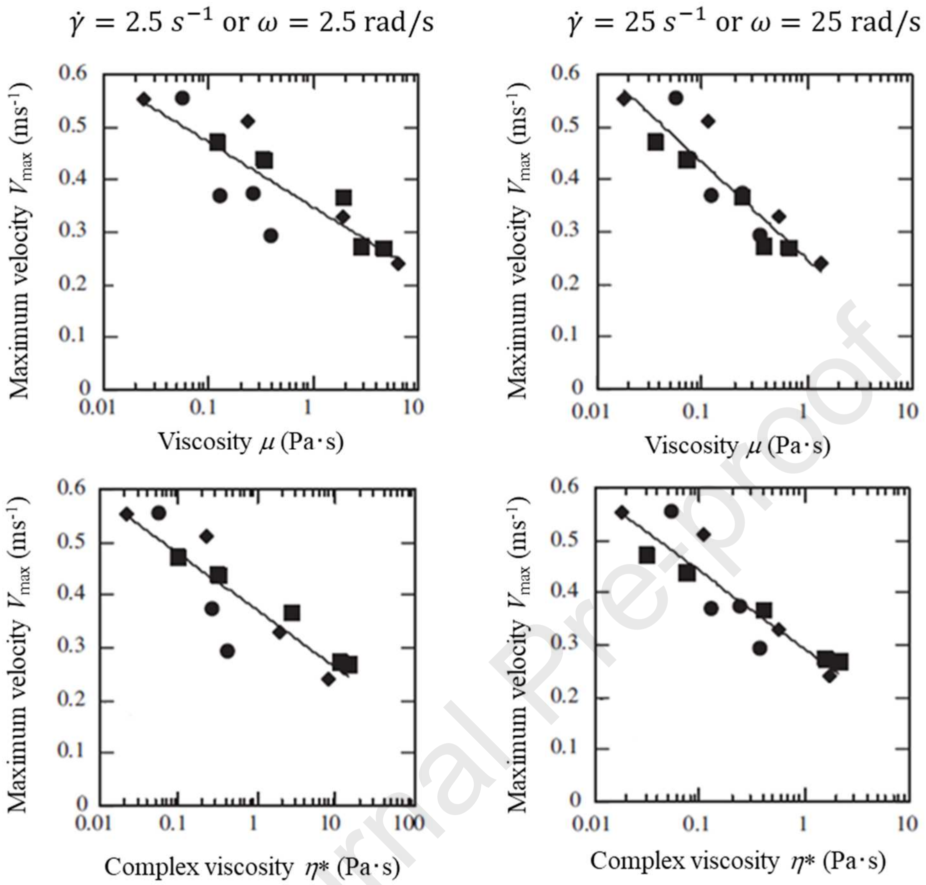

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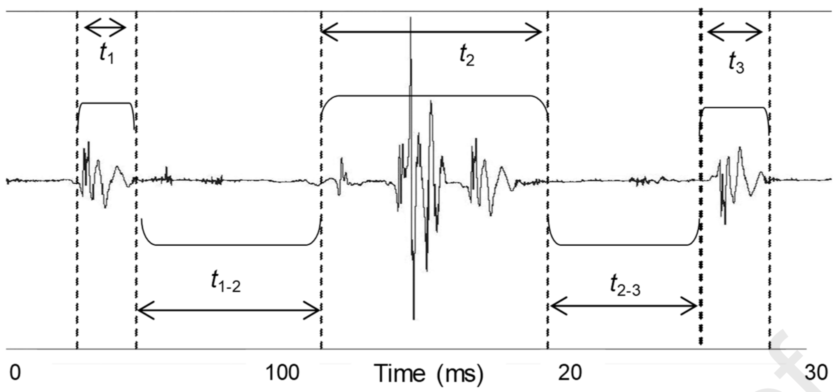

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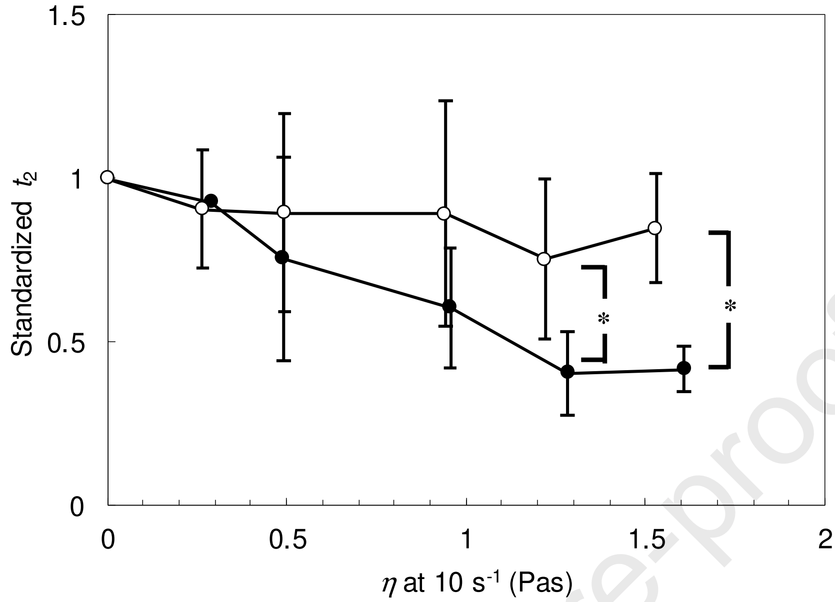

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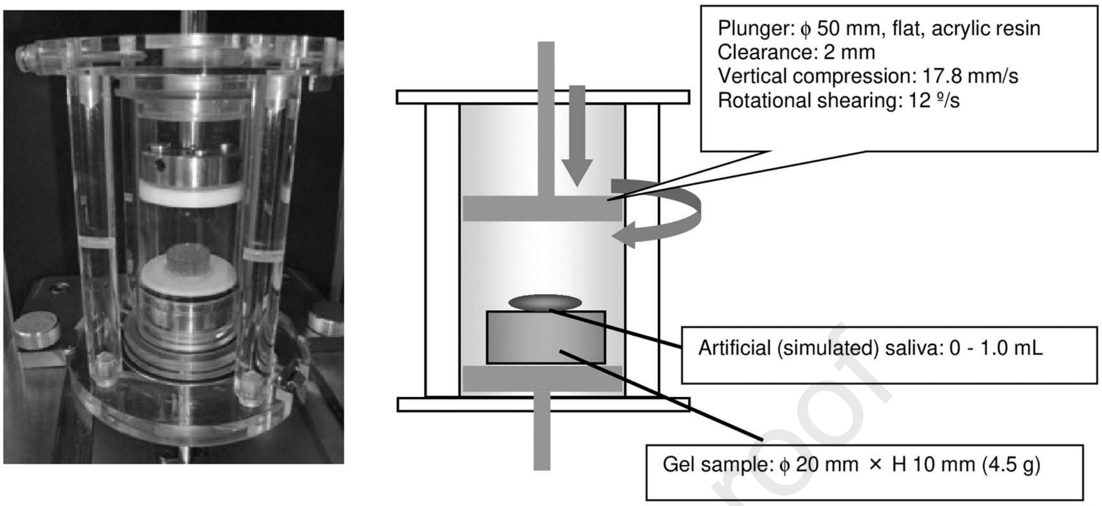

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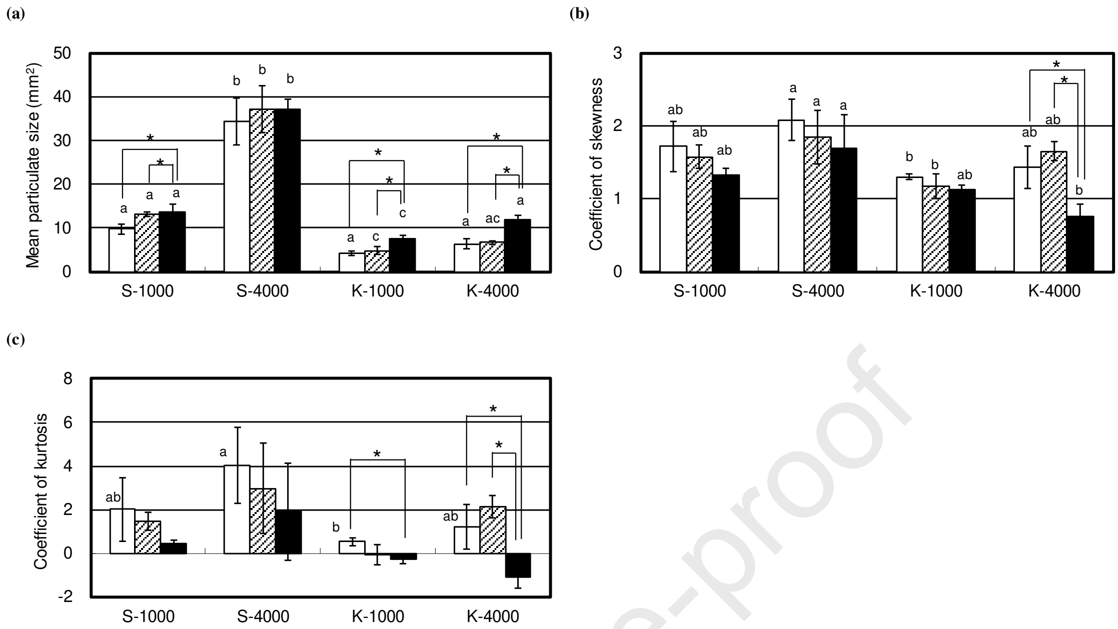

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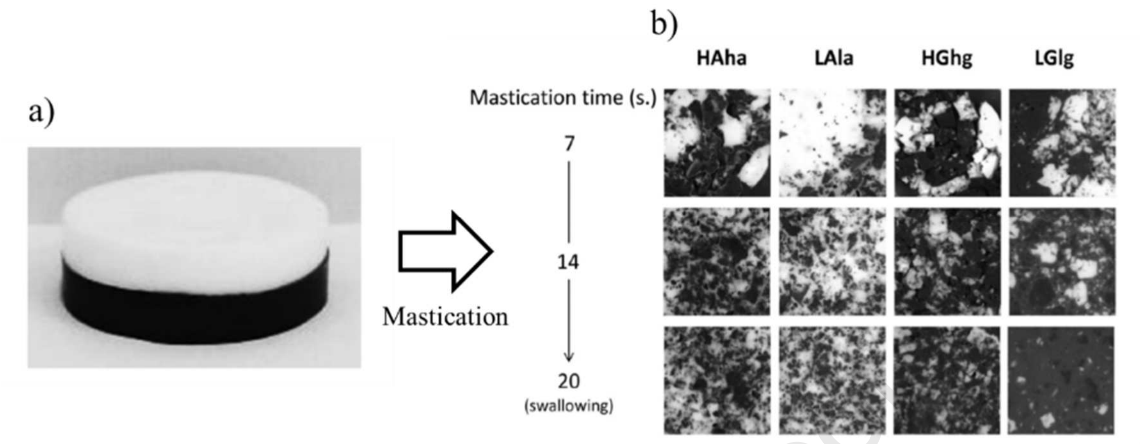

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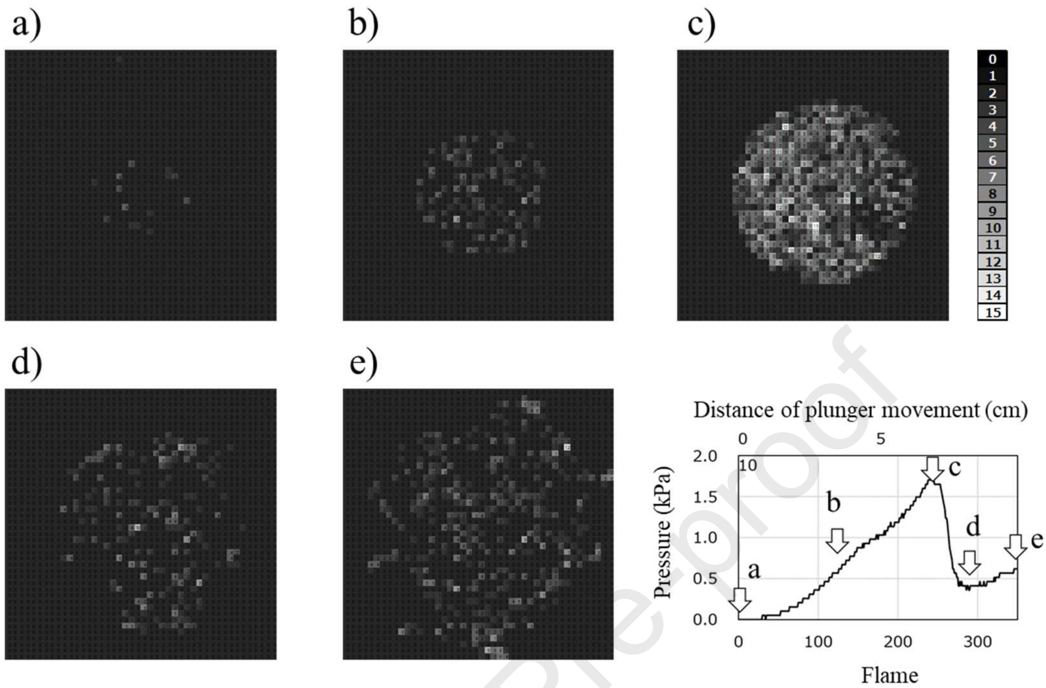

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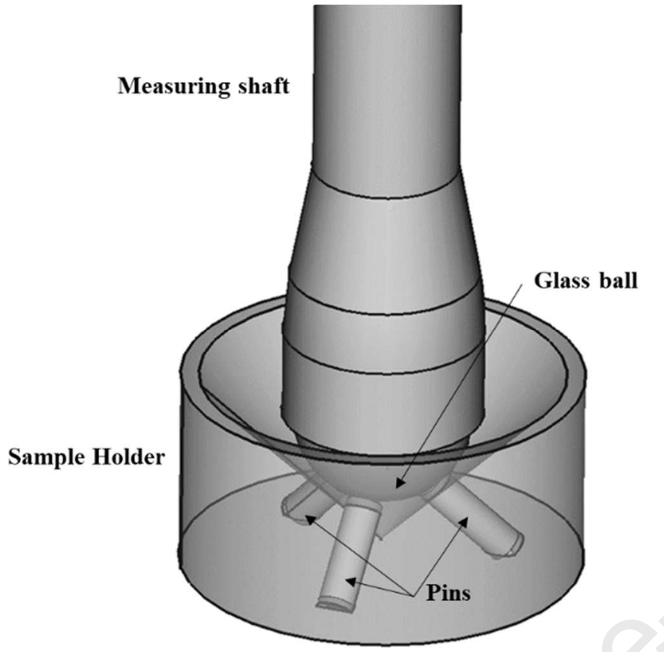

Fig. 11 Instrumental set-up for tribology measurements

Highlights

Food texture evaluation through instrumental measurements is overviewed.
The measurements consider mechanics of food oral processing in human.
Palatal reduction and swallowing in human can be simulated instrumentally.
Bolus formation in food oral processing can be analyzed by imaging technique.
Surface lubrication properties of foods can be studied by tribology.

Conflict of Interest

The authors declare that they have no conflicts of interest.