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REVIEW PAPER

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Perception and measurement of food texture: Solid foods

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Abstract

There is still a gap between instrumental measurement and sensory evaluation because of the complexity of food texture in spite of many efforts. In sensory evaluation, the terms describing the texture should be well understood by panelists, which poses a problem of establishing lexicons and training panelists. In the instrumental measurement, more efforts are required to understand the large deformation and fracture behavior of foods. The texture profile analysis (TPA) proposed by Alina Szczesniak, Malcolm Bourne, and Sherman has been applied to many foods, and was useful to develop the understanding of textures. But sometimes confusion of the interpretation of TPA parameters appeared. Many new techniques have been introduced to quantify TPA parameters. Recent efforts to fill the gap between sensory evaluation and instrumental measurements, human measurements, or physiological measurements have been introduced. This endeavor is an effort of synthesizing the dentistry and biomedical approach, sensory and psychological approach, and material science approach, and therefore, the collaboration among these disciplines is necessary. This manuscript mainly discusses texture studies for solid foods.

Practical applications

To fill the gap between the sensory evaluation and the instrumental measurement of texture, it is necessary to examine the physical change of foods during the oral processing. This will give us the designing principle of palatable and safe foods.

KEYWORDS
flavor release, oral processing, sensory, soft foods, texture, TPA

1 | INTRODUCTION

Recently, food oral processing has been an active research area in texture studies. Material science approaches have been introduced a long time ago, and the so-called soft matter physics offers important tools to understand relation between the microscopic structure and physico-chemical properties of foods. The stark difference between nonfood material science and food science lies in the point that the former generally aims to make a durable and resistant product while for the latter solid or semisolid foods should be comminuted and mixed with saliva to be swallowed (Hutchings & Lillford, 1988). On the other hand, food engineers are required to make foods which can be stored safely before the consumption with a longer shelf life, which is necessary for emergency rations required in the disasters caused by great earthquakes and inundations. Therefore, apparently contradictory and incompatible requirements need to be satisfied, which is a difficult task to realize. For example, in the development of biodegradable packaging, the material should be strong enough before usage and immediately or as early as possible become degradable after usage.

Texture has been widely recognized as one of most important attributes of food, and thus taken as a theme of the First Food Summit in 1999 in Wageningen. Both Alina Szczesniak and Malcolm Bourne acted as important contributors. The conference report of this summit was published in Food Quality and Preference (Szczesniak, 2002). Another Food Summit Conference held at the same place focused on "Making sense of food" (Hamer, Prinz, Dransfield, & Westerterp-Plantenga, 2006), where more psychological and physiological aspects were discussed, and papers were published in the special issue of *Physiology and Behavior* (2006). The first International Congress on Mastication and Health was held jointly with the 13th Meeting of the Japanese Society for Mastication Science and Health Promotion in Yokohama September 2002 (Nishinari, 2009). The special issue collecting six papers presented at a symposium at this international conference that explored the common ground of texture interests among

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food scientists and medical scientists was published as a special issue of *Journal of Texture Studies* (2004). Following a very successful review paper "Food Oral Processing – A Review," *Food Hydrocolloids* (Chen, 2009), by Jianshe Chen, the present chief editor of JTS, a series of international conferences with the same name has been organized every 2 years since 2010. Texture studies have been developing to include contributions from medical and dental scientists. In addition to subjective (sensory) evaluations and objective (instrumental) measurements, now physiological measurements aim to fill the gap between the former two approaches. The inclusion of these types of studies began more than two decades ago (Nishinari, Nakazawa, Katsuta, & Toda, 1999; Nishinari, Ogoshi, Kohyama, & Yamamoto, 2005).

Unfortunately, last year, we lost important pioneers in the field Alina Szczesniak and Malcolm Bourne, who acted chief editors of JTS in the past. It is useful to provide a retrospective of the achievements of these two pioneers and an outlook on the future direction of texture studies. Pioneering achievements of other another important scientist, Philip Sherman, who also served as a chief editor with Alina Szczesniak of *Journal of Texture Studies* will also be discussed.

Sensory evaluations have some limitations such as the difficulty to have reliable trained panelists, and even when it is possible, fatigue and adaptation of panelists (Nishinari, 2005; Peleg, 2006), and therefore, the number of food samples evaluated is limited (Peleg, 2006). Panelists should be trained and it should be confirmed whether they all agree to give similar evaluation (Bourne, Sandoval, Villalobosc, & Buckle, 1975; Civille & Szczesniak, 1973).

Frankly speaking, Szczesniak's word "texture is a sensory property"(Szczesniak, 2002) struck me as incongruous because whether the word "property" can be used or not was not evident for me. Most students having studied physics and chemistry may hesitate to use the word "sensory property" side by side with "mechanical property" or "optical property" and so on, which can be measured objectively, that is, using measuring instruments. As Hutchings and Lillford (1988) stated, "texture cannot yet be measured objectively because it exists, like other perceived food qualities such as colour and flavor, within the brain." George William Scott Blair, who was the founder of the journal *Biorheology* and an important advisor for Alina Szczesniak and Malcolm Bourne in the launching of *Journal of Texture Studies*, used a word "quasi-property" which was criticized harshly by famous physicists, Andrade, Weissenberg, de Waele Ostwald when he presented the idea at the British Rheologists' Club in October 1946 (Reiner, 1960). This will be discussed in a separate paper.

Methodologies used in texture studies have had a remarkable development along with studies of nutritional aspects because consumers are health-conscious and, therefore, demanding both palatable and healthy foods. During mastication in the mouth, digestion occurs as a result of the combination of mechanical and (bio)chemical actions; food is reduced into smaller size by mechanical degradation by teeth for hard foods and by the tongue and palate for soft foods, and in addition enzymatic degradation also occurs by saliva, especially by α-amylase. However, it should be reminded that the enzymatic effect of saliva on the texture during oral processing depends on foods. For liquid foods, it may be almost negligible because of the short passing time. For solid foods with low moisture, saliva plays an important function of moistening/hydrating first before the enzymatic degradation. For starchy foods like custards, the effect of α-amylase on the perceived texture during oral processing was shown in the experiment that changed the concentration of added α-amylase or arcabose, an amylase inhibitor (de Wijk, Prinz, Engelen, & Weenen, 2004). In this experiment, de Wijk and his coworkers used starch-based vanilla custards and nonstarch-based vanilla carboxymethyl cellulose (CMC) custards. In unrestricted sessions, panelists orally processed the custards in their preferred manner for 5 s, while in the restricted sessions, panelists compressed the custards between tongue and palate for 5 s. In either case, the panelists started to assess the texture and flavor after 5 s. In both unrestricted and restricted sessions, they found that amylase resulted in increased melting (becoming thin in the mouth and spreads throughout the mouth at different rates) and decreased thickness (perceived when custards are compressed through up and down motions of the tongue against palate) sensations, whereas acarbose had the opposite effect, that is, decreased melting and increased thickness for starch-based vanilla custard desserts. Since they also found that neither additional amylase nor acarbose affected sensations for a CMC vanilla custard dessert, they concluded that the effects of amylase on viscosity-related sensations of starch-based custards, such as perceived melting and thickness, are caused by amylase-induced breakdown of starch. They also found that perceived flavor was affected by amylase. It should be also mentioned that saliva incorporated in bolus acts later and also stimulates secretion of digestive liquids in the gastrointestinal organs, which likely contribute to digest the food. Needless to say, food cannot be characterized only by texture; taste and aroma are also important attributes as well as texture, and these attributes interact and influence each other (Chen & Engelen, 2012; Guichard, Salles, Morzel, & Le Bon, 2017; Nishinari, 2006, 2014, 2015a, 2015b).

The interest for researchers working in different areas is different as symbolized in the terminology. Physiologists classify food properties such as hardness, other rheological properties such as elastic/plastic, sample size as *extrinsic factors*, and age, gender, and tooth loss as *intrinsic factors* when they study mastication behavior (Hamer et al., 2006; Woda, Foster, Mishellany, & Peyron, 2006). Food scientists may prefer to use physiological factors and physicochemical factors (Chen, 2009). Physiologists study food oral processing from the viewpoint of oral organs, and the brain using nonrefined food models, while food scientists are more interested in understanding the molecular and structural basis of the texture. However, it is evident that texture is perceived in the brain and, therefore, food scientists recognize the importance of studying physiology and psychology.

As is well-known, people assessing the same stimulus differ in their ratings of that stimulus and their oral physiological parameters also exhibit interindividual variation (Engelen & van der Bilt, 2008). While most food scientists try to prepare model foods which are reproducible, they tend to fear individual differences among panelists because it is not possible to get "reproducible" panelists even if they are trained. The difference between attitude and common sense makes it more difficult to fill the gap, but it should be pursued to progress further.

In Section 2, a brief history on the recognition of texture as an important attribute of foods by Szczesniak's group in United States is described, and also work in Japan stimulated by this work along with the characteristic problem of language differences in characterizing sensory properties of texture. In Section 3, the texture profile analysis (TPA) proposed by Szczesniak and supported and developed by Bourne is described, and then Sherman's TPA, which emphasized the importance of temporal aspects is described. The oral process models by Hutchings and Lillford and by Hiiemae and Palmer are then discussed together with recent arguments. The process models are discussed based on papers where peanuts, wheat flakes, cucumbers, and apples with different degrees of structure (e.g., paste, fragmented, and whole for peanuts) were masticated. The relation between mechanical properties of foods and the mastication behavior is described, and especially adhesiveness and cohesiveness are discussed in detail based on recent studies. Section 4 is devoted to the recent physiological measurement of soft gels and the eating difficulty and the interplay between texture and flavor.

Since many excellent review papers have already been published on food oral processing (Chen, 2009; Foegeding, Stieger, van de Velde, 2017; Kohyama, 2015), this review will limit the discussion to the perception and measurement of texture for solid foods. Readers will find that the legacy and achievements of these pioneers have not been "digested and absorbed" completely, and there are still so many things to be done in the future.

2 | SIGNIFICANCE OF TEXTURE IN FOODS: PSYCHOLOGICAL APPROACH

2.1 | Consumer awareness of texture: Word association approach

Before food texture was so recognized for its importance, Alina Szczesniak pointed out that it is the texture which contributes to the palatability of foods. Based on word association tests she discovered that texture is more important than flavor for some foods (Szczesniak & Kleyn, 1963). In their word association test, respondents were instructed to give the first three words that came to his/her mind upon hearing a food product mentioned. Seventy four foods (coffee, salads, ham, sandwich, orange juice, green peas, raisins, cocoa, cake, bacon, milk, spinach, spaghetti, cucumber, tea, sauerkraut, scrambled eggs, mayonnaise, pudding, French-fried potatoes, noodles, turkey, pretzels, butter, avocado, Frankfurters, liver, pancakes, pear, coconut, fish, chocolate, rice, coleslaw, ice cream, shrimp, peanut butter, chicken, toast, pie crust, water, celery, Parmesan cheese, sirloin steak, cream cheese, carrots, apples, Coca-cola, tomato, baked beans, watermelon, roast beef, hard-boiled eggs, orange marmalade, lettuce, baked potatoes, boiled potatoes, mashed potatoes, potato chips, etc.) were selected and 100 employees of General Foods Corporation participated in this interview as respondents. The selection of these 74 foods in the test reflects the common and popular foods familiar for respondents in United States in 1960s, and was different from word association tests carried out in Japan as will be discussed in Section 2.2. Approximately, 20 min were required to complete the test for one respondent. Responses were classified into menu uses, food attributes, type, personal preference, health and nutrition, and regional origin. Foods were mostly associated with menu uses (the response was related with other foods as in the response "butter" to "toast," or related with a component as in the response "lettuce" to "salad," or related with an occasion as in the response "Friday" to "fish," or related with method of serving as in the response "bowl" to "soup"), followed by food attributes (texture, flavor, form or temperature, appearance, aroma, and others). Since this first test was done by 100 employees of General Foods Corporation, another similar test by 150 people, taking into account to have a good balance in gender (male 75 and female 76), living in three cities (Chicago, Illinois, Denver, Colorado and Charlotte, North Carolina), ages (18–59, 2 persons 60 and over) and economic social classes were tested with 29 of the original 74 foods. (Szczesniak, 1971). Very similar results were obtained. It was concluded that although people's awareness of texture on a conscious level is limited, it plays a very essential role in determining their feelings about foods. A strong interaction between texture and flavor was recognized: the blander the flavor, the greater the awareness of texture. The number of times mentioned for texture terms in descending order of frequency was as follows: crispness (71), crunchy (44), juicy (37), smooth (37), creamy (29), soft (26), sticky (24), stringy (24), tender (21), fluffy (21), dry (19), chewy (14), hard (12), greasy (11), and lumpy (11) in the association test for 29 food items by 149 respondents.

Based on the examination of consumer awareness of texture and other attributes (Szczesniak, 1971; Szczesniak & Kleyn, 1963), the definition and the classification of texture characteristics were proposed (Szczesniak, 1963a, 1963b), and standard rating scales of hardness, brittleness, chewiness, gumminess, viscosity, and adhesiveness were proposed to evaluate food texture quantitatively (Szczesniak, Brandt, & Friedman, 1963), and the texture profile method was proposed (Brandt, Skinner, & Coleman, 1963). Then, methods of instrumental measurement using a texturometer (Friedman, Whitney, & Szczesniak, 1963; Szczesniak, 1963a, 1963b) were proposed, which is discussed in the next section.

It was a sensational idea to grasp the texture as an important and quantifiable property in 1960s because most food scientists had paid attention mainly to tastants and aroma compounds based on analytical chemistry. It is noteworthy to see that she started the study from words to describe the food attributes. Delicate nuances of every word could not be understood rigorously by foreigners not only because of the language difference but also because of the cultural difference conditioned by history and geography. Although some trials to compare corresponding texture terms for foods have been published (Drake, 1989; Hayakawa, 2015; Nishinari et al., 2008; Rohm, 1990), it is still necessary to do more effort to understand each other without misunderstanding in the present global age especially because food scientists have the privilege to communicate each other by virtue of the fascinating power of foods which unite people in a friendly convivial atmosphere (Nishinari, Fang, Mleko, & Tomczynska-Mleko, 2016).

Szczesniak and Skinner (1973), based on the same word association test described above, examined how consumers understand the meaning of the texture words. In the previous study, the name of foods was used as the stimulus and the texture terms generated as the response, while in the work of Szczesniak and Skinner (1973) texture words were used as the stimulus and specific foods were generated as the response. This was performed by asking 102 respondents for each texture term to record the first three food items that came to mind. Pairs of a texture term and food items of most frequent associations were found for terms relating with "hardness" such as "soft"—potatoes, "firm"—apple, "hard"—candy, terms relating with "brittleness" such as "crumbly"—cake, "crunchy"—cereal, "crisp"—lettuce, potato chips, and celery, terms relating with "brittleness" such as "tender"—steak and meat, "chewy"—meat and caramels, terms relating with "gumminess" such as "short"—pie crust and cookies, "mealy"—potatoes, "pasty"—macaroni, noodles, and spaghetti, "gummy"—taffy and caramel, terms relating with "viscosity" such as "thick"—gravy, "thin"—broth, terms relating with "adhesiveness" such as "sticky"—syrup and candy, "gooey"—marshmallows, fudge, jams and jellies, terms relating with "moisture" such as "dry," toast and cracker, and cereal, "wet"—water and watermelon, "watery"—watermelon, terms relating with "fat" such as "oily"—salad dressing and oil, "greasy"—French fries and bacon, and so on. Other associations for texture terms related with geometrical parameters were also found: "airy"—whipped cream, meringue, "chalky"—powdered milk, "fibrous"—celery, meat and asparagus, "flaky"—pie crust, "fluffy"—whipped cream and mashed potatoes, "grainy"—cereal, "granular"—sugar and salt, "lumpy"—potatoes, gravy and oatmeal, "powdery"—confectioner's sugar and flour, "pulpy"—oranges, "sandy"—spinach, clams and oysters, "stringy"—string beans. Other associations related other texture terms were also found: "body"—meat, potatoes and bread, "creamy"—cream, pudding, ice cream, and butter, "doughy"—bread, doughnuts, dumplings, and cake, "elastic"—taffy and gum, "heavy"—cream, "juicy"—oranges, peaches, and steak, "light"—sponge cake, "mushy"—oatmeal and mashed potatoes, "rubbery"—gelatin dessert, "slimy"—clams and oysters, "slippery"—clams, oysters, and gelatine dessert, "smooth"—pudding and ice cream, "spongy"—sponge cake, "soggy"—bread, potatoes, cake, and pancakes, "springy"—sponge cake, and so on. Some associations having connotations other than inherent texture of mentioned food were also found, for example, "thin" for spaghetti because of the shape, "dry" for liquor because of the flavor, "hard" for liquor because of the alcohol content, "sandy" or "gritty" for spinach, clams and oysters because of extraneous matter, "gummy"—gum because of the word root, and so on. They thought that this pairing should be useful in explaining the meaning of texture words to people unfamiliar with the nomenclature or in situations where a language barrier exists, for example, when training texture profile panels in foreign countries.

2.2 | Word association study in Japan

Stimulated by a series of papers of Szczesniak and her coworkers in General Foods, Yoshikawa, Nishimaru, Tashiro, and Yoshida (1970a, 1970b, 1970c) carried out a similar survey of Japanese texture terms. They asked 140 female students to describe the texture of 97 foods, and collected 406 texture descriptive words. Compared with English, Yoshikawa et al. noticed that more onomatopoeic words; that is, those which imitate natural sounds, such as *tsurutsuru* (smooth and slippery), *paripari* (crispy), were included (about 250, which is more than 60% of all the responses). Frequencies of responses were found well balanced for some expressions with opposite meanings; for example, tough versus tender, but not so for most of the adjectives and adverbs. For example, there were many mentions of "juicy," while there were only a few mentions of "not juicy." They also noted that there were many words describing stickiness and viscoelasticity, such as *nicha-nicha*, *gunnyari*, *torori*, *doro-doro*, and *beta-beta*. If the attributes of a certain food could be described adequately by these response words alone, the responses would evoke the original stimulus by way of reverse association. However, there will be only a few such cases, since other important characteristics such as taste, flavor, color, appearance, and so on, are not given. They took an example of a sponge cake called castilla in Japanese made from flour, egg, and sugar syrup but without butter which is an important ingredient in a western sponge cake. When this castilla was depicted using only texture terms such as "very soft, *fuwafuwa* (deformable), *shittori* (moist), nonchewy, crumbly, less watery," respondents could not identify it because this sponge cake has a special taste and aroma, and color (yellowish) and if these attributes were not given, it was difficult for respondents to identify it only from textural attributes. This reverse association test was complementary to that performed by Szczesniak and Skinner (1973).

Yoshikawa et al. (1970c) classified the texture terms into five categories.

1. Terms representing mechanical and acoustical properties, sound and appearance during mastication and deglutition, softness, viscosity;
2. Terms representing temperature-related attributes;
3. Terms representing water content-related attributes;
4. Terms representing elasticity, brittleness and light; and
5. Terms representing attributes related to flaky and smooth.

Unfortunately, this classification seems difficult to be understood, for example, although the word "smooth" is classified into the fifth category, the word *zarazara*, an adjective used to represent rough surface or coarse grain thus having an opposite meaning, is classified not in the same fifth category but in the first category.

Hayakawa et al. (2005) recently re-examined the texture terms and also found 445 terms. They reconfirmed that there were many onomatopoeias in texture terms as had been found by Yoshikawa et al. (1970a, 1970b, 1970c), and that the usage of terms had changed after 40 years. They found that some terms are not used so often nowadays, and that some new terms had been introduced to represent texture, which is related with the appearance of new processed foods such as dessert jellies and fizzy drinks. To know whether all these 445 terms are used by consumers or not, taking into account that some words are recognized as texture terms but rarely used, Hayakawa et al. (2006) examined the frequency of these terms in 2,437 collected questionnaires, and obtained 135 terms actually used by consumers living in Tokyo metropolitan, Kyoto, Osaka, Kobe areas. Among 135 terms, 66 terms were found more to be more frequently used. The recognized tendency that onomatopoeias are highly frequently used (ca. 52%) was similar as in the first survey (70%) (Hayakawa et al., 2005). The terms judged as food expressions at 90% or greater were 66 terms such as “katai (hard),” “creamy,” “saku-saku (crispy),” “pari-pari (crispy),” and “neba-neba (sticky),” These terms were considered to be the core terms of the texture vocabulary of Japanese consumers and also widely used in other languages (Bourne, 2002, p. 5; Rohm, 1990). Since the usage of terms is different for different genders, age, and regions, Hayakawa et al. (2007) analyzed these aspects and found that females seemed to have a larger vocabulary for food texture than males because of the different sensitivity and experience of cooking. Younger consumers (junior high school students and <34 years old) were found to have a poorer food texture vocabulary compared to middle-aged 35–49 years old), mature (50–64), and elderly (>65) age groups. This seemed to be due to the decrease in vocabularies in younger generations who are strongly influenced by modern mass media and advertisements of food companies, and use newly created words but do not know the traditional words. Consumers living in Tokyo metropolitan areas seemed to have a larger food texture vocabulary than consumers in the Kyoto–Osaka–Kobe area. Several factors such as eating experience, food boom, popular expressions, and dialect might be responsible for the observed differences.

Matsumoto and Matsumoto (1977) carried out a similar test choosing 16 common foods, typical and traditional Japanese foods, cooked rice, *kuromame* (a black soybean, rich in anthocyanin, and boiled with sugar), *kuri-kinton* (chestnut cooked with sugar), *neriyoukan* (sweet red bean paste gelled with agar and sucrose), *mizuyoukan* (sweet red bean paste gelled with agar and sucrose with a higher water content), *kofukiimo* (boiled potatoes), *dango* (dumpling), *sake* (rice wine), *nukamisozuke* of eggplant (immersed in salted rice bran), boiled spinach, egg curd with a similar hardness of soft *tofu* (soy bean curd), and also including Western foods such as beefsteak, potage soup, orange juice, cookies, carrot glacé. They classified the attributes into taste, aroma, appearance (shape color and luster/gloss), texture, and temperature, and then categorized the results as chemical attributes (taste and aroma) and physical attributes (appearance, texture, and temperature). They compared the contribution ratio of physical and chemical factors to palatability, and omitted temperature. Foods of which the contribution of chemical factor exceeds 50% are orange juice, *sake*, and *nukamisozuke* of eggplant and physical factors are rated more important for other foods. It was found that physical properties played a major role in determining the palatability in solid foods while chemical attributes such as taste and aroma were more important in liquid foods (Matsumoto & Matsumoto, 1977). A chemical factor was rated important for beefsteak and *nukamisozuke* of eggplant although they are solid foods because they have strong characteristic flavors. Nishinari (2004) interpreted their results raising three reasons: (a) texture change is much more conspicuous in solid foods than in liquid foods before and after the mastication, (b) the human sensory organ is more sensitive for changes in the elasticity than in viscosity, (c) liquid foods are usually swallowed immediately.

Further efforts using word associations to establish texture term lexicons have continued; notably to obtain a systematic and comprehensive glossary of texture terms (Jowitt, 1974), in making a polyglot list of texture terms collecting 22 different languages (Drake, 1989), in the comparison of English and German (Rohm, 1990), Finnish and English (Lawless, Vanne, Tuorila, 1997), in the comparative study of texture terms in four languages, English, French, Japanese, and Chinese (Nishinari et al., 2008) and a recent revisiting of Japanese texture terms by Hayakawa (2015).

Hayakawa et al. (2007) continue to analyze the structural characteristics of Japanese texture terms. She points out that the number of foods recalled from the texture terms is smaller than the number of texture terms recalled from the name of foods, which is in accordance with Yoshikawa’s previous observation (Yoshikawa, Yamazaki, Yamazaki, & Ikukawa, 1965). She raises some examples: tofu, sponge cake, porridge, bread were recalled from the texture term “soft,” but peach, kiwi-fruit, beef were not recalled although the quality “soft” or “tender” are important textural characteristics for these foods; they are not the symbolic foods representing softness.

2.3 | Ambiguity of languages and the necessity of lexicon

As noticed by Bourne (2002, p. 5), the most frequently used texture term in Japan is “hard” although “crisp” is more frequently used in United States and in Europe. In the Japanese language, more than three different ideograms 硬, 固, and 堅 (Chinese origin) are widely used to represent hardness or firmness or toughness although the general public uses these letters without distinguishing so strictly. Some scholars specialized in Chinese letters would make distinctions between these three letters but very few ordinary people would not. Most teachers of Japanese language do not teach the rigorous difference among these three letters in primary and secondary schools. Peleg (2006) poses a similar question about the ambiguity of the texture term: “Is a ‘firm peach’ softer than a ‘hard peach’?” In English, the opposite of both “firm” and “hard” is soft! Whether, such terms have exactly the same meaning in different languages is of course another issue altogether.

Apart from the linguistic problem, the distinction is actually not so clear in food science and technology although in some mechanical engineering schools, they distinguish between firmness and toughness. When we compare the force–deformation curves of a 4.4% agar gel and a 25% gelatin gel shown in Figure 1, it is clear that the Young’s modulus determined from the initial slope is larger for the agar gel, but the fracture stress is larger for the gelatin gel. Since at this compression speed, the volume change of gels could be neglected and thus the Poison’s ratio could be assumed as 0.5, and the true stress could be estimated by dividing the force by the cross sectional area at each instant. Thus, not only the fracture force but also the fracture stress is found larger for gelatin gels.

Most Japanese people may have no definite choice of one letter from the three ideograms 硬, 固, and 堅 when they think about the Young’s modulus or fracture stress. When we compare the hardness or firmness or toughness of agar gels with different concentrations, we do not encounter such a problem, but when we compare different types

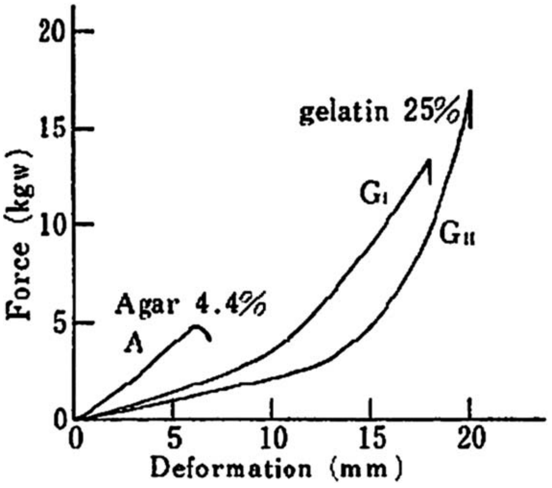


FIGURE 1 Force–deformation curves for uniaxial compression of 4.4% agar gels and 25% gelatin gels. Cylindrical gels with 20 mm diameter and 30 mm height were compressed at 10 mm/min. The curves GI and GII for gelatin gels were obtained with approximately equal probability. Measurement temperature: 15C (Nishinari et al., 1980)

of food gels, deformable gels, and brittle gels, this problem always arises.

Another difficult problem is that most food solids are not an ideal Hookean elastic body nor a purely Newtonian liquid, but viscoelastic materials and therefore the measurement of time scale plays an important role as is described in standard textbooks of rheology. Let us remind here an example of a problem which, a father of psychorheology and a mentor for Szczesniak and Bourne, Scott Blair (1947) reflected on. In the comparison of the "firmness" of materials, time plays an important role. In sensory assessment, the firmness of a material may be judged by its strain, and material showing a smaller strain may be judged firmer. When the firmness of a purely elastic material **E** and a purely viscous material **V** is compared under a step-like constant stress, the strain of **E** occurs instantaneously and keeps the same constant value while that of **V** increases at a constant rate proportional to the stress (Figure 2). Therefore, when the time at which a subject makes a judgement is shorter than the time t_c at which **E** and **V** show the same strain, the subject will judge that **V** is firmer than **E** because the strain of **V** is smaller. If the time of the judgement is longer, the opposite judgement will be done.

When we ask panelists how firm or hard a food is, we implicitly assume that they will chew at their normal and habitual speed. But as is shown in Figure 2, the order of the firmness might depend on the biting speed. In addition to this, it is well known that the viscosity of non-Newtonian liquids decreases with increasing shear rate in most cases (shear thinning), but some fluids show the opposite behavior (shear thickening). Sherman's group studied it and the followers continue to study this problem, which is also one of the most important problems in texture studies in food science (Nishinari, 2015a; Nishinari, Takemasa, et al., 2016), but will not be discussed in detail in the present paper. The problem of compression/biting speed will be discussed later in Section 3.4.

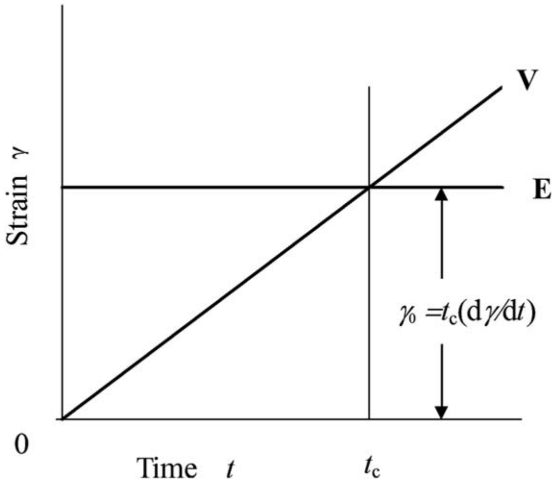


FIGURE 2 Comparison of the firmness of a purely elastic material E and a purely viscous material V. Strains of both materials under a constant stress show the same value at a time tc

3 | TEXTURAL PROFILE ANALYSIS: CLASSIFICATION OF TEXTURAL CHARACTERISTICS

3.1 | Texture profile of Szczesniak and Bourne

As applied to the evaluation of food attributes, "profiling" could be defined as the act of describing applicable food characteristics through testing according to a predetermined set of references. The term was first used with the method of flavor characterization. As is widely accepted, texture cannot be defined by one simple characteristic but should be described by a composite of multiple characteristics (Szczesniak, 1975b).

Szczesniak tried to rationalize the definition of texture, criticizing the inconsistency or the limitation of the definition to a certain specific food and not generalized, and proposed the classification of textural characteristics into three main classes (Table 1) (Szczesniak, 1963a, 1963b, 2002);

1. Mechanical characteristics,
2. Geometrical characteristics,
3. Other characteristics (referring mainly to moisture and fat content of the food).

She divided mechanical characteristics into five basic parameters which she called primary parameters:

A Hardness, defined as the force necessary to attain a given deformation.

B Cohesiveness, defined as the strength of the internal bonds making up the body of the product.

C Viscosity, defined as the rate of flow per unit force.

D Springiness (First it was called Elasticity), defined as the rate at which a deformed material goes back to its undeformed condition after the deforming force is removed.

TABLE 1 Classification of textural characteristics (Szczesniak, revised in 2002 based on 1963)

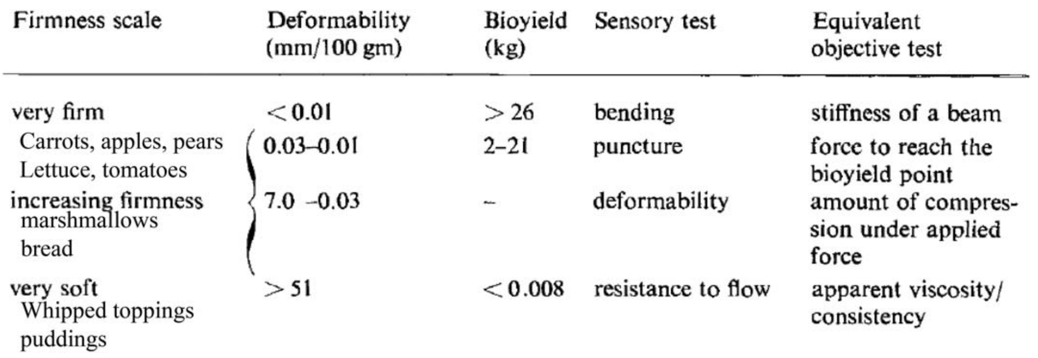
Mechanical characteristics Primary parameters	Secondary parameters	Popular terms
Hardness		Soft → Firm → Hard
Cohesiveness	Brittleness	Crumbly → Crunchy
	Chewiness	→ Brittle
	Gumminess	Short → Mealy
		→ Pasty → Gummy
Viscosity		Thin → Viscous
Springiness		Plastic → Elastic
Adhesiveness		Sticky → Tacky → Gooey
Geometrical characteristics		
Class		Examples
Particle size and shape		Gritty, Grainy, Coarse
Particle shape and orientation		Fibrous, Cellular, Crystalline
Other characteristics		
Primary parameters	Secondary parameters	Popular terms
Moisture Content		Dry → Moist → Wet → Watery
Fat Content	Oiliness	Oily
	Greasiness	Greasy

Brittleness proposed in 1963 was replaced later by fracturability, springiness took over elasticity used in 1963. See also Bourne (1978)

E Adhesiveness, defined as the work necessary to overcome the attractive forces between the surface of the food and the surface of other materials with which the food comes in contact (e.g., tongue, teeth, palate, etc.)

The definitions of elasticity and viscosity are slightly different from those in standard textbooks of physics probably because Szczesniak tried to make these definitions more accessible to individuals accustomed to popular terminology. However, it may be difficult to go ahead without understanding the basic definition of elasticity defined based on the ideal Hookean body which shows the proportionality between the stress and strain and the instantaneous restoring to the initial state after removal of the stress. Szczesniak and Bourne (1969), in their paper "Sensory evaluation of food firmness" stated that the term "viscosity" that they used in their paper was intended in a broad rather than in a well-defined rheological sense. It refers to the general resistance to flow. Although the intention of these authors to bridge the gap between the popular terms and scientific terms is precious, physicists may not be able to agree with the usage of the same word in such a different meaning. An important conclusion of Szczesniak and Bourne (1969) is that the method of objective measurement depends on the firmness of food samples, and the observation of consistency, deformation, puncture, and flexure are suitable as the degree of "firmness" increased from a low (whipped toppings) to a very high (carrots) level shown in Table 2. In this paper, nine different pairs of foods (whipped toppings, milk puddings, marshmallows, tomatoes, bread, lettuce, pears, apples, and carrots) were presented to 131 people, who were asked to determine by nonoral methods which sample in the pair was more firm. With soft foods, firmness was generally determined by means of some kind of viscosity test (e.g., resistance to stirring with a spoon). A deformation test was used on foods of intermediate firmness. Foods with high firmness were tested by a puncture technique, and foods of very high firmness were tested by bending (flexure).

TABLE 2 Suggested objective tests corresponding to sensory firmness tests found most applicable to the situation (Szczesniak and Bourne, 1969)



Firmness scale	Deformability (mm/100 gm)	Bioyield (kg)	Sensory test	Equivalent objective test
very firm	< 0.01	> 26	bending	stiffness of a beam
Carrots, apples, pears Lettuce, tomatoes	0.03–0.01	2–21	puncture	force to reach the bioyield point
increasing firmness marshmallows bread	7.0 –0.03	–	deformability	amount of compression under applied force
very soft Whipped toppings puddings	> 51	< 0.008	resistance to flow	apparent viscosity/ consistency

The different understanding of the concept of hardness in physical science and in physiological/psychological science should be noticed. In the former discipline, the hardness of metals or solid plastics or any other soft matters are usually defined by the fracture stress or indentation hardness (a harder material shows a smaller indentation depth) or scratch hardness (a harder material scratches a softer material). These definitions can compare and quantify the hardness of the material irrespective of the size and shape, and thus it is represented by the strength. The strength is represented not by the force but by the stress and can be measured objectively and quantitatively by instruments. However, the hardness perceived in the food oral processing depends strongly on the size and shape of the food material. The hardness defined in the instrumental TPA is thus represented by the force and not by the stress. This is suitable for food materials with different sizes and shapes. For example, when the hardness of peanuts, beans, peas, berries, jujubes, and so on is examined, these foods are in most studies subjected to a uniaxial compression. Unfortunately, the size and shape are not necessarily always reported together with the force required for the fracture. Therefore, the reported hardness value cannot be unfortunately compared with other reported values. Some researchers may advise to cut out a well-defined shape from these foods to obtain a well-defined mechanical parameters such as elastic modulus or fracture stress which can be represented by SI unit, N/m^2 or Pa., or for the oral organs, the cross-sectional area of a canine or a molar can be measured although these values may show a wide distribution among individuals. Users of TPA parameters must not forget these limitations.

Material scientists should recognize that the hardness in the texture studies is a perceived physical quantity. This term "perceive physical quantity" may be easier for material scientists to accept than the term "sensory property" proposed by Szczesniak. The hardness is the perceived force required to make a crack or a fracture in the ingested food in the mouth, and therefore, the first bite is the most closely related to the hardness, but the hardness perception continues during the subsequent mastication process. Therefore, it is important to admit that the hardness in the texture studies is represented by the force (N in SI unit) and not by the stress, the force normalized by the cross sectional area. When a solid food is very soft, it is not bitten by teeth, but crushed between the tongue and the hard palate, and in this situation also the hardness is perceived as the force and not the stress required for the yield (for plastic foods such as butter, paste, or mashed potatoes) or the fracture (for elastic foods such as polysaccharide or protein gels). In all these texture perception, both the shape and size are equally important as the force because the force depends on both shape and size.

Szczesniak identified three secondary parameters, brittleness, chewiness, and gumminess, relating especially to the primary parameter cohesiveness, to make the characterization as meaningful as possible to individuals accustomed to popular terminology, while at the same time keeping it in agreement with basic rheological principles.

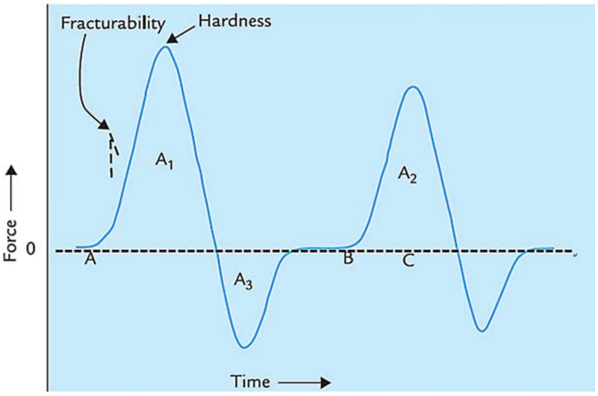


FIGURE 3 A typical texturometer curve, force versus time, consisting of compression- decompression curves. Cohesiveness = A_2/A_1, adhesiveness = A_3 (Bourne, 1978, 2002; Szczesniak, 1963)

B-1. *Fracturability (originally called Brittleness). defined as the force with which the material fractures. It is related to the primary parameters of hardness and cohesiveness. In brittle materials, cohesiveness is low and hardness can vary from low to high. Brittle materials, especially when possessing a substantial degree of hardness, often produce sound effects on mastication (e.g., celery, toasted bread).* Note that the word "brittleness" in the secondary parameters in 1963 was changed into "fracturability" in Civille and Szczesniak (1973) and in Szczesniak (2002). Bourne (1978) defined the fracturability as the force at the first significant break in the TPA curve shown in Figures 3 and 4.

B-2. *Chewiness, defined as the energy required to masticate a solid food product to a state ready for swallowing. It is related to the primary parameters of hardness, cohesiveness, and elasticity.*

B-3. *Gumminess, defined as the energy required to disintegrate a semi-solid food product to a state ready for swallowing. It is related to the primary parameters of hardness and cohesiveness. With semi-solid food products, hardness is low.*

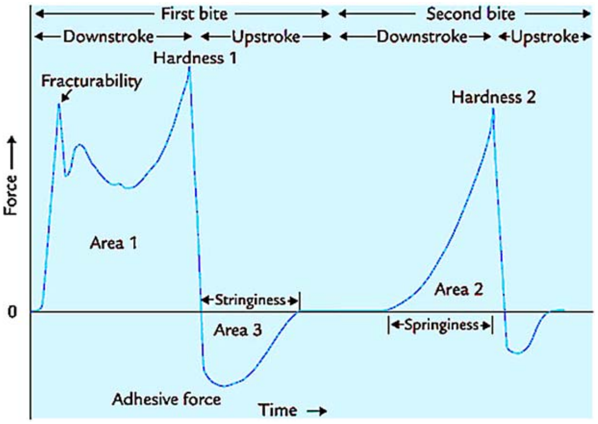


FIGURE 4 Generalized TPA curve, by an Instron type machine. The test consists of two complete compression- decompression cycles (Bourne, 1978, 2002)

Since it is necessary to correlate the sensory evaluation with instrumental measurement, and to train the sensory panel, the correspondence between the physical definition and the sensory perception should be established. It could be seen that she tried hard to choose suitable terms to bridge the rigorously defined terms used in physics and the terms used by laymen in daily conversation, which was very important to develop the texture study of common foods. However, KN now regrets that he did not have the opportunity to discuss with her, for example, the definition of brittleness. We think that brittleness should be defined by the smallness of the deformation (or strain) because hardness can vary from hard to low as she writes. Examples, celery, toasted bread, she has given show a fracture at a small strain irrespective of the magnitude of the force. These foods are called brittle probably because they fracture at small deformation and not by a small force (Szczesniak, 1975a, 1975b).

It is a pity to see that some papers published after 1975 without seeing this change and use the brittleness in an original version proposed in 1963. In her most recent revision of the classification of textural characteristics (Szczesniak, 2002), the physical meaning of the fracturability which replaced brittleness was written as the force with which a material fractures: A product of high degree of hardness and low degree of cohesiveness and the corresponding sensory explanation was force with which a sample crumbles, cracks, or shatters. Again, we think that the fracturability cannot be defined so definitely by the force or by the deformation. Let us take an example of a raw carrot and a carrot stored in a refrigerator for one week. As was shown clearly by a tensile test of a dog-bone shaped carrot (Thiel & Donald, 1998), the textural difference in two carrots appeared in the failure strain or the elastic modulus in the smaller strain because the failure stress showed almost the same value. However, Szczesniak might have thought that it was the force and not the deformation humans perceive to evaluate the fracturability. In this case, how to unify the physical definition and sensory definition seems to be difficult.

3.2 | Texture profile of Sherman

Sherman (1969) thought that the texture profile (Figure 5) should be based on well-defined physical concepts because, as mentioned above, some texture terms used in the texture profile proposed by Szczesniak were confusing since these terms were different from the concept of elasticity and viscosity established in physics and he criticized the texture profile of Szczesniak and proposed another texture profile.

Sherman thought that the only criterion for the new classification is whether a characteristic is a fundamental property, or whether it is derived by a combination of two, or more, attributes in unknown proportions. Thus, Sherman introduced the properties previously labeled geometric and analytical characteristics by Szczesniak into the primary category. From the viewpoint of Sherman that all the properties should be related with microscopic and macroscopic structure, all other attributes should then be derived from these geometric and analytical characteristics. In Sherman's texture profile, primary attributes were analytical composition, particle size and size distribution, particle shape, air content, air cell size, and its distribution, and so on. He classified the basic rheological parameters, elasticity, viscosity and adhesion, as the secondary category, and the remaining attributes as a tertiary category, since they are a complex mixture of these secondary parameters. Sherman's idea was based on the concept of Scott Blair who is considered the father of food rheology (Bourne, 2002, p. 29). According to Scott Blair (1947), firmness ψ can be written as a function of shear stress S, shear strain σ, and the time t for a viscous fluid $\psi = \eta = S\ \sigma^{-1}\ t^{1} = ML^{-1}T^{-1}$, ($\eta$ represents the viscosity) and for an elastic solid $\psi = E = S\ \sigma^{-1}\ t^{0} = ML^{-1}T^{-2}$ (E represents the elastic modulus) and

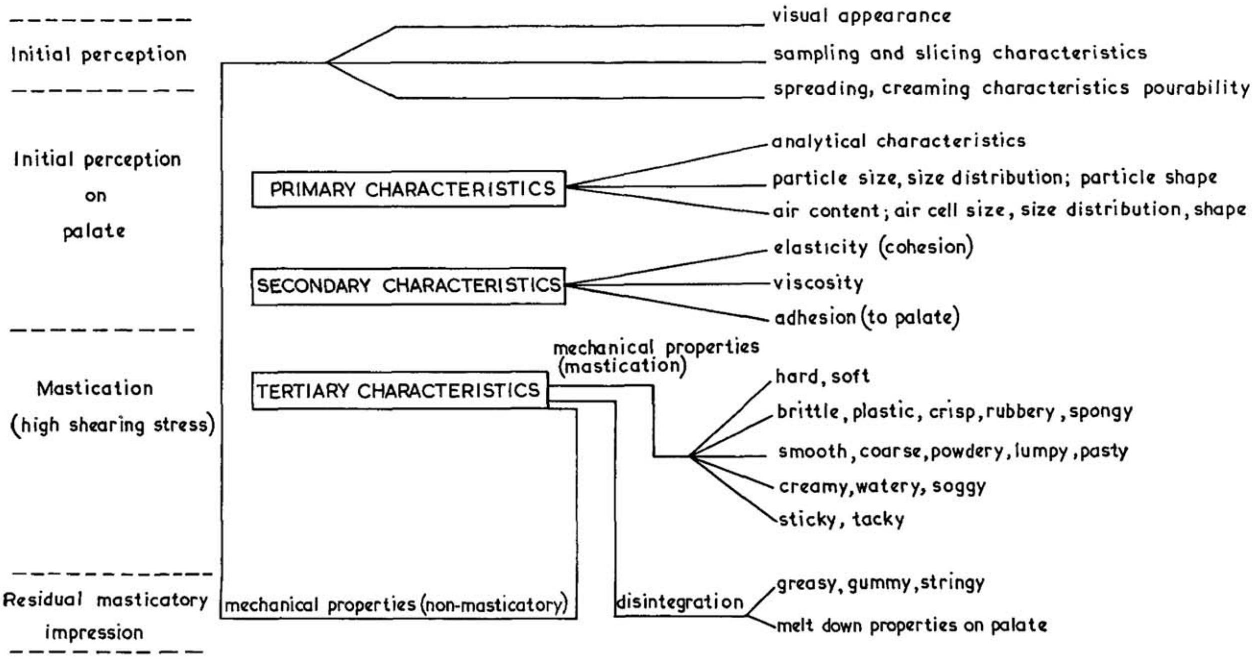


FIGURE 5 Sherman's texture profile (Sherman, 1969)

generally for an intermediate between these two extremes $\psi = S\ \sigma^{-1} t^{k} = \mathrm{ML}^{-l}\mathrm{T}^{k\ -\ 2}$, where the exponent k, the "dissipation coefficient," has a value of 1 for viscous fluids and a value of 0 for elastic solid. Materials that fall between these two categories show fractional values of k. In this way, it is possible to define textural characteristics by a limited number of physical terms.

Sherman (1969) introduced "adhesion *N*" as the secondary characteristic, and since each tertiary textural characteristic is a complex mixture of two or three secondary characteristics, it can be represented in three dimensional space of E, η, and N as a point (αE, $\beta\eta$, γN), where α, β, and γ define the location of the attribute with respect to the three coordinate axes, and represent the respective magnitudes of the three secondary attributes. Both α and β decrease when the material changes from a hard solid to a semisolid and then to a fluid, while γ varies with the degree of stickiness.

3.3 | TPA by instrumental compression

Although instrumental compression is used to understand food texture it does not incorporate the somatic sensory system in the oral cavity consisting of mechanoreceptors, thermoreceptors, nociceptors, proprioceptors, periodontal receptors, and so on (Engelen & van der Bilt, 2008). The most important reason why the instrumental measurement cannot be correlated well may be the absence of receptors and saliva and flavor (see Section 4.5) in the classical instrumental measurement (Peyron & Woda, 2016; Salles et al., 2010). Even in the mechanics, the complex manipulation of foods in oral processing is not a simple compression but mixed mode of compression and shear. Some of these aspects have been recently incorporated in various simulating masticators.

It is obvious that we should take into account the temperature effect for foods of which the rheological properties are sensitive to temperature change such as butter or thermoreversible gels when the sensory evaluation and the instrumental measurements are compared.

Szczesniak (1975a, 1975b, 1987) has reported the TPA by controlling temperature to study the temperature sensitive foods such as whipped cream and gels of gelatin and iota- and kappa-carrageenans.

Bourne worked out the effect of temperature on the texture, viscosity, puncture force, yield stress of various foods including fruits and vegetables (Bourne, 2002, pp. 310, 347) and advised that the test temperature should be controlled for most fruits and vegetables but more rigorous control is required for liquids and temperature-sensitive foods such as butter and margarine.

Recently, the importance of taking into account the temperature effect has been reiterated in the extrusion test where a series of gels including gelatin with wide range of texture was examined (Brenner, Tomczynska-Mleko, Mleko, & Nishinari, 2017). This will be discussed later again.

In addition to the effect of temperature on physicochemical properties of foods, different responses of thermoreceptors to the temperature change should be taken into account in the texture study. There are two types of thermoreceptors in the skin: cold (range: 20–40C) and warm (range: 30–48C) receptors (Engelen & van der Bilt, 2008; Goldstein, 1996). Cold and warm receptors are known to stop firing altogether as the temperature extends into the noxious range (below 5C and above 50C) (Gardner et al., 2000). At these stimulus temperatures, humans perceive freeze and heat pain rather than sensations of cold and warmth. Engelen and van der Bilt (2008) examined the effect of product and oral temperatures on the texture of custard dessert and mayonnaise controlling the oral temperature by rinses at different temperatures, and found that a high oral temperature increased melting and heterogeneity sensation probably because of enhanced enzymatic action in addition to the viscosity decrease. They found that this temperature effect was larger in custard dessert than in mayonnaise. They also pointed out that flavor intensities and fat after feel also increased with increasing temperature which should also influence the texture indirectly.

Instrumental methods for texture measurements have been divided into three classes (Bourne, 1978, 2002; Scott-Blair, 1958; Szczesniak, 1963a, 1963b):

Fundamental tests measure properties that are familiar to engineers, for example, ultimate strength, Poisson's ratio, elastic moduli, which can be compared with other materials. However, the correlation between sensory evaluation is poor as Bourne commented. He attributed this poor correlation to the material science aiming the strong materials used in utensils, cars, building, and so on, while foods should be smashed into thousands of little pieces in oral cavity. In addition to this, the deformation and flow are very complex in the oral cavity which are generally the mixed mode of compression, shear, extension including large deformation, and non-Newtonian fluid mechanics, which are not well understood.

Empirical tests cover a miscellany of tests such as puncture, shear, extrusion, and the like that, although poorly defined, have been found to be correlated with texture perception.

Imitative tests are tests that attempt to imitate with instruments the conditions to which the food is subjected in the mouth or on the palate. It is in this area that TPA falls.

In parallel with the fundamental approach to the notion of textural characteristics, the instrumental method to quantify the texture profile parameters was proposed (Friedman et al., 1963). This so-called General Food texturometer was used widely especially in the early stage of texture studies until 1970s in Japan where texture studies flourished because of the wide varieties of texture in Japanese foods. Other similar apparatuses have also been used. A typical texturometer curve (called TPA curve) is shown in Figure 3.

Hardness is defined as the peak height of the first chew when the plunger is pushed down. When the plunger is raised from the sample, it is pulled back by the sample, and therefore, the force exerting the plunger is opposite (negative) to the force when the plunger is pushed down. Adhesiveness is defined as the area, in arbitrary instrumental units, A_3, of the negative peak beneath the base line of the profile, and represents the work necessary to pull the plunger from the sample. Cohesiveness is defined as a ratio of the area, in arbitrary units, under the second peak and the area under the first peak A_2/A_1 in Figure 3.

As noted by Breene (1975), Bourne was the first to use an Instron type machine to obtain a TPA. His paper on TPA of ripening pears

(Bourne, 1968) has been cited by almost all subsequent workers as the basic method for the Instron TPA (Figure 4). Bourne contended that the Instron is a better tool for determining TPA parameters than the Texturometer for several reasons. In contrast to the GF Texturometer, the speed of Instron compression is constant at all times during the downstroke. This and the immediate reversal of the compression stroke at the end of the "first bite" results in sharp peaks in the curves (Figure 4).

Since the compression speed of an Instron type machine is constant, the TPA curve can be regarded as force–deformation curve instead of force–time curve obtained by a GF Texturometer. Therefore, the area enclosed by a curve and the abscissa represents the work. The Texturometer has been widely used in Japan for more than 10 years, and then uniaxial compression by Instron-type material test machines have prevailed. TPA curves are surely convenient and easy to obtain, giving useful information for improving the recipes or cooking procedures in the food industry. Corey and Finney (1970) and Breene (1975) reviewed the 10 years progress of texture studies using TPA. Tanaka (1975) reviewed the texture studies in Japan. Pons and Fiszman (1996) published a comprehensive review on the TPA mainly paying attention to food gels. They discussed the effects of testing conditions such as sample size, and shape, size of compression unit versus sample, extent of deformation, cross-head speed, time elapsed between bites, lubrication between the sample and plunger, and further the physical meaning of TPA parameters.

Let us take another example. Kohyama, Nakayama, Fukuda, Dan, and Sasaki (2003) performed electromyography (EMG) of the masseter muscles of healthy adults while masticating 7 g of cucumber for a pile of thinly sliced samples (ca. 1 mm) and a thicker slice (10 mm). They found that a pile of thinly sliced samples required more mastication than a single 10 mm slice, as indicated by a greater number of chews (33.5 versus 30.2), longer mastication time (22.2 versus 19.8 s), and higher EMG activity (1.94 versus 1.64 mVs). This suggested that a pile of thinly sliced cucumber required more effort than a 10 mm slice for mastication of the same weight. The cause of this observation may be speculated as follows: when the incisor and molar teeth try to penetrate into sliced cucumber, the slippage between slices might occur even when teeth movement is almost vertical to the slices so that the teeth could not penetrate effectively into the cucumber slices.

Kohyama, Nakayama, Watanabe, and Sasaki (2005) compared the EMG variables for grated apple, thinly sliced apple and cubic apple, and found that number of chews and mastication time decreased about one third for grated apple, and EMG activity also decreased. However, no difference was found for number of chews and muscle activity between sliced apple and cubic apple in the whole processing. This tendency is opposite to the finding for cucumbers. For apples, sliced samples needed shorter duration and smaller muscle activity. The difference was found only for the first five chewing strokes, which is reasonable because the sample size was reduced by chewing, and the initial piece size does not affect the bolus state after the first several chews. They found statistical significance in the EMG duration (0.341 s for sliced and 0.378 s for a cube, $p < .01$) and cycle time (0.685 and 0.725 s, $p < .05$) of the first five chewing strokes. Kohyama et al. (2005) attributed the difference between apple and cucumber to the slightly larger value for hardness for apple than for cucumber. Citing Bourne's argument (Bourne, 1977) that beyond the limit of comfortable power output, the power remains approximately constant, and chewing rate slows down as toughness increases, Kohyama et al. (2005) stated that the subjects reduced their contraction speed for large pieces of raw apples and because raw apple is hard to crush within the limit of power output. However, another possible cause for the difference in apple and cucumber may be speculated. This may be caused by the different frictions between sliced cucumbers and sliced apples. While slippage may occur between sliced cucumbers, it may be negligible between sliced apples.

In the comparison of mastication behavior for sliced food and block food, Kohyama et al. (2007) found that number of chews, masticatory time, EMG muscle activity were greater in sliced samples than in block samples for hard foods such as raw fruits, vegetables, and nuts, having a high Young's modulus and a high fracture stress but not a high fracture strain. In contrast, they found the opposite tendency, that is, number of chews and EMG muscle activity decrease by slicing roast pork and *surimi* gel which are soft and tough type foods, and fracture with a low stress at a high strain. They stated by preliminary test that some other soft foods such as chicken meat ball and fish mousse showed a similar tendency as pork and *surimi* gels. The important finding here is that cutting foods into smaller pieces does not necessarily reduce the effort of mastication, the number of chews and EMG activities when the quantity of the intake (mass) is kept constant.

It is expected that TPA parameters will still be used because TPA measurements are easy but it is necessary not to forget that it is an imitative test, and the parameters obtained could be affected by measuring conditions. Rosenthal (2010) stated "From the literature, it is clear that some researchers report TPA parameters in their papers as if the results are absolute and comparable directly with others. ...comparisons between TPA results are only likely to be valid if identical test protocols including test geometry, speed of compression, percentage compression are all kept constant." More critical discussion on TPA parameters is given in Sections 3.4–3.7.

3.4 | Hutchings and Lillford model and Hiiemae and Palmer model

Sherman's TPA was graphically simplified as a mouth process model by Hutchings and Lillford (1988) who represented a food trajectory in three dimensional space, structure (z-axis), time (x-axis), and lubrication (y-axis) (see Lillford's paper in this issue). According to this model, solid food should be comminuted into smaller fragments and mixed with saliva to be lubricated and forms a bolus before swallowing.

Prinz and Lucas (1997) examined the mastication of foods and the formation of a bolus introducing a breakage function to represent the size distribution of broken solid food and the probability to be selected for further chewing. Broken food particles are lubricated by saliva and made into a cohesive bolus in the pharynx. Accordingly, they suggested that the resulting bolus has optimized particle size and cohesiveness for swallowing. A cohesive bolus that sticks together without falling apart is suitable for swallowing. They also suggested that if swallowing is delayed, excessive saliva can flood the bolus, separating particles, and reducing cohesion.

Hiiemae and Palmer (1999) emphasized the importance of the coordination of mastication and swallowing based on the critical examination of the four stage model (oral preparatory, oral propulsive, pharyngeal, and esophageal) used for the analysis of liquid swallowing which has been deduced by analyzing the swallow commanded by the experimenter. In the four stages model, it was hypothesized that these stages are sequential, and that bolus propulsion to the pharynx normally did not occur until the time of swallow onset. Hiiemae and Palmer (1999) proposed a new mouth process model for bolus formation and deglutition based on the videofluolographic (VF) observation of movements of barium-sulfate-coated foods (8 g chicken spread, banana, hard cookie) and in combination with electromyographic observation (Palmer, Rudin, Lara, & Crompton, 1992). They elaborated the temporal aspect as a process model for feeding where after ingestion, food is transported through Stages 1 and 2 before arriving at the judgement of threshold for swallowing. In each stage, the signal feedback determines whether the food is transported to the next stage or not, and in some cases such as the processing of apple with peel swallowing partially occurs after each stage before the final swallowing (Hiiemae, 2004). They tracked the jaw movement by a sirognathographic observation.[1]

Hiiemae and Palmer (1999) could analyze the barium-infused food movement and also the tongue movement by radiopaque markers in the oral cavity detected by VF. However, the quantitative analysis of tongue movement was technically irreconcilable with documentation of food position and movement because the addition of barium to the food obscures the position of markers on the tongue surface. VF recording is also constrained by restricting to 5 min per lifetime per subject. The duration of foods in different stages is shown in Figure 6b, c for a variety of foods.

The duration of each stage in the oral processing sequence was analyzed by Hiiemae and Palmer (1999) as follows (see Figure 6a):

Stage I transport: The time the food crossed the incisors (start maximum gape) until hard foods (the first tooth–food–tooth contact occurred, determined visually and from rate changes in the jaw movement profile) or soft foods was disrupted.[2]

Processing: From the end of Stage I until the initiation of Stage II transport in which food is broken down by chewing, processed by the tongue acting against the hard palate, or both.

Stage II transport: defined as beginning at the time food was clearly detected distal to the fauces, that is, between the soft palate and the pharyngeal surface of the tongue. It is important to reemphasize that processing and Stage II can occur concurrently, that is, food is processed as triturated food accumulates to form a bolus.

HTT: Hypopharyngeal transit time, that is, the time elapsed from the moment the leading edge of the bolus leaves the valleculae to the time the trailing edge enters the esophagus. HHT1 refers to HHT of the first swallow, and HHT2 refers to HHT of the second swallow. The second subsequence began immediately after the first swallow; the second swallow occurred at the end of the second subsequence. This definition of HTT1 and HTT2 was not described in Hiiemae and Palmer (1999), but now given by Palmer. Authors would like to thank him for the clarification.

The duration of each stage in the oral processing of four foods with different textures, chicken spread, banana, cookie, and peanuts is shown in Figure 6c. As can be seen clearly, the duration for Stage 1, HTT1 and HTT2 were not so different for soft foods (banana and chicken spread) and for hard foods (cookie and peanuts) although total sequence durations differed with food type, with peanuts and cookie being significantly longer ($p < .0001$) than banana or chicken spread. The hardness of foods influenced strongly on the duration for Processing and OPAT; harder foods show longer duration.

The important finding of Hiiemae and Palmer (1999) is that triturated food is accumulated on the pharyngeal surface of the tongue for a considerable percentage of the total time from the beginning of the oral processing to the initiation of the first HTT (HTT1) for a bolus. Matsuo and Palmer (2009) noted that oral preparatory phase (food processing) and oral propulsive phase (Stage II transport and bolus aggregation) can overlap in time. After a variable period of elapsed time, the pharyngeal bolus is swallowed. As shown in Figure 6c, both the time HTT1 and HTT2 are not so different for four foods with different textures, which may suggest that the bolus that is ready to enter the esophagus have similar textures. It means that the initial textural differences are obliterated just before the swallowing. The influence of food texture on mastication behavior should be further studied taking into account the intraindividual variation.

Based on the VF observation of oral processing of barium-infused solid foods (banana and chicken spread, cookie, and peanuts) by healthy subjects sitting upright and quadruped (facedown), Palmer (1998) found that transport of chewed solid food from the oral cavity to the pharynx was driven actively by tongue-palate contact and did not depend on gravity. A bolus was thought to be accumulated in the valleculae for several seconds before the swallow. Saitoh et al. (2007) using foods with a broader range of textures; liquid barium, corned beef hash with barium, shortbread cookie with barium, and a two-phase mixture of liquid barium and corned beef hash. They found that the movement of liquid into the hypopharynx before swallowing was dramatically reduced by placing subjects in the facedown position, and suggested that transport to the hypopharynx was largely caused by gravity. They confirmed again that chewed solid food is propelled to the pharynx by an active process driven by action of the tongue pressing against the palate (Hiiemae & Palmer, 1999; Palmer, Rudin, Lara, & Crompton, 1992). The findings of Saitoh et al. (2007) that the leading edge of the barium for chewed solid food (barium-infused cornbeef or shortbread cookie) was usually in the oropharynx (either in the upper oropharynx or valleculae) at the time of swallow onset and was not altered by facedown position were in good agreement with the

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[1] Methods of tracking jaw movement have been reviewed and still many new methods are being proposed (He et al., 2016).

[2] Tooth–food–tooth contact: The moment during jaw closing when the food positioned on the occlusal surfaces of the lower teeth first makes contact with the occlusal surfaces of the upper teeth as the jaws close.

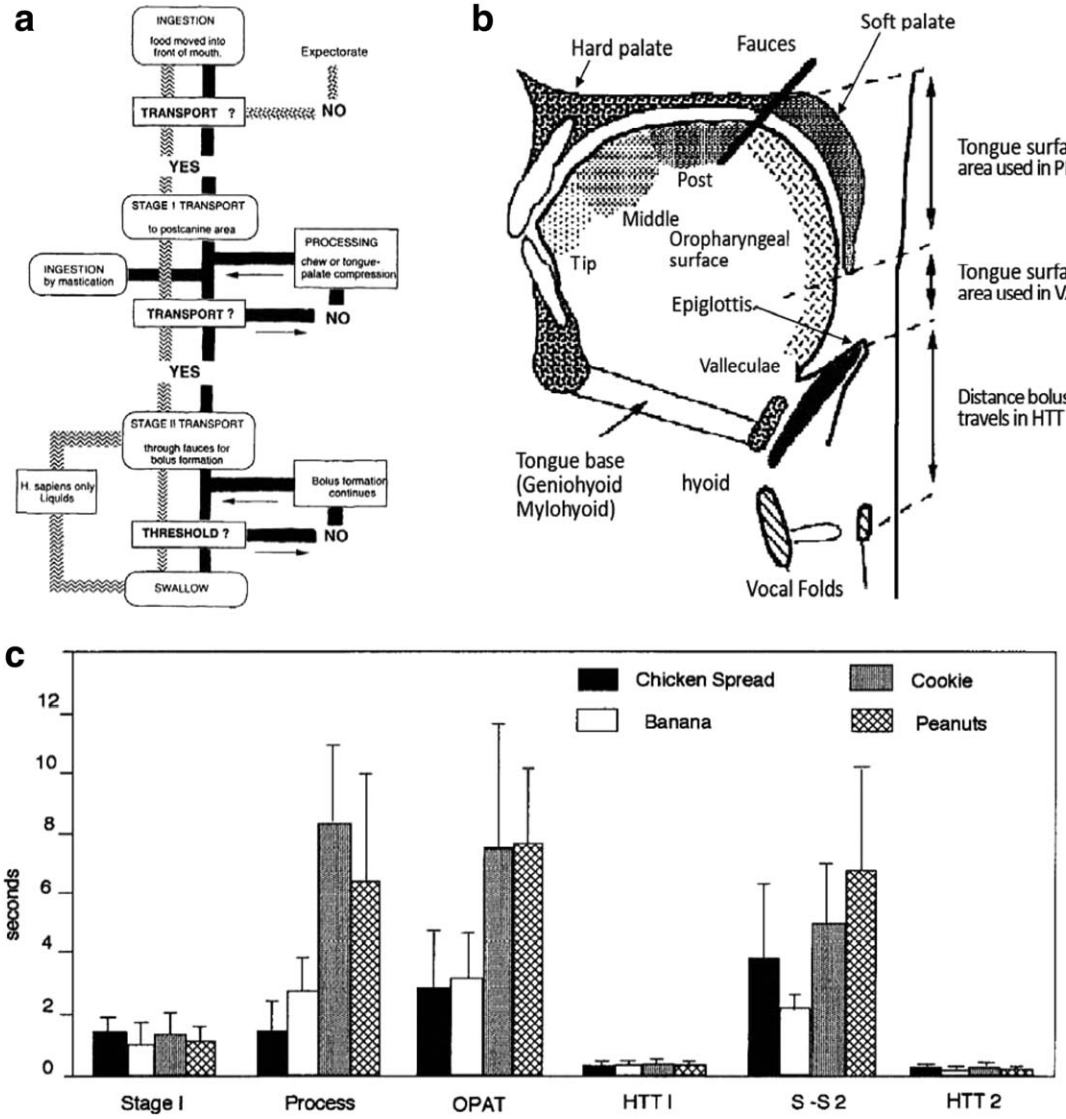

FIGURE 6 (a) Oral processing model (Hiiemae, 2004); (b) Diagrammatic mid-line sagittal section through the oral cavity and oropharynx. The pharyngeal surface of the tongue is that part of the tongue facing either the soft palate or, below the uvula, the oropharynx. HTT, hypopharyngeal transit time; PFAT, postfaucial aggregation time; VAT, vallecular aggregation time (Hiiemae & Palmer, 1999); (c) The duration (mean ± *SD*) for each component of the feeding sequence for all subjects and each food. Initial food consistency affects the duration of processing (process), Stage II transport with processing (oropharyngeal aggregation time; OPAT) and the second subsequence (S-S2) but with neither Stage I transport nor the duration of hypopharyngeal transit time. HHT1 refers to HHT of the first swallow, and HHT2 refers to HHT of the second swallow. The second subsequence began immediately after the first swallow; the second swallow occurred at the end of the second subsequence. First subsequence: $n = 10$ for chicken spread, banana and cookie, 6 for peanuts; second subsequence: $n = 9$ for chicken spread and cookie, 5 for peanuts. No attempt was made to distinguish processing or OPAT in S-S2 given the variability of behavior observed (Hiiemae & Palmer, 1999)

previous findings (Hiiemae & Palmer, 1999). Chewed solid food was found only rarely to enter the hypopharynx before swallow onset.

Recently, the method of endoscopic observation was improved, and the entire upper aerodigestive tract from the nasal vestibule to the gastroesophageal junction could be easily and safely visualized. Thus, long-duration evaluation of masticatory function which was not possible for x-ray videofluorography was used to study the hypothesis that Stage II transport and bolus aggregation in the pharynx are related to the number of chewing strokes (Yamashita, Sugita, & Matsuo, 2013). Since Yamashita et al. (2013) could not visualize the tongue movement for the Stage II transport or bolus movement from the fauces to the oropharyngeal area on the endoscopic image, they defined bolus aggregation on the oropharynx on the endoscopic image as the Stage II transport, and the start of Stage II transport was defined as the timing when the bolus was first observed on the endoscopic image. In combination with EMG observation, they found the total number of chewing strokes 37.9 ± 14.6 (mean ± *SD*), and the numbers of chewing strokes for pre-stage II transport and for post-stage II transport were 29.8 ± 12.4 and 8.1 ± 6.7, respectively. Their finding, that the mean number of chewing strokes of post-stage II transport was 8.1, was in agreement with those by Palmer et al. (1992), Hiiemae and Palmer (1999), and Matsuo and Palmer (2009). Since large variations in the number of chewing cycles until swallowing have been reported, Yamashita et al. (2013) selected the ratio of the number of chewing strokes for pre-stage II transport to that for post-stage II transport to eliminate the effect of individual differences, and the average ratio was 4.0–1.0. Thus, they concluded that Stage II transport started at four fifths of the way along the way of mastication supporting the hypothesis that Stage II transport and bolus aggregation in the pharynx are related to the number of chewing strokes. They continue to study how Stage II transport is related to the act of chewing.

The collaboration between these physiological studies and sensory texture studies is required to get further understanding. The transport of chewed foods has been studied by physiologists as described briefly above but the relation between the physicochemical properties of foods and the sensorily detected signal which is transmitted to a central pattern generator is not yet clarified.

In the sensory studies of food attributes especially for flavors and aroma, food scientists recognized the necessity to record some attributes during consumption which is different from the static sensory methods such as quantitative descriptive analysis. In the time intensity method, the perceived intensity of an attribute is recorded as a function of time during oral processing, which was regarded as a standard sensory procedure by the 1970s (Cliff & Heymann, 1994; Dijksterhuis & Piggott, 2001). If the panelists are well trained, not only one attribute but also a few more attributes could be recorded. In the sensory evaluation of various foods, panelists are influenced not only by textures but also by other factors such as taste and aroma. Therefore, it is reasonable to pick up the most dominant factors attracting the attention of panelists. By virtue of the development of computer technology, it is nowadays possible for panelists to input the dominant attribute in real time during eating by operating the cursor of the computer. This method called TDSs (temporal dominance of sensations) was introduced recently (Di Monaco, Su, Masi, & Cavella, 2014) and used quite often in sensory studies. Although this method is not yet established, it seems that this method can shed some light upon at which stage in the oral processing the sensation of the firmness is taken over by the adhesiveness, and temporal changes of other attributes. Although humans may not be able to concentrate on so many attributes simultaneously, which attribute is more important should be pursued in oral processing. See Fiszman and Tarrega (2017) for detailed description.

Recently, Stokes, Boehm, and Baier (2013) proposed a schematic representation of six key stages (a) first bite, (b) communition (chewing), (c) granulation, (d) bolus formation and processing, (e) swallow, (f) residue, during the oral processing of solid food which changes the most strongly perceived sensation from crispy—crunchy—rough—sticky—smooth. Traditionally, the mechanics studied the first two stages, and the tribology enters from the third stage. The later three stages are studied by rheology and tribology. While the creaminess has been studied extensively, it was difficult to understand by traditional rheology, and recent advances of understanding was brought about by using tribology (Stokes, 2012; Stokes et al., 2013).

When we see the Hutchings and Lillford (HL) and Hiiemae and Palmer (HP) model, some questions may arise. If the degree of structure of food is lowered by cutting, slicing, fragmenting, pulverizing before ingestion into the mouth, how does it reduce the processing time? How about the degree of lubrication? Does the addition of water or oil to food before ingestion reduce the processing? During her stay in Sweden, Pangborn examined the secretion of saliva when six subjects masticated and swallowed pieces and powders from four types of Swedish crisp breads using a precision sialometer (Pangborn & Lundgren, 1977). They found that significantly more saliva was required for oral manipulation of the powders than for the corresponding pieces, as the greater surface area of the former required more saliva for lubrication in preparation for deglutition. As will be discussed in 3.5.2, the addition of water reduced the oral processing time (van der Bilt, 2012).

Recently, Rosenthal and Share (2014) examined the breakdown path of peanuts, peanut meal, and peanut paste in the framework of the mouth process model of Hutching and Lillford using TDS. Since the structure of the latter two foods are broken down, the time required for the first swallow (37, 28, and 21 s, respectively) and for clearance (49, 36, and 30 s) decreased with decreasing the degree of structure. However, more detailed TDS analysis showed that peanut paste, which starts as a soft suspension with lower structure than peanut and peanuts meal appears to thicken and stick to the palate during oral processing. They explained this sticky sensation and apparent difficulty to swallow arose out of water absorption from the saliva as they mix in the mouth, which was consistent with the increase in the instrumentally evaluated hardness of peanut paste by the addition of water (Abegaz & Kerr, 2006). The observation of the sticky sensation dominant for some time prior to clearance led them to interpret that the progressive lubrication of the sticky bolus resulting in a gradual loss of stickiness allows swallowing to occur. Since the time required for the first swallow and for clearance was shortest for peanut paste, this increase of stickiness did not delay so much the trajectory. Although the x-component (time) of the trajectory monotonically increases, the z-component (degree of structure) and the y-component (degree of lubrication) could increase before the final swallow, which is consistent with Hiiemae's process model for feeding where the processing cycles are repeated until the second "transport?" question (the judgement for the bolus to go to the next step) can be answered in the affirmative.

Lenfant, Loret, Pineau, Hartmann, and Martin (2009) using the TDS method examined the temporal change of perception of eight texture attributes in French for six different wheat flakes. Twenty-five panelists were trained to understand the definition of attributes, *dur* (hardness), *craquant* (crackliness), *croustillant* (crispness), *friable* (brittleness), *leger* (lightness), *collant* (stickiness), *granuleux* (grittiness), and *sec* (dryness). Since TDS data of panelists cannot be compared directly because the speed of oral processing is different for each panelist, Lenfant et al. (2009) normalized the time so that TDS data for all the panelists can be incorporated in the same time scale. They found that hardness and crackliness appeared in the early period of mastication, and while vanishing these perceptions gave way to crispness. Brittleness was perceived as dominant in the middle stage, and followed by lightness. In the last stage of mastication, stickiness became dominant just before swallowing, which is in accordance of the statement in the abstract of Lucas, Prinz, Agrawal, and Bruce (2004).

Peyron et al. (2011) examined the temporal change of TPA parameters for 3 g petal wheat flakes at different stages of mastication until swallowing by 25 subjects. After the training, panelists expectorated the bolus at different stages, which was collected for measurement of hardness, adhesiveness, cohesiveness, springiness. Sensory evaluation for hardness, stickiness, dryness was also performed. Particle size distribution in boli was determined by dry manual sieving, and the monotonic decrease was found with the time of mastication. It was found that hardness decreased while adhesiveness, cohesiveness, and dryness increased, which was necessary to form a bolus to be swallowed safely. The tendency for an increased dryness perception at the end of the masticatory sequence was interpreted as the exchange between the solid and aqueous phases in the bolus caused by the saliva absorption.

It is evident now from the above discussion that we should take into account various factors which may influence the breakdown process in the mouth process model of Hutchings and Lillford (1988) or of Hiiemae and Palmer (Hiiemae, 2004) as in studies on the mastication behavior of peanuts, wheat flakes, cucumbers, apples, carrots, roast pork, *surimi* gels described above. Even though starting from a weaker structure such as sliced form than the original food materials, it does not necessarily reduce the mastication time and muscle activity. Structure of starchy foods may be degraded by amylase in saliva, but when a newly created structure such as the increased adhesiveness through the interaction of saliva during comminution, the coordinate of the trajectory for the degree of structure (*z*-axis) may go up, but how should we think about the time (*x*-axis)? Back to the future? The moment, stay, thou art so beautiful (du bist so schoen)!? Sticky foods such as caramels and rice cake made from waxy rice may stay on the palate or teeth, and would not go to the next step so fast, but go slowly by the action of the tongue and saliva.

3.5 | Deformation/Biting speed

3.5.1 | Effect of deformation speed on TPA parameters

Before examining the rate of deformation of instrumental test, let us see the chewing rate in our mouth. As Bourne (2002, p. 46) stated, the first few chews on a piece of food are generally slow as one manipulates the piece within the mouth to soften it with saliva or cut it into smaller pieces with the incisors. When the bolus reaches a consistency that can be readily managed, the chewing rate is stepped up to the normal chewing rate, which then remains fairly constant for the remainder of that chewing cycle.

The rate of movement of the jaw is known to be approximately a sine curve, and the compression rate between teeth depends on the position of teeth. Incisors farthest from the tempomandibular joint move at about twice the speed of molars which are close to the joint. Bourne estimated the average compression rate as 1,200 mm/min (=20 mm/s) assuming humans chew 60 times per minute in average, and the average stroke length as 10 mm, but emphasized that this average is very different for incisors and molars (Bourne, 2002; Book, p. 48).

Bourne (1978) stated that chewing rate as a function of toughness of foods stays constant up to a certain toughness which is achieved by increasing power output of the jaw, and that beyond this toughness the power output remains approximately constant, which is achieved by slowing the rate of mastication.

Bourne (2002, p. 303) pointed out that the force–deformation curve for some foods such as apples, potatoes, crispy puffed foods are strain rate insensitive, but emphasized the importance of the selection of experimental compression speed taking an example of the compression test of cheeses by Shama and Sherman (1973a, 1973b). In the force–deformation curve of two cheeses, Gouda and White Stilton, the latter cheese showed a larger force at a compression speed at 5 cm/min at a whole range of compression from 0 to 80%, but Gouda showed a larger force at a certain intermediate compression range at higher compression speed 20, 50, and 100 cm/s, while in the sensory evaluation Gouda was always rated harder (Shama & Sherman, 1973a, 1973b). Bourne concluded that it is necessary to select a suitable compression speed to get a good correlation with sensory evaluation. Voisey (1975) commended to do an instrumental compression at three different rates and extrapolated the obtained TPA parameters to a higher compression rate 150 cm/min (=25 mm/s) reported as an oral deformation rate by Bourne in order to get a better correlation with sensory evaluation.

Takahashi and Nakazawa (1992) employed the compression speed 0.5 mm/s in their study of mastication using agar and gelatin gels as model foods because the compression rates of 1, 5, and 10 mm/s gave poor signal to noise ratio as compared with that at 0.5 mm/s. Although 0.5 mm/s is a very low compression rate to simulate the human mastication rate, the purpose of these instrumental measurements is not to simulate the compression rate of human mastication but to obtain the strength of the gels.

Moiny, Meullenet, and Xiong (2002) examined also the effect of compression rate for 20 commercial Cheddar cheeses, and found that the best correlation between sensory evaluation and instrumental tests was obtained for crosshead speeds of 1 and 10 mm/s although it was expected that the higher loading rates, being more representative of those observed during biting, would offer some significant improvements. The effect of loading rates on correlations between instrumental and sensory measurement was found inconclusive. Meullenet, Finney, and Gaud (2002) reported the average biting velocity of ten cheeses using an electrognathograph for seven trained subjects, which ranged from 19.8 to 35.1 mm/s. They also performed the instrumental compression of cheeses at 10 mm/s, and reported that the perception of hardness was described well by imitative instrumental compression tests using dental replicas for each subject although the instrumental test is still not a faithful imitation of the actual human mastication. They concluded that the peak load and energy to peak are better predictors of hardness by sensory evaluation. Meullenet and Gandhapuneni (2006) reported that fracture peak force decreased with increasing bite duration in ten different cheese samples evaluated by seven trained subjects, and attributed it to stress relaxation because cheese is a viscoelastic material.

Kohyama and Nishinari (1992) examined the effect of puncture rate from 0.05 to 1.0 mm/s on the stress and strain curves of tofu (30 mm thickness) using a cylindrical plunger of 5 mm diameter. They found that the fracture stress σ_f decreased and then increased slightly while the fracture strain ε_f decreased with increasing puncture rate. Yuan and Chang (2007) cited more than 30 papers which described the TPA of tofu with different compression speeds. They reported that the hardness increased with increasing cross-head speed for 10 tofu products and only one product showed the opposite tendency, which is in good agreement of the conclusion for food gels surveyed by Pons and Fiszman (1996). Dan and Kohyama (2007) found that fracture stress and work for fracture increased while impulse for fracture decreased with increasing test speed for four cheese samples. They did not find a definite correlation of fracture strain and the test speed for all the four cheeses.

Compression and extension of heat-induced gels of ovalbumin (egg-white protein) and soybean protein in the concentration range from 10 to 35 g/100 g were examined, and it was concluded that the fracture strain for both the pH 5 and pH 10 gels is independent of the deformation rate (crosshead speed) and, within experimental error, was also independent of protein concentration although the experimental data were scattered (van Kleef, 1986). Extension measurements were difficult to perform mainly because of experimental variations, such as variations in the way the tensile strips were fixed between the clamps, although they did use 224 experiments.

Luyten (1988, p. 85) compared the stress–strain curves of Gouda cheeses at different compression speeds. She found that the fracture stress σ_f increased while the fracture strain ε_f also increased but decreased for some cheeses with increasing compression rate. Since the fracture phenomenon is sensitive to structural defects such as a small crack or air bubbles, Luyten and van Vliet (1995) studied the fracture stress in tension of potato starch gels with notches of different size. Luyten and van Vliet (1995) reported that decreased σ_f was inversely proportional to the square root of the notch length while the small deformation properties are far less dependent on the size of cracks present in the sample.

Large deformation and fracture properties of food gels are more strongly dependent on the deformation speed than small deformation properties. The stochastic nature of the size distribution of the defects plays an important role, and different energy-dissipating mechanism may occur, and therefore, fracture is not simple and depends on the structure (van Vliet & Walstra, 1995: Figure 7).

Rosenthal (2010) found that the hardness of a model Turkish delight dessert jelly (10% acid thinned starch, 60% glycerol and 30% water) increased with increasing compression speed from 0.1 to 10 mm/s, and fitted by a logarithmic curve. He found it as a good agreement with Pons and Fiszman's conclusion that the slower the speed of compression, the more time the sample has to relax and dissipate the applied force, and thus he validated logarithmic curve representation.

More recently, Yang et al. (2015a, 2015b) reported that both fracture stress σ_f and fracture strain ε_f of 1% agar gels containing sucrose increased with increasing compression speed. Their data also showed that both σ_f and ε_f of 1% agar gels increased with increasing concentration of sucrose up to 50% when sucrose was added after the dissolution of agar (Figure 8).

The tendency that both the fracture stress and strain increased with increasing compression speed is in good agreement with Nakamura, Shinoda, and Tokita (2001) who observed the compression behavior of gellan gum gels in a wide range of compression speed as shown in Figure 9. Although the compression speed employed in Nakamura et al. (2001) was far from a normal biting speed in the mouth, their experiment showed an interesting aspect of gel structure which has never been reported before. Their results clearly showed that water in a gellan gel exuded out by slow compression, and a clear fracture point was not observed at slow compression speeds. This also gives interesting information on the frequently reported hardness. When the food material does not show a clear fracture, the maximum stress has been often reported as a hardness value. Figure 9 shows that, in such a case, the hardness as a function of compression speed shows a minimum at a compression speed of 0.1 mm/min (represented by a symbol +) even though there may be no such person who bites so slowly.

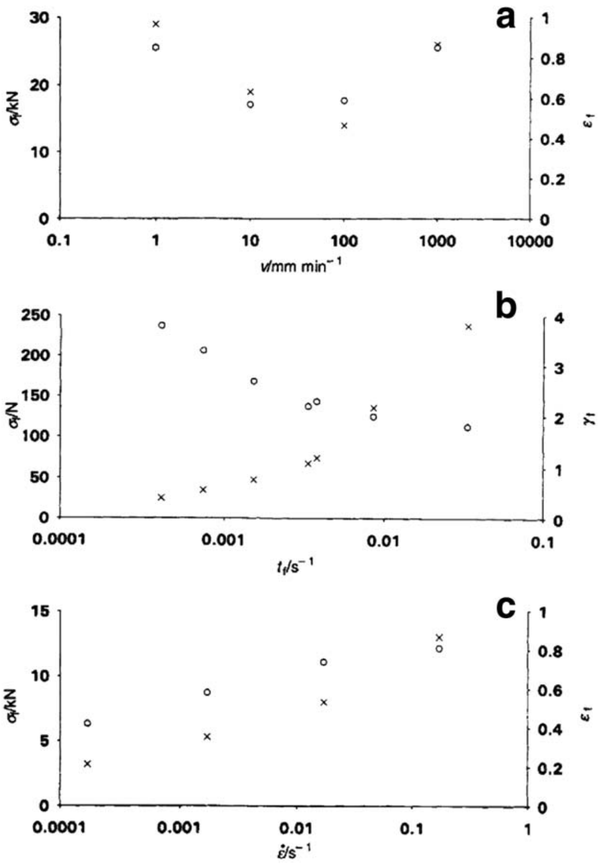

FIGURE 7 (a) Fracture stress σ_f (×) and the relative deformation at fracture ε_f (○) as a function of the deformation speed *v* for 20 wt % gelatin gels; (b) Fracture stress σ_f (×) and fracture strain in shear γ_f (○) as a function of deformation rate (t_f is the time after stress application at which fracture of the gel occurred) for 2.8 wt % rennet-induced casein gels; (c) Fracture stress σ_f (×) and fracture strain in uniaxial compression ε_f (○) as a function of Hencky strain rate $d\varepsilon/dt$ for 10 wt % potato starch gels (van Vliet & Walstra, 1995)

3.5.2 | Effects of mechanical properties of foods on biting speed

How do humans control the biting speed for foods with different firmness? If the biting speed changes during the mastication process, when

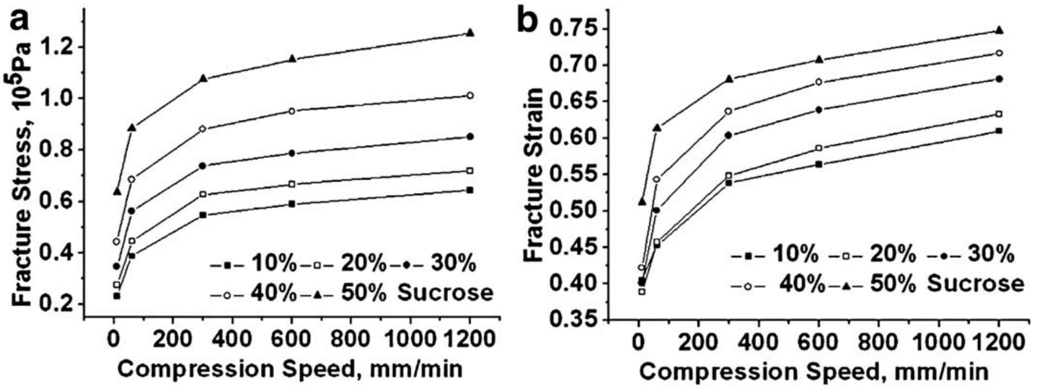

FIGURE 8 Relationship between fracture stress (left) or strain (right) and compression speed of 1 wt % agar gels containing sucrose with different concentrations (Yang et al., 2015a)

and how is the "firmness" judged? These physiological questions related with mechanical measurements have been studied extensively in physiological and neurophysiological research fields (Peyron & Woda, 2016; Woda, Mishellany, & Peyron, 2006).

Peyron, Lassauzay, and Woda (2002) studied the effects of hardness on the mastication behavior using four different gelatin jellies with compression hardness (CH), which was determined from the maximum stress at the first 50% compression, and varied from 39 to 114 kPa. They observed a power law relation between sensory hardness (SH) and CH: $SH = 207(CH)^{1.69}$. Their jellies were all elastic in the sense that they all show almost the same stress–time curve at the second compression. They found from EMG measurements that sequence duration, number of chewing cycles, mean vertical amplitude, mean lateral amplitude increased with increasing hardness. Mean closing velocity was found to increase from 46.6 to 50 mm/s with increasing hardness. In a subsequent study, Foster, Woda, and Peyron (2006) examined the effects of mechanical properties of foods on the mastication behavior using elastic food (gelatin gels) and plastic food (caramels) with different hardness values characterized by compression measurements. While elastic foods showed a similar tendency as in their previous paper, that is, closing velocity increased with increasing hardness, plastic foods showed a different behavior. They pointed out that other rheological properties than hardness should be taken into account, and that the effect of hardness on masticatory frequency was only important during the initial stages of a masticatory sequence and that overall frequency is better described by the food type (i.e., elastic or plastic) than by the hardness. Plastic products were chewed at lower frequencies than elastic products. They suggested that different adaptations in the masticatory parameters observed in response to changes in food characteristics showed that the adaptation of mastication was highly complex and that the modulation of the masticatory process occurred in response to many textural characteristics of the food and was certainly not limited to food hardness. Then, they proposed two mechanisms: The first mechanism (cortical-brain stem preprogrammed mechanism) may mostly depend on the knowledge obtained before the introduction of the food inside the mouth through memory and visual or other sensorial cues. The second mechanism (brain stem mechanism) may mostly be a rapid reaction to a previously unplanned food property. Foster et al. (2006) also pointed out that the past studies reported contradictory results on the effects of hardness on the mastication frequency which increased or decreased or did not change with increasing hardness, and emphasized the necessity to take into account other mechanical properties. Peyron, Maskawi, Woda, Tanguay, and Lund (1997) pointed out that it is not so simple to find the relationship between the perceived hardness of food although the hardness of food is usually evaluated during the first bite (Boyd & Sherman, 1975; Brandt et al., 1963; Vickers & Christensen, 1980) because the biting can be an isolated voluntary act or the first step of the consecutive masticatory process. Grigoriadis, Johansson, and Trulsson (2014) reported that the number of chewing cycles was larger for hard food (27 ± 13.9) than for soft food (21.0 ± 9.5) comparing gelatin-based model foods of two different hardnesses.

It is also necessary to take into account that the masticatory cycle does not occur as simple unidirectional movements depending on the closing phase of the masticatory cycle (Hiiemae, 2004; Peyron, et al.,

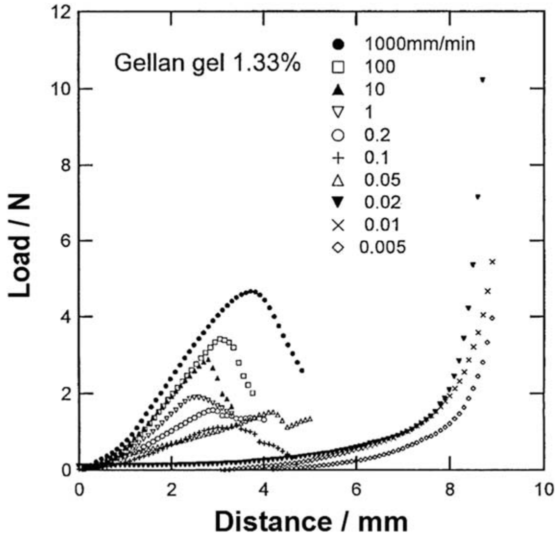

FIGURE 9 Load-compression curves of a cylindrical 1.33% gellan gum gels at various compression speeds (temperature, 22.5 ± 1.0C, diameter and height of a gel: 11.5 mm and 10 mm, respectively (Nakamura et al., 2001)

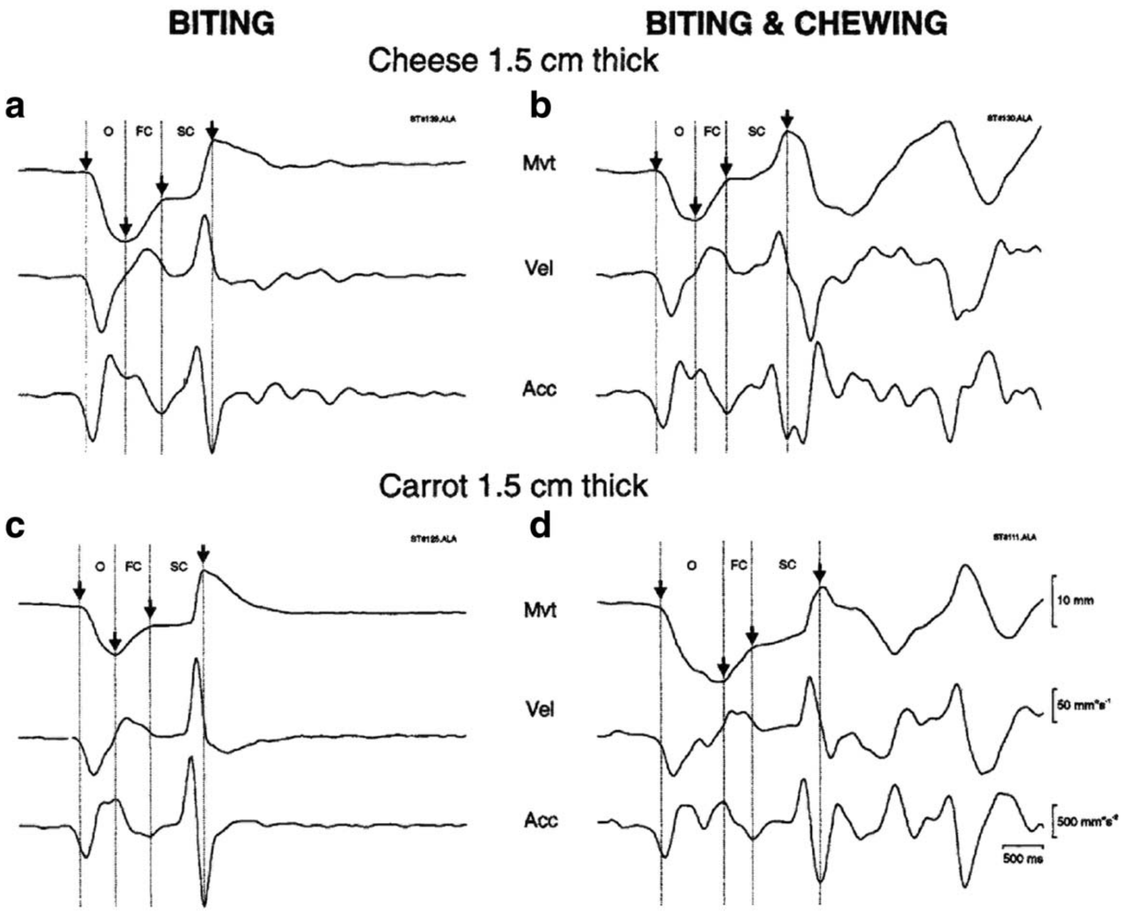

FIGURE 10 Four examples of recordings of the vertical movement of the mandible (Movement, Mvt) together with the first derivative (Velocity, Vel) and second derivative (Acceleration, Acc) for a single subject. During these trials, the thickest samples of cheese (a and b) and carrot (c and d) were used. (a) and (c) Represent biting alone, while biting was followed by chewing and swallowing in (b) and (d). The vertical arrows divide each cycle into three phases: Opening(O), Fast Closing (FC), and Slow Closing (SC) (Peyron et al., 1997)

1997; van der Bilt, 2011). The vertical movement of the mandible is plotted as a function of time for a subject chewing samples of cheese and carrot (Figure 10).

Whether biting occurred on carrot or cheese, and whether it was followed by mastication, the forms of the movements in the vertical plane were roughly the same (Peyron et al., 1997). Each bite had three distinct phases that were named Opening (O), Fast Closing (FC), and Slow Closing (SC):

- FC occurs as a free movement and continues until tooth-food-tooth (*tft*) contact when the resistance of the food slows the lower jaw and then the adductor muscles (masseter, medial pterygoid, and temporalis) become very active
- SC begins with teeth-food contact, mandibular movement and speed depending on food characteristics
- very slow closing during food crushing, at the end of cycle, very slight mandibular movement (occlusion).

Peyron et al. (1997) found that the change in thickness of food showed a stronger effect on biting movement than the food type (carrot and cheese), and the hardness perception was dependent on the thickness of food. Cheese was perceived less hard (16.8 visual analog scale unit of 100 mm long) than carrot. Food type had its strongest effect on the slow-closing phase. In particular, the peak velocity that followed the fracturing of the food sample was much greater for carrot than for cheese (thin, 34.1 versus 26.6 mm/s), and the difference between foods increased with thickness.

Takeshita and Nakazawa (2007) measured the velocity of the teeth during chewing of various foods in a natural way for two healthy (normal dentition) young female subjects and examined the effects of consistency of foods on the chewing behavior. The velocity of the first molar was measured by magnetic method detecting the motion of a small disk type magnet placed on the cheek side of the gum of the first molar. A similar principle using a jaw-tracking system has been adopted to observe the closing and opening movement of mandibular motion during mastication (Kuninori et al., 2014; Peyron, Mioche, Renon, & Abouelkaram, 1996; Piancino, Bracco, Vallelonga, Merlo, & Farina, 2008). A masseter myograph simultaneously made a measurement for identification of the first bite (Takeshita & Nakazawa, 2007). The maximum mastication velocity of the molar at the first bite was found to be 37–74 mm/s depending on the food. Takeshita and Nakazawa (2007) pointed out that this velocity is 4 or 7 times faster than the commonly

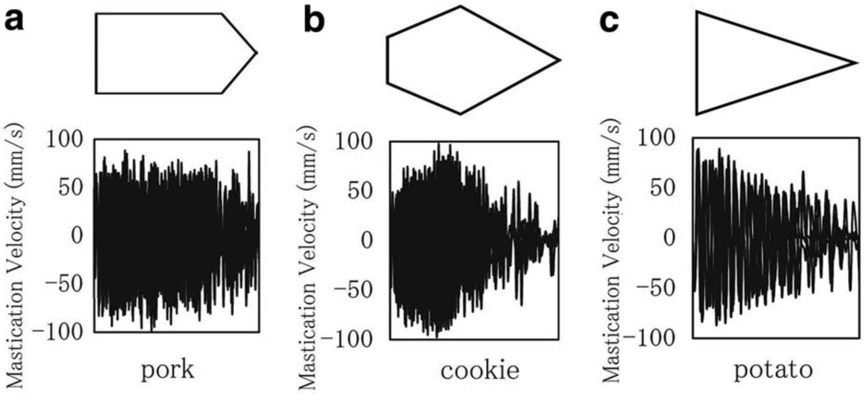

FIGURE 11 Mastication velocity patterns of the first molar in the up and down direction from the beginning of eating to swallowing. (a) Mastication velocity changed little while chewing the food, but then decreased for bolus preparation; (b) Mastication velocity increased gradually at the initial stage of mastication, but then decreased on the way toward finishing the chewing; (c) An initial fast mastication velocity decreased steadily but evenly. The abscissa (time) is normalized so that the time required from the beginning to the end of mastication becomes the same length in the figure. Size of the bite is 10 × 15 × 10 mm for pork and potato (both boiled) and 30 mm diameter and 5 mm height for cookie (Takeshita & Nakazawa, 2007)

used instrumental compression speed 10 mm/s, and that the reported values of the mastication speed in papers where the mastication speed was measured from the motion of incisor are three times faster than their values. They believed that one mouthful size solid food (10 × 15 × 15 mm) will be masticated by molars, and therefore, the determination of mastication speed should be done from molar motion and not from incisor motion. Changes in the velocity of the molar from the beginning of mastication to swallowing were assessed for 22 kinds of food, and typical examples are shown in Figure 11.

Takeshita and Nakazawa (2007) divided foods into three groups. (A) Mastication velocity changes little while chewing, then decreases for bolus preparation as seen in boiled pork, *mochi* (sticky rice cake), boiled squid, boiled octopus, *kamaboko* (fish paste gel), meat ball, ham, cucumber, radish, boiled carrot, gummy candy, and boiled soybean, (B) Chewing velocity increases gradually at the initial stage of chewing as seen in cookie, and *senbei* (crisp rice cracker), (C) Initial fast mastication velocity decreases steadily but evenly as seen in boiled potato, boiled sweet potato, *yokan* (sweetened red bean paste gelled with agar and sucrose), and processed cheese. Although this method of classification is obviously an oversimplification because it is known that the mastication time is longer for firm foods than for soft foods and thus the abscissa (time) is reduced to the same length in spite of the difference among different foods, it may have a significance in comparison of mastication speed patterns. Takeshita and Nakazawa (2007) found that the mastication velocity decreases with increasing Young's modulus in tested foods, and the clear relation between the mastication velocity and the fracture stress was not found, which might indicate that the mastication speed was determined in the initial stage of the deformation before reaching the fracture. They explained the different behaviors of these foods as follows: Water content of foods in group (A) was comparatively high, and the structure of fragments produced by mastication are not so different from the initial structure, and did not change so much by saliva. Water content of foods in group (B) was low and saliva was absorbed into foods during mastication, then foods were softened leading to the decrease in the Young's modulus thus mastication speed was enhanced, and structure was broken down to form a bolus. Young's modulus of foods in group (C) was small, and thus the mastication speed in the jaw closing was high, and structure was broken down to form a bolus. As for the effect of water content, their results are in good agreement with van der Bilt (2012) who compared the relation between the chewing activity and the number of chewing cycles for peanut, carrot, cheese, and cake with and without the addition of 5 or 10 ml water. The additional water reduced the number of chewing cycles until swallowing and the muscle activity for melba toast, cake, which are dry products requiring more saliva to form a bolus for safe swallowing, while this effect of the additional water was not observed for carrot.

Dan and Kohyama (2007) examined the effect of mechanical properties of foods on the mastication behavior for nine healthy subjects using four different cheeses, *W* (Snow Brand Hokkaido cheese), *X* (Kraft cheese), *Y* (New Zealand Gouda cheese), and *Z* (Gruyere cheese). They found that both fracture load and work for fracture increased linearly with increasing crosshead speed from 1 to 8 mm/s, and logarithm of impulse for fracture, which was determined by the area under the force–time curve until the fracture, decreased with increasing crosshead speed. They determined for the first time the bite velocity from *tft* contact using a sheet sensor until the initial fracture of the sample surface. While measurement of the bite time–force profile could not produce the jaw trajectory, the *tft* contact and fracture phenomena can be confirmed as force-change points in the bite time–force profile although the insertion of a sheet sensor might influence the biting behavior. These measures are not obtainable from the jaw movement measurement. Biting velocity estimated by dividing the fracture displacement by the duration until the first peak in each sample ranged from 4.839 mm/s for *Z* (Gruyere cheese) to 7.547 mm/s for *Y* (New Zealand Gouda cheese), which are much slower than biting velocity reported by Meullenet et al. (2002) mentioned above, which was attributed to the biting velocity of the latter group being measured at

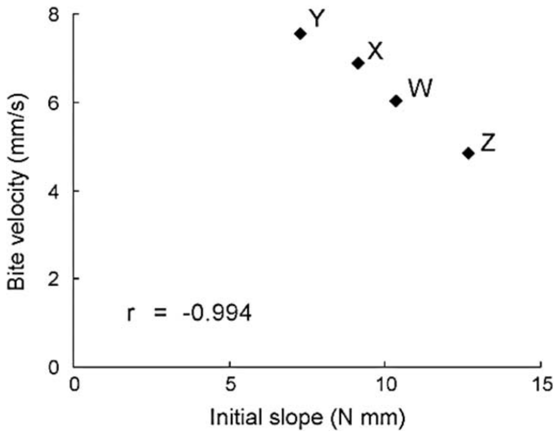

FIGURE 12 Relationship between the bite velocity and the initial slope of instrumental force-deformation curve for four different cheeses, *W* (Snow Brand Hokkaido cheese), *X* (Kraft cheese), *Y* (New Zealand Gouda cheese), and *Z* (Gruyere cheese). The velocity was measured at the first bite with the molar teeth (Dan & Kohyama, 2007)

the incisor, far from the molar. The important finding in Dan and Kohyama (2007) is that the bite velocity detected by a sheet sensor showed a negative correlation with initial slope of instrumental force–deformation curve which is proportional to Young's modulus, indicating that the initial slope is the mechanical factor that modifies the consequent bite velocity (Figure 12). They thought that the increase in the initial slope led to a reduced biting velocity, which would be sensed by muscle spindles of the jaw-closing muscles.

The relation between the bite velocity and the initial slope which is proportional to Young's modulus, using four different cheeses, showed a high negative correlation ($r = -.994$) and is essentially in good agreement with Takeshita and Nakazawa's correlation of the mastication velocity versus Young's modulus obtained by using 22 different solid foods. However, in the latter report, the correlation was scattered with $r = -.614$ probably because of the different nature of these 22 foods in contrast with relatively similar nature among four cheeses. Here, it is necessary to take into account that a solid food with a higher Young's modulus does not always show a higher fracture stress as exemplified by agar and gelatin shown in Figure 1. But, humans may have a memory that a food with a higher Young's modulus usually shows a higher fracture stress, and it may affect the biting behavior at the moment when teeth contact the food. This should be studied further.

As for the effect of food hardness on biting speed, some contradictory reports are found. Pröschel and Hofmann (1988) used winegum as a tough food and equally sized bread crumb as a soft food. They reported the maximum jaw closing velocity as 79.7 mm/s for the tough food and 101 mm/s for the soft food, and they found that the chewing of tough food was executed more frequently with wide lateral grinding movements whereas in soft food, the slim, and drop-shaped patterns were predominant. Takada, Miyawaki, and Tatsuta (1994) reported a similar tendency using hard jelly and soft jelly. They found that jaw closing velocity was faster for soft jelly than for hard jelly, and found that lateral jaw excursion was enhanced when chewing hard gels. In the study on effects of compositional differences in cheese and caramel samples on mastication behavior, Çakır, Koç, et al. (2012) found a similar tendency; the closing velocity decreased with increasing firmness; 69.1, 68.1, and 67.8 mm/s for three cheeses with sensory evaluated firmnesses of 6.9, 8.7, and 8.8.

In contrast to these reports, Piancino et al. (2008) used winegum as a hard bolus and a chewing gum as a soft bolus with the same size ($20 \times 1.2 \times 0.5$ mm^3), and found that maximum mastication 13.1 cm/s (right) and 12.8 cm/s (left) for a soft bolus, and 15.2 cm/s (right) and 15.2 cm/s (left) for a hard bolus for twelve healthy young subjects. Yoshida, Ishikawa, Yoshida, and Hisanaga (2009) also reported a similar tendency for the relation between the hardness of foods and the jaw closing speed observed from 23 healthy young subjects. Using chewing gums with three different hardnesses determined after chewing 3 min, Yoshida et al. (2009) found that the maximum closing velocity increased with increasing hardness of chewing gums.

More recently, using soft (hardness 69.8 kPa), medium (109.6 kPa), and hard (150.2 kPa) gummy jellies with the same ingredients except gelatin content (6, 8, and 10% for soft, medium, and hard jelly, respectively) Komino and Shiga (2017) reported the maximum closing velocity of 127.9 mm/s for soft jellies, 143.3 mm/s for medium jellies, and 151.7 mm/s for hard jellies. They found that lateral jaw excursion was enhanced when chewing hard gels where subjects could not manage only by vertical movement, which seems to be widely recognized. Shiga commented that winegums made in Germany were too hard, and the hardest gummy jelly used in Komino and Shiga (2017) was much softer than winegums, and therefore, if the highest gelatin content 10% was increased more, then one might expect to observe the slowing down of the closing velocity. However, their main interest is limited to food samples which are normally eaten in Japan. This is indeed the difference between the general material science and food related science where ultra-hard food is excluded.

Kuninori et al. (2014) reported that the lateral jaw movement was more enhanced in subjects with low biting force than in subjects with high biting force, which is consistent with their previous finding that the lateral jaw excursion was enhanced when chewing hard gels. For a food with a fixed hardness (5.5 g hard gummy jelly), the subjects with high biting force might find it softer than the subjects with low biting force, and therefore, the lateral excursion might be larger for the latter subject group. Maximum closing velocity was found to be 139 mm/s for the subjects with high biting force and was 95.5 mm/s for the subjects with low biting force. It seems that subjects with low biting force grinds (i.e., with more movement in lateral direction) food to compensate for his/her weak biting force.

Koc et al. (2014) compared the mastication behavior of agar gels *A* (1, 2, and 3%) and κ-carrageenan (KC)-locustbean gum (LBG) mixed gels (1:0, 3:1, and 1:1 mixing ratio). The former *A* gels are brittle, fracture strain 0.95 and fracture stresses were 40, 158, and 261 kPa, respectively, while the latter KC-LBG gels are deformable, fracture stress only slightly increased and decreased by adding 25 and 50% LBG to KC, and the fracture strain increased from 1.2 to 2.5 by adding LBG. Both these gels were less adhesive. The jaw closing velocity increased slightly for agar gels 49, 52 and 53 mm/s with increasing fracture stress while it was constant about 54 mm/s for KC-LBG mixed gels.

Kohyama, Kato-Nagata, Shimada, Kazami, and Hayakawa (2013) estimated the mean bite speed as 19–23 mm/s by dividing the thickness of the cucumber sample (10 mm) by the total bite time (0.42–0.52 s) using the multiple sheet sensor. They compared the hardness by both physiological and instrumental measurement of the middle part of cucumbers at 4C and 22C. The human-bite force for cucumber slices of 4C was found significantly lower than that of 22C. In the instrumental compression test, they used a wedge plunger with different angles 30° and 60°, and found a good correlation when they used the wedge with 60° at a higher compression speed of 16 mm/s. They attributed the reason why they could get a good correlation between human-bite and instrumental measurement to the fact that their instrumental measurement condition was more close to the human-bite behavior. This is contrast to a previous report by Vincent, Jeronimidis, Khan, and Luyten (1991) who studied the fracture mechanics of plant materials using a wedge with a lower angle ($<10°$) and an extremely slow speed (1 mm/min). Another reason may be also taken into account: although a sharp wedge or thinner rod may be suitable to detect the different parts of plant tissue (e.g., to identify the histological structure such as cortex, phloem, cambium, xylem, and pith), a larger plunger is more suitable to get a stable and better averaged value of a test piece as a whole as was shown by Horiuchi, Nishinari, Niikura, and Hakamada (1976). Thus, although it is difficult to understand why a sharper wedge with a lower angle ($<10°$) could not mimic better the human-bite with incisor than a wider wedge with 60°, the choice of a faster compression speed seems to be necessary.

It seems that dental and food scientists have different interests. Dental researchers measure the jaw kinematics at middle stages of mastication, where the chewing movements become most stable, are repeated rhythmically, and thus individual chewing patterns appear more clearly. For this purpose, most food samples used are gummy gums or chewing gums which can be chewed many times. In contrast, food researchers are more interested in more common various foods and often analyzed the first bite or initial stages of mastication because characteristics of such foods measured using an instrument change rapidly in the mouth. Most such foods are broken at the initial bite, and size of fragments decreased and number of fragments increased during oral processing. Evidently size of food influences the jaw movement. Harder foods likely have greater fragment sizes in the mouth after a fixed number of chews. A bolus containing greater food fragments may be chewed with greater movement. The velocity would become faster if the chewing rhythm of an individual is constant (it is almost constant in middle stage of mastication).

To find a general tendency in the effects of hardness on biting velocity, it might be convenient to have a range of hardnesses for example, as described in Bourne's textbook (Bourne, 2002, p. 262), although biting behavior evidently is influenced by many other factors especially on size as discussed in the next section and taste, aroma, and so on. Most researchers used model jellied foods with different hardness (Peyron et al., 2002) trying to keep other factors constant as possible.

Most instrumental methods reported used a linear movement of piston head since the proposal of Bourne using an uniaxial compression apparatus. Although it simplified the mechanics of the apparatus in comparison of a prototype General Foods Texturometer, and made it possible to compare the data on nonfood materials, the linear movement cannot mimic well what happens during real mastication. For example, a non-linear mandibular movement with a sinusoidal compression of the food sample (Salé, Noel, Lasteyras, & Oleon, 1984) was proposed, and more recently robotic machines have been introduced to mimic more precisely the mastication process (Mielle et al., 2010; Mishellany-Dutour et al., 2011; Peyron & Woda, 2016; Salles et al., 2010; Takanobu, Shoda, Takanishi, & Yanagisawa, 2002).

It is also necessary to validate the results obtained by one method using other independent methods to confirm. The combination of EMG and optical tracking device (Peyron et al., 1996) was effective, and the comparison with videofluography was used to validate their results (Hennequin, Allison, Veyrune, Faye, & Peyron, 2005).

3.5.3 | Effect of size on biting speed

Not only the hardness or other mechanical properties but also the size of a food influences bite speed. Miyawaki, Ohkochi, Kawakami, and Sugimura (2000) reported that the jaw-closing velocity was faster for a 10 g jelly than for 5 g jelly. Bhatka, Throckmorton, Wintergerst, Hutchins, and Buschang (2004) examined the effect of bolus size on the mastication behavior and they found that the maximum anterior–posterior velocity for the 8 g bolus was 152% faster than for the 1 g bolus. Woda et al. (2006) reported that the closing velocity increased with increasing sample size and also with the rheological change from elastic to plastic as descried above. More recently, Shiozawa et al. (2016) examined the effects of serving size on chewing behavior. They used cylindrical biscuits with the same length of 100 mm but with different diameters: 3, 3.5, 4, and 8 mm, and found that the bite weight and number of chews increased, but the number of chews per bite weight decreased with increasing diameter. Then, they stated that decreasing the serving size is an effective way to reduce the overeating and thus prevent the obesity. On the other hand, Kohyama et al. (2016a) discussed this from another point of view to serve foods for people with difficulty in mastication. They point out that reducing the serving size increases the mastication effort per fixed amount of food or per energy and thus may reduce the intake of foods, and thus it is not always a good way to reduce the serving size to assure the sufficient intake of the energy (calorie) and nutrients for these people, which will be described later in relation with Figure 19.

Hutchings et al. (2009) examined the bite size or the serving size of food in a mastication study. Six types of manufactured food bars, Moro (chocolate and nougatine whip, Cadbury), Crunchie (hokey pokey and chocolate, Cadbury), Fruit and Nut Bar (Tasti Products Ltd.), Muesli Bar (Flemings), Apricot Pie (doughy bar with an apricot filling, Tasti Products Ltd.), and Pixie Caramel (hard chocolate and caramel, Nestlé) were assessed with 45 subjects (21 males and 24 females). These bars were chosen because they were commonly available in New Zealand

and distinct in their physical properties. Bite weight was determined and the volume and length of each bite were calculated using the density and dimensions of each bar. They found that natural bite weight, volume, and length varied significantly between bars, while bite length varied least. They suggested that food bite size is not controlled by weight nor volume, but by bite length, when food bars are being consumed. They recognize that no ideal serving method exists. The bite length was found relatively regular which might suggest that constant volume servings may represent normal feeding behavior more so than constant mass. However, one dimensional bar shape food could not represent all the foods, and when the similar study using cubic or spherical shape food is performed, it may be found that food bite size is controlled by weight or volume. In the end, they stated that an ideal method for serving size in mastication studies is yet to be identified and researchers need to carefully consider what particular serving method will most effectively match the requirements of their work, which is a good advice but difficult to take into consideration.

Wintergerst, Throckmorton, Buschang (2008) examined within-subject variability for chewing gums of different sizes (1, 2, 4, and 8 g) and found that the coefficient of variation became the smallest for a 2 g bolus. Then, they concluded that a 2 g bolus of soft gum should be used in studies of chewing cycle kinematics in order to reduce within-subject variability and increase statistical power. Although this size may be ideal for a chewing gum, it may not be applicable for other foods.

3.5.4 | Effect of other factors on biting speed

Above discussions pose us to reconsider another factor which might influence biting speed, namely how some flavors may influence the biting behavior.

Neyraud, Peyron, Vieira, and Dransfield (2005) examined the influence of bitterness on mastication behavior. Using gelatin-based gels containing sugar and glucose syrup with added quinine of various concentrations, they observed the mastication pattern by EMG. Sensory evaluation showed that the sweetness and acceptability decreased while the bitterness increased with increasing concentration of quinine. Their results indicated that the number of chews decreased consistently, from 30 chews for a gel without quinine to 22 chews for a gel containing 1,446 μmol quinine/kg. They stated that total muscle effort was not significantly affected by quinine concentration, but tended to decrease with increasing concentration of quinine. However, it is surprising to see that gels that are twice as hard (hardness 44 kPa) with quinine concentration 241 and 362 μmol needed less number of chews ($NC = 27$ or 25) than a softer gel (hardness 22 kPa) without quinine $NC = 30$. Does it indicate that the addition of quinine (241 and 362 μmol) increased the gel strength or did bitter taste reduce both the number of chews and the total muscle effort? It might be possible for normal people to reduce the number of chews for bitter tasting foods because they do not wish to continue to chew and rather finish the oral processing earlier.

As far as the authors are aware, there have been no reports on the effect of sour taste on biting speed. Although there have been many reports on the effect of sour taste on swallowing behavior (Nishinari, Takemasa et al., 2016), the effect on biting speed has not been reported. This problem is not so simple because by changing the degree of sour taste it may also change other properties of the food as, has been studied in pH dependence of the viscoelasticity of gels (Djabourov, Nishinari, Ross-Murphy, 2013; Morris, Nishinari, Rinaudo, 2012; van der Linden & Foegeding, 2009), in other words, it is not so easy to make a series of food samples different only in the degree of sour taste keeping the other characteristics the same. Perhaps, this is the reason why there have been no such reports.

3.6 | Adhesiveness

As Szczesniak (1963a, 1963b) and Sherman (1969) pointed out, adhesiveness is a fundamental textural attribute in TPA. The problematic nature of instrumental determination of the adhesiveness of foods for different surfaces at large deformation was recently reexamined (Brenner & Nishinari, 2014). In particular, the ambivalence of using such instrumentally evaluated adhesiveness parameters as measures of textural adhesiveness, which can be evaluated at different stages of eating, was emphasized. The contact area between the fractured food fragment and the plunger may vary depending on the brittleness of the food, and therefore, it was suggested to estimate instrumental adhesiveness from a small-deformation compression test separately from the TPA where fracture is usually encountered (Brenner et al., 2014). For example, Okadome et al. (1998) observed a good correlation between the adhesiveness of a cooked rice grain at lower compression rate (25%) with stickiness obtained by sensory evaluation.

Adhesiveness is one of the most important textural characteristics of cooked rice. While rice grains sticking to each other are not preferred in France, appropriate adhesiveness is preferred in Japan. Even if sticky rice is not liked in France, some stickiness is necessary to make *sushi* which is becoming popular in Europe. Matsuo, Takaya, Miwa, Moritaka, and Nishinari (2002) obtained a good correlation between the stickiness which was determined by sensory evaluation and the instrumentally measured stickiness by combining the adhesiveness A_3 and the maximum force of the curve with negative force in a TPA curve (as shown in Figures 3 and 13). To find a good correlation with sensory evaluated stickiness and instrumentally observed adhesiveness, it is necessary to take into account both the negative peak force and the area closed by a force–distance curve as shown in Figure 13.

The palatability of cooked rice in Japan is highly correlated with the stickiness determined by sensory evaluation (Kohyama, Ohtsubo, Toyoshima, & Shiozawa, 1998; Matsuo et al., 2002; Okadome et al., 1998). This is because cooked rice has no strong odor and taste, and the texture is the critical factor for the preference in Japan.

Kohyama et al. (1998) examined the effect of amylose content varying from 1.8% for waxy rice to 29.17% for a high amylose rice on the eating property of cooked rice of different cultivars. They showed that both adhesiveness and stickiness decreased while the hardness increased and that balance (the ratio of the stickiness to firmness) also decreased with increasing amylose content, thus reduced the palatability for most Japanese. They also showed that cooked rice of high amylose required higher total muscle activity of the jaw closing observed by EMG.

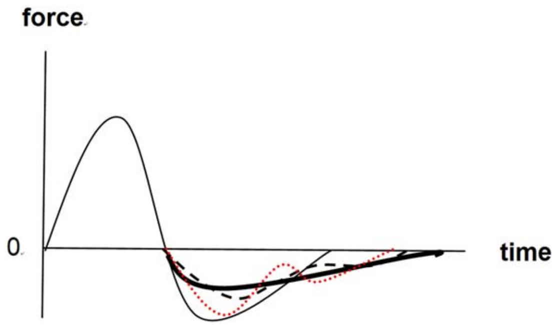

FIGURE 13 Typical force–time curves observed when a plunger is compressed onto cooked rice. When the plunger is raised from the lowest position, the negative force exerting downwards appears. While the area enclosed by the curve and the time axis (distance) is the same for two curves, a thin curve and a thick curve, the negative peak force is larger for the sample depicted by a thin line. A plateau (black broken line) or the second small peak (red dot curve) appears in some samples (modified from Nishinari, 2007; Sakasegawa et al., 2010)

Kohyama et al. (2005) studied the mastication behavior of cooked rice with different water contents, at water to rice weight ratios of 1.5, 2.0, 3.0, and 4.0. They found that the firmness decreased from 51.2 kPa (1.5 time water) to 18.0 kPa (4.0 time water) while the adhesiveness increased from 0.80 kJ/m^3 (1.5 time water) to 1.81 kJ/m^3 (4.0 time water) with increasing water content in TPA analysis. Their finding of EMG variables for one mouthful (8 cm^3) cooked rice, the activity of jaw-closing muscles decreased from 0.034 mVs (1.5 time water) to 0.029 mVs (4.0 time water) while the activity of jaw-opening muscles increased from 0.028 mVs (1.5 time water) to 0.033 mVs (4.0 time water) with increasing water content, corresponded well to TPA results; the firmness decreased and thus the jaw-closing muscle activity decreased, and the adhesiveness increased and thus the jaw-opening muscle activity increased. With increasing adhesiveness, they also found that the burst duration (see Figure 14a for the definition) for jaw-opening muscles increased.

Kohyama, Sohdi, Suzuki, and Sasaki (2016) compared textural properties of cooked rice for eight Japanese cultivars with different amylose and protein contents. Using EMG and two-bite TPA, they found that the number of chews, mastication time, and sum of muscle activities were significantly higher in the harder rice samples from high amylose cultivars. The burst duration and muscle activities per chew were also found high; however, the interburst duration was found low in rice with a high amylose content. This is in good agreement that the adhesiveness decreased with increasing amylose content (Kohyama et al., 1998; Okadome, Toyoshima, & Ohtsubo, 1999) because sticky grains might adhere to teeth. Whether the sensory adhesiveness could be evaluated separately for the adhesion on the teeth or tongue or palate is a difficult problem, and should be studied in the future.

Çakır, Koç, et al. (2012) examined the chewing behavior of caramel samples based on EMG and jaw tracking system. They prepared two caramel samples with different stickiness and hardness: 10% SP and 30% SP caramels containing 10 and 30% sweetened condensed skim milk (S) and palm kernel oil (P) at the ratio of (S) to (P) of 2:1. The hardness was 49.5 kPa for 10 SP and 41.6 kPa for 30 SP, and the former showed a higher stickiness. The closing velocity for 10 and 30 SP were found to be 65.0 and 72.1 mm/s, respectively, which is in accordance with a widely reported tendency that the closing velocity decreases with increasing hardness (as discussed in 3.4.2). They found that opening duration was 364 ms for 10 SP and 317 ms for 30 SP indicating that the more adhesive caramel required a longer duration. As for the closing duration, 357 ms for 10 SP and 311 ms for 30 SP indicating that the harder caramel required a longer duration. For caramels, the adhesiveness played an equally important role as hardness in the mastication process, and therefore, the difference in closing velocity could not be determined only by the hardness although here again the closing velocity was slower for a harder sample. In a subsequent paper, Wagoner, Luck, and Foegeding (2016) found that the adhesiveness of a caramel containing agar was higher than that containing gelatin while the hardness showed the opposite. They recognized a good correlation between the inverse of the maximum value of creep compliance and hardness, but it may not mean that adhesiveness and hardness are always in an inverse relation. It might be necessary to compare the sensory evaluation with objective measurement at the body temperature especially when a temperature sensitive ingredient such as gelatin is involved. They continue to study the adhesiveness of caramels with different mixing ratios of ingredients including corn syrup, sucrose, skim milk, butter fat, and soy lecithin (Wagoner & Foegeding, 2017). While Wagoner and Foegeding take into consideration the effects of the surface properties of the probe, which is important (Matsuo et al., 2002), it is a pity that the effect of temperature of the objective measurement mentioned in Section 3.1 was not taken into account for caramel samples containing fat.

Nitta et al. (submitted) measured the adhesiveness of noodles made from rice flour because the slipperiness is one of the most desired characteristics of noodles as well as hardness. Since the amylose content in Japonica type rice is low and the rice flour noodle is too soft and sticky, it is required to increase the hardness and reduce the stickiness. They lowered a noodle (8 mm length) with a square cross section fixed to the base of the plunger to horizontally laid another noodle of the same length, and then observed the force when the upper noodle was raised to evaluate the effect of the addition of pectin, which confers the hardness and slipperiness.

In the study of the effects of cross-linking density on the adhesion of cross-linked polymers, Sakasegawa, Tsuzuki, Sugisaki, Goto, and Suzuki (2010) pointed out that adhesion force curves depend not only on the material parameters (cross-linking density, surface tension, surface roughness, and thickness), but also on the experimental parameters (separation velocity, normal load, waiting period prior to separation, and temperature). They observed adhesion force curves by contacting one cylindrical gel to vertically positioned another cylindrical gel. They classified adhesion force curves into three or four types; in addition to the fast (thin line) and slow (thick line) decreasing behavior after the peak force depicted in Figure 12, they also found other shapes which showed a plateau (black broken line in Figure 12) or the second smaller peak (red dot line in Figure 12) in a certain range of

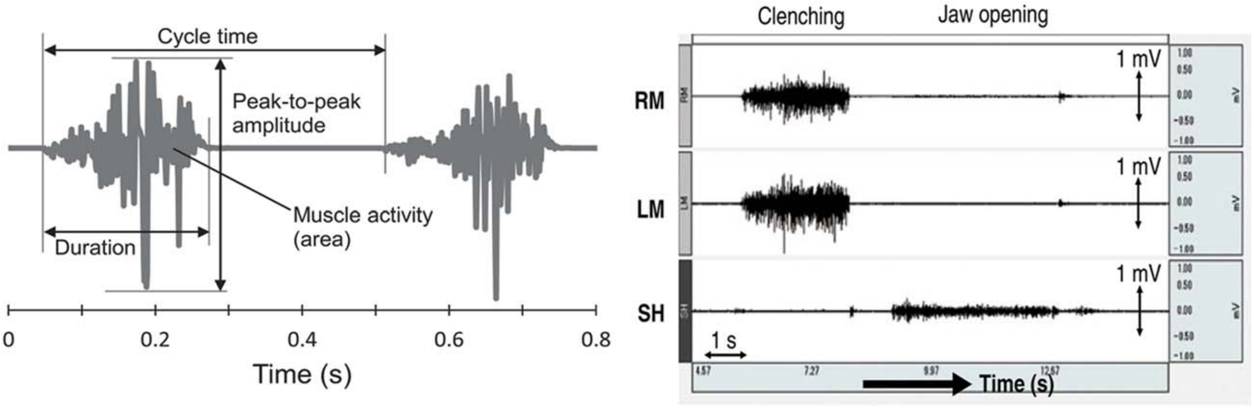

FIGURE 14 (a) Muscle activity, peak-to-peak amplitude, burst duration, cycle time observed in EMG (Kohyama, Hayakawa, Gao, et al., 2016); (b) An example of EMG signals during clenching and jaw opening. EMG signals from right masseter muscle (RM), left masseter muscle (LM), and suprahyoid muscles (SH) were recorded using a young female as a subject (Funami et al., 2014)

crosslinking density in a fast (8.0 mm/s) or slow (0.04 mm/s) separating velocity.

Grillet, Wyatt, and Gloe (2012) classified the failure mechanisms in the separation of contacted crosslinked polymer gels into adhesive separation and cohesive failure. In the adhesive separation, first the cavitation occurs, which rapidly grows and then leads to the fibrillation before complete debonding. Yield stress fluids are reported to exhibit cohesive failure where air enters the center of the fluid layer. In such a cohesive failure, the measured force during separation quickly reaches a maximum and then gradually decreases to zero. These authors, however, have not found such a cohesive failure in the separation of contacted crosslinked polymer gels. They found that the dependence of work of adhesion on the pull off velocity (separation velocity), *v*, could be represented by a power law in the *v* range from 0.01 to 10 mm/s. At slower separation velocities $v < 0.01$ and at faster separation velocities $v > 10$ mm/s, the work of adhesion was not found to depend on the separation velocity. This was found to correspond well with the mechanical loss tangent as a function of frequency: tan δ was almost zero at low frequency and showed a plateau at higher frequency than 10 Hz. As was described in 3.5.2, the stress versus strain curves depend on the compression speed. An equivalent situation is also found in the measurement of stress and strain in the separation mode when studying the adhesiveness of contacted crosslinked polymer gels. At a separation velocity of 0.01 mm/s, relatively low forces were found to be required because only the gel backbone is being deformed while most of the polymer is able to relax. For separation velocities between 0.1 and 10.0 mm/s, much of the increase in adhesion energy was attributed to the development and enhancement of the peak adhesive force observed at low strain values. For separation velocities above 10.0 mm/s, the stress versus strain curves become almost independent of separation speed. This corresponds to the plateau in tan δ at higher oscillation frequencies than 10 Hz (i.e., the polymer gel behaves similarly at 10.0 and 100.0 mm/s). This was interpreted as follows: at low frequencies and slow separation speeds, the response is dominated by the equilibrium modulus due to deformations of the gel network. At high frequencies or fast separation speeds, the physical entanglements dissipate energy through internal friction requiring a larger peak force to deform the gel and a larger overall work of adhesion.

3.7 | Cohesiveness

Since the original TPA diagrams in Figure 3 proposed by Friedman et al. (1963) or revised by Bourne as shown in Figure 4, both take the horizontal *x*-axis as time and not distance. This physical meaning was sometimes misunderstood in many papers that followed. Peleg (1976) takes the distance as *x*-axis so that the area under the curve represents the work = force × length. In addition, he pointed out that deformation decreases after the plunger reached the predetermined maximum deformation and, therefore, the TPA curves in Figure 3 or 4 should be depicted as in Figure 15 where the correct directions of the deformations are taken into account. As Peleg points out, the apparent error in Figures 3 and 4 curves is due to the fact that the chart direction was not reversed during the outstroke and, therefore, the abscissa to the right of the point LF are in fact time coordinates and not deformation. In that case, the $\Delta A'_1$ and $\Delta A'_2$ in Figure 15 represent the recoverable work after the deformation of the specimen to the predetermined length, while $\Delta A'_1$ and $\Delta A'_2$ represent the irrecoverable work. Here, note that definition of cohesiveness in Peleg's paper is wrong (the subscripts 1 and 2 should be exchanged). Peleg continues to propose to redefine the cohesiveness and other parameters of gumminess and chewiness using this corrected recoverable work, but he advises that evidence should be provided that these mechanical parameters really and generally represent the sensory textural properties, as in other cases of textural evaluation by mechanical means.

Peleg proposes to define the degree of elasticity as the ratio of the recoverable work to the total work

$$\text{Degree of elasticity} = \Delta A'_1/(A'_1 + \Delta A'_1)$$

He has been trying to find the relation between this degree of elasticity with sensory perception based on the relationship between the % correct identifications and the difference (Peleg, 2006) as was done in a series of psychophysical studies by Scott Blair.

Pons and Fiszman (1996) agreed with the criticism of Breene (1975) who doubted the validity of A_2/A_1 as cohesiveness and gave examples like chewing gum and certain types of gels with a low A_2/A_1 value, despite being perfectly cohesive, in the sense that the internal bonds maintain the integrity of the product, avoiding fracture. Chewing gum may be designed with less stickiness because, if it is too sticky and sticks to teeth, tongue, and palate, then it will cause an unpleasant feeling. Therefore, adhesiveness determined from A_3 should be small. Usually in TPA measurements, the clearance is fixed, and if the stickiness is small, then the sample height in the second compression has stayed low, and thus leads to the small value for A_2. Therefore, the validity to use A_2/A_1 value as a measure of cohesiveness may depend on mechanical characteristics of samples. Indeed, originators of TPA, Friedman et al. (1963), stated the necessity of coating the sample with talcum powder before recording the cohesiveness profile if the food sample exhibits adhesiveness, because of the distortion created by the negative adhesiveness peak.

It should be kept in mind that structural elements change their position from the initial position after the first compression and, therefore, it is meaningless to expect to extract some information on molecular forces from the value of A_2/A_1 value even after the correction proposed by Peleg. Taking into account these problems that a TPA parameter A_2/A_1 should not be called cohesiveness because users may overestimate or expect the mechanical and sensory meaning. This should rather be called *structural recoverability* which may be also influenced by adhesiveness as mentioned above, and also depends on the elapsed time from the end of the first cycle and to the beginning of the second cycle, and cannot have a simple mechanical or sensory meaning. The TPA parameter A_2/A_1 should be discussed carefully for each food taking into consideration that it depends on the measurement condition not only on an evident one such as temperature but also on the compression and decompression speed, the time between the first and second bite, and so on.

The misuse of TPA parameters for liquid foods has led to misunderstandings and confusion. Nishinari, Kohyama, Kumagai, Funami, and Bourne (2013) warned the risk of misuse of TPA parameters for liquid foods. They showed that if the TPA was applied to xanthan solutions, the cohesiveness decreased with increasing concentration of xanthan, thus the expected meaning of the cohesiveness for solid or semisolid food could not be applied for liquids. Although the cause of such a misinterpretation of cohesiveness was obvious, such an erroneous experiment and interpretation could sometimes prevail. A penetrometer widely used in the petrol industry or a simply modified penetrometer used for evaluation of thickness of liquid foods for dysphagic patients (Nishinari, Fang, et al., 2016) can be useful, However, analysis of the so-called back extrusion (Bourne, 2002, p. 128), where the liquid food is forced to flow around the space between the edge of the compressing platen and the inside wall of the cell, is not yet well established. Sandoval-Castilla, Lobato-Calleros, Aguirremandujano and Vernon-Carter (2004) combined the back extrusion and TPA for characterizing texture of yogurt with different consistencies, which were characterized well by the Ellis equation (Lobato-Calleros, Martinez-Torrijos, Sandoval-Castilla, Perez-Orozco, & Vernon-Carter, 2004) and showed TPA parameters firmness, adhesiveness, cohesiveness, and springiness. They stated that yogurts less firm and adhesive were more cohesive. However, the meaning of cohesive here seems to be different from the majority of papers which use cohesiveness as “the strength of the internal bonds making up the body of the product” (Szczesniak, 1963a, 1963b). It should be noted that thinner liquid as water shows much higher cohesiveness than that of 6% xanthan solution, 1.0 versus 0.693 (Nishinari et al., 2013) if TPA is applied without critical thinking. It is against a commonly accepted notion that a too thin liquid has a risk to cause aspiration because it scatters into less coherent smaller fragments (Ishihara, Nakauma, Funami, Odake, & Nishinari, 2011; Nakauma, Ishihara, Funami, & Nishinari, 2011).

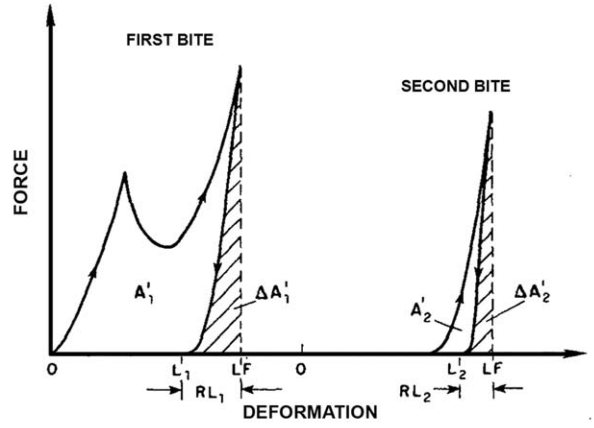

FIGURE 15 The corrected shape of a TPA curve obtained by the Instron Universal Testing Machine. LF is the predetermined maximum deformation; L1 and L2 are the retained deformations after the removal of the force after the first and second bites; RL1 and RL2 are the recovered deformations after the first and second bite. $\Delta A'_1$ and $\Delta A'_2$ represent the recoverable work after the deformation of the specimen to the predetermined length, while A'_1 and A'_2 represent the irrecoverable work (Peleg, 1976)

3.8 | Effect of the sample size and the plunger

In the compression test, using a plunger with a much larger diameter than that of a food sample gives a clear physical meaning, but the puncture test sometimes shows a better correlation with sensory evaluation. Bourne (2002, p. 124) advises to select a correct size of plunger in the puncture test: generally the diameter of the sample should be at least three times the diameter of the punch.

It should be emphasized here that the size and shape of both a probe (plunger) and a sample should be clearly written in the figure caption or in the table showing TPA parameters. Unfortunately, many papers lacking these informations have been published. When the hardness is represented by the force (*N*), this value is meaningless if these informations are not given. For the samples with curved surfaces such as peas, strawberries, tomatoes, and so on, which are subjected to penetration tests, the size, and shape including curvature should also given.

Cone penetrometry was shown to predict SH better than uniaxial compression, while “needle” (referring to a cylinder 2-mm in diameter) penetrometry showed the highest correlation with the sensory adhesiveness of cheese (Breuil & Meullenet, 2001). Similarly, Matsuo et al. (2002) reported for cooked rice that the perception of SH was better predicted using cylinder penetrometry than uniaxial compression. On the other hand, Sitakalin and Meullenet (2000) found that the SH of cooked rice was better predicted from the results of an empirical extrusion test than uniaxial compression penetration of cylindrical probes. In a recent publication, Brenner et al. (2014) demonstrated for a series of polysaccharide hydrogels that parameters from an empirical extrusion test correlated better than parameters from extension, compression and puncture tests with perception of large-deformation texture. Specifically, Brenner et al. (2014) showed that the force (or stress) measured in extrusion correlated highly with the sensory cutting effort of gels (Hayakawa et al., 2014); the ratio of the extrusion force (stress) to the Young's modulus correlated with the sensory extensibility; and a logarithmically weighted average of the extrusion force (stress) and the Young's modulus correlated with the sensory firmness.

4 | TEXTURE STUDIES OF SOLID FOODS

We have been studying texture using gels as solid food models, and trying to understand the molecular basis of the texture. We learned a lot about the importance of texture from Drs. Szczesniak and Bourne, who both demonstrated more interest in sensory aspects and thus participated also conferences on texture modifiers/hydrocolloids. Szczesniak (1986) emphasized the importance of rheological properties and summarized the functions of hydrocolloids as thickeners and gelling agents. Bourne (2000) pointed out the important unchallenged parts of food rheology highlighting the complexity of food texture at the fourth international conference on hydrocolloids. He points out the insufficiency of the present prevailing rheology which cannot include and explain the measurement and perception of food texture. In this section, physiological measurement of gels, eating difficulty, and relationships between flavor and texture are described taking into account the correlation between sensory evaluation and physicochemical properties of solid foods.

4.1 | Physiological measurement of texture of solid foods

Physiological measurement of mastication cycle numbers, sequence duration time, masticatory frequency, vertical and lateral amplitudes, and closing velocity which are finely adjusted to food characteristics and behavior in the mouth during mastication could be useful for texture studies. The adjustment is governed by a continuous control by the central nervous system to which the peripheral information from the mouth is conveyed (Hiiemae, 2004; Peyron & Woda, 2016).

To measure mastication force, Nakazawa and Togashi (2000) used three pressure transducers embedded in a resin plate. One transducer is located in the center between the upper incisor teeth, the second in the center between the bicuspid teeth, and the third on the side near the molar usually used. Nakazawa and Togashi (2000) measured simultaneously the mastication pressure and the EMG of masseter and temporal muscles using surface electrodes, and also the right and left jaw movement as described in Section 4.3.

Simultaneous measurement of jaw movement, muscle activity (EMG) and muscle work during chewing a piece of bread (13 cm^3) was examined for two subjects (van der Bilt, 2011, 2012). The jaw gape was measured by recording the position of two infrared light-emitting diodes, one on the chin and one on the forehead. The work performed by the jaw muscles during the various cycle was determined by the areas of the bursts of the instantaneous work signal. It was observed that EMG and work bursts occur while the jaw is closing. In both subjects, work bursts declined while mastication proceeds and the food bolus is softened. One subject chewed the bread 8 times whereas the other subject chewed the bread 34 times, thus more than four times longer, before swallowing. Such a large inter-individual differences is found in Woda et al. (2006) who examined the interindividual variability for EMG recordings and vertical displacement of the mandible in two subjects during a complete sequence of mastication of a hard elastic model food.

Kohyama (2015) recently reviewed the multipoint sheet sensor which she has been using to analyze the mastication of foods with different consistencies. This sensor is thin and flexible, and can measure the load and contact area during mastication of foods between the sensors. Although the bite force and bite duration detected are different in each subject, a common pattern is observed for each food. Hard food with a high modulus produces a steeper slope in the load–time curve at first stage. Two peaks appeared for carrot and *yokan* (sweetened red bean paste gelled with agar and sucrose), and more multiple peaks were observed in brittle and crispy foods such as cracker and *senbei* (rice cracker), but the first peak was missing for the bread mastication (Kohyama, Sakai, & Azuma, 2001).

EMG using electrodes attached onto the surface of the human face has been used to measure the muscle activity during chewing to fill the gap between the sensory evaluation and instrumentally observed TPA parameters (Espinosa & Chen, 2012; Funami, Ishihara, & Kohyama, 2014; Kohyama, Hayakawa, Gao, et al., 2016; van der Bilt, 2012). EMG variables obtained are shown in Figure 14a,b.

Mioche (2004) showed an excellent correlation between muscle activity and sensory evaluated tenderness of meat suggesting that such a tenderness perception was based in muscle activity; the muscle work was shown to increase linearly with decreasing tenderness. Imai and Sato (2008) applied EMG to 24 thinly sliced or leaf-shaped foods such as seaweeds, vegetable leaves, fried tofu (*aburage*) for which conventional uniaxial compression cannot be simply applied, and got a high correlation with sensory evaluation by combining results obtained for other 24 foods which were formed into cubes of a mouthful amount and were subjected to both uniaxial compression and EMG. Combination of the data collected by EMG and the conventional TPA parameters obtained by uniaxial compression has been proved efficient to improve the understanding of the relation between the sensory evaluation and instrumental measurement (Funami et al., 2014; Kohyama, Hayakawa, Gao, et al., 2016).

Jaw closing muscles, anterior tempolaris, masseter or orbicularis oris, and jaw opening muscles anterior belly of the digastric, mylohyoid,

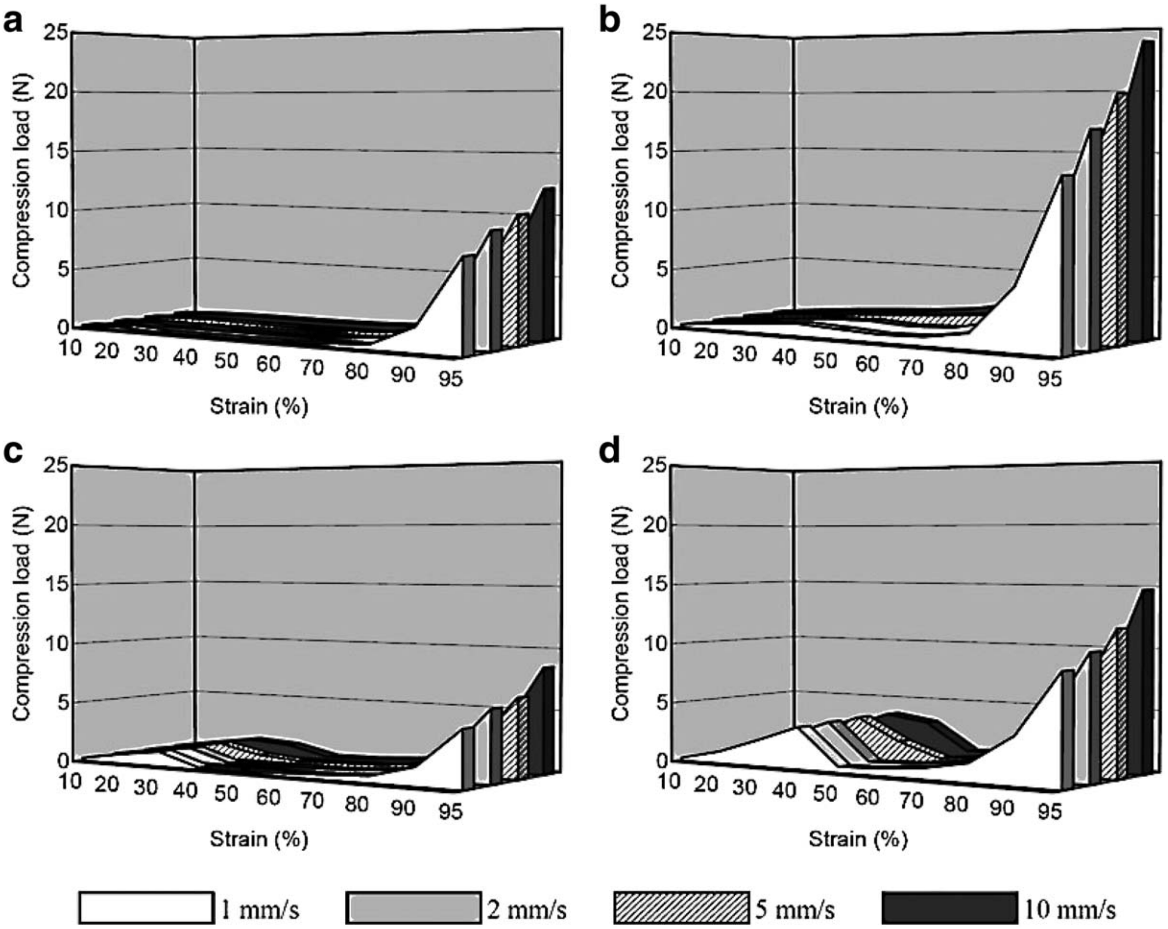

FIGURE 16 Strain–load curves, at various compression rates, of deformable gels (a) S-1000; (b) S-4000; and brittle gels (c) K-1000; (d) K-4000 up to 95% strain by uniaxial compression. Measurements were carried out at 20C by compressing cylindrical gel samples (20 mm diameter, 10 mm height) using a 100 mm-diameter flat plunger at various compression rates: 1, 2, 5, and 10 mm/s (Ishihara et al., 2011)

geniohyoid, and suprahyoid muscles have been chosen for EMG studies on food texture, and the good correlation between the muscle activity and the mechanical properties of foods has been obtained. As is shown in Figure 14b, EMG signals can be seen only for right and left masseter when a subject clenches the upper and lower teeth, and only the EMG signals for suprahyoid can be detected when the jaw is opening.

Previous reports on human mastication have clarified the correlation of the EMG activity with mechanical properties of foods. Most of the EMG studies have focused on solid foods fractured by mastication using the back teeth during oral processing.

4.2 | EMG study of mastication process of gels

Recently, Ishihara et al. (2011) discussed the relation between EMG data and the mechanical properties of soft gels with different mechanical characteristics, brittle gels made from deacylated gellan gum (K-1000 and K-4000 gels, with the yield gel strength 1,000 Pa and 4,000 Pa, respectively) and deformable gels made by mixing deacylated gellan gum and psyllium seed gum (S-1000 and S-4000 gels, with the yield gel strength 1,000 Pa and 4,000 Pa, respectively). Force–deformation curves of these four gels at different compression speeds are shown below (Figure 16).

Deformable S gels exhibited no distinct yield peaks while brittle K gels exhibited a distinct peak at around 30–40% strain at each compression speed, which has been observed also for other brittle gels such as agar gels. Both gels showed the maximum load at the largest strain 95%. The compression load increased with increasing concentration of gelling agent and compression speed. When compared at equivalent gel strength, the compression load for S-gels was more dependent on the deformation rate than that for K-gels, which is consistent with the different natures of S-gels and K-gels: the mechanical loss tangent is smaller in K-gels than in S-gels, indicating that the former is more solid-like than the latter, thus the behavior of the latter is more time-dependent.

Since both S-gels and K-gels used in this study were designed for people with difficulty in mastication and swallowing, all these gels were crushed between tongue and hard palate by healthy young subjects, and therefore, the muscle activity was only seen for suprahyoid and not for masseter. The EMG activity of the suprahyoid musculature correlated well with the compression load of gels at extremely large strains (≧90% strain) and with sensory perceived hardness. This high correlation of EMG activity with SH was similarly observed for harder foods which are

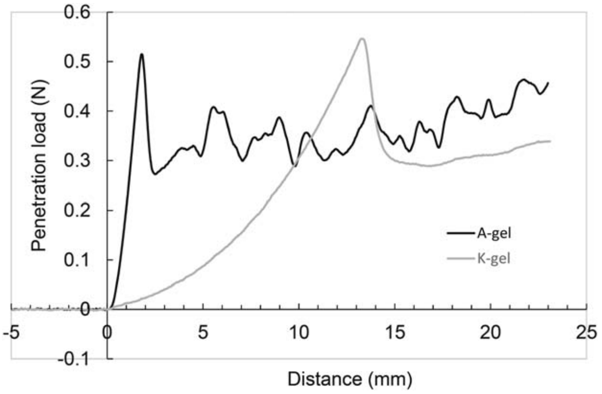

FIGURE 17 Typical penetration curves of (*A*) agar and (*K*) mixed gels. A gel sample in a cup with a diameter of 60 mm and a height of 25 mm was penetrated at a crosshead rate of 10 mm/s using a cylindrical stainless plunger of 3 mm in diameter at 20 ± 1C. The test was terminated at a clearance of 2 mm (Kohyama, Hayakawa, Gao, et al., 2016)

masticated by teeth. For solid foods processed by mastication, it has been reported that any mechanical property under small strains, particularly within the linear viscoelastic region, does not influence the behavior of human mastication, but mechanical properties under large or extremely large strains do (Kohyama, Sasaki, & Hayakawa, 2008).

Kohyama, Hayakawa, Gao, et al. (2016) studied the mastication behavior of two gels with the same fracture force but different fracture deformation. As brittle gels, 1.2 w/w% agar gels (*A* gels hereafter), and as deformable gels, mixed gels consisting of 0.26 w/w% konjac glucomannan, 0.46 w/w% kappa-carrageenan, and 0.46 w/w% locust bean gum (*K* gels hereafter) were prepared. A result of a typical penetration test and EMG signal for *A* gel and *K* gel are shown in Figures 17 and 18. Since the swallowing event is not identified with certitude only from EMG activity of masticatory muscles, each subject was asked to press the button with the opposing thumb of the ground electrode to indicate the start of chewing, every swallow, and the end of eating (longer signal).

The first fracture of *A* gels occurred when the penetration distance from the top surface of gels was about 2 mm (Figure 17). While *A* gels showed multiple fracture points, *K* gels had a fracture point peak at a penetration distance of about 13 mm, but did not fragment further after the test. It should be noted that although the fracture force was approximately the same for an *A* gel and a *K* gel, the fracture stress in *A* gel was higher than that in *K* gel because the cross sectional area of *A* gel at fracture point was much smaller than that in *K* gel. This difference between a brittle gel and a deformable gel is often seen for other gels. After fracture at about 0.5 N, both gels showed load drops with similar magnitudes of approximately 0.2 N.

The time for oral processing was defined as the time between the first EMG activities close to the start signal and the end of EMG activities close to the end signal (top horizontal arrows in broken line in Figure 18). The entire time for oral processing was divided into the Stages T1, from the beginning to the first swallowing signal and T2, from the end of Stage T1 until the last swallowing signal (Funami et al., 2014; Kohyama et al., 2014).

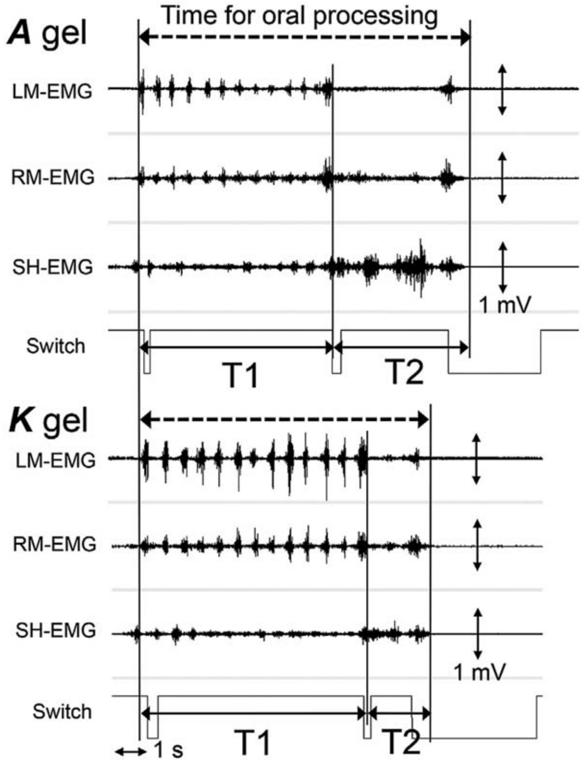

FIGURE 18 Example of electromyograms during free eating of gels. From the top; EMG signals of left masseter (LM), right masseter (RM), and suprahyoid (SH) muscles, and output of button switch. Subjects were asked to push a button to indicate the start of the oral processing, every swallow, and the end of eating (longer signal). Times for oral processing are shown at the top with broken lines. Stages T1 (from the start to the first swallow) and T2 (following period until the end) were also analyzed. Samples are 6-g of agar (*A* gel) and mixed gels of konjac mannan, κ-carrageenan, and locust bean gum (*K* gel). The numbers of swallows were two in both cases (Kohyama, Hayakawa, Gao, et al., 2016)

EMG variables, number of muscle actions, time for oral processing, number of swallows increased with increasing a mouthful mass of *A* gels and *K* gels. A double logarithmic plot of EMG variables and a mouthful mass showed a straight line with a slope about 0.7 as shown in Figure 19. With increasing amount of served gels from 3, to 6, 12, and 24 g, increased EMG activity, number of chews, and time for processing increased. The slope 0.7 (evidently smaller than 1) indicates that the physiological measures did not increase at the same proportion to the increase in gel size.

Kohyama further studied the effect of chewing side on the EMG variables in natural eating gels of different serving size. Eleven subjects participating in the test had different preferred sides of chewing: five the left, two the right, and four with no preferred side. With the increasing size of served gels from 3, to 6, 12, and 24 g, EMG activity, number of chews, the time for processing increased as shown in Figure 19 and the contribution of nondominant side (NDS) increased (Table 3) because humans chew small quantity of gels with only a DS. The numbers of chews, total muscle activities, and entire oral processing times for gels with similar fracture stress but with different fracture strain and elastic moduli were similar when similar masses were served.

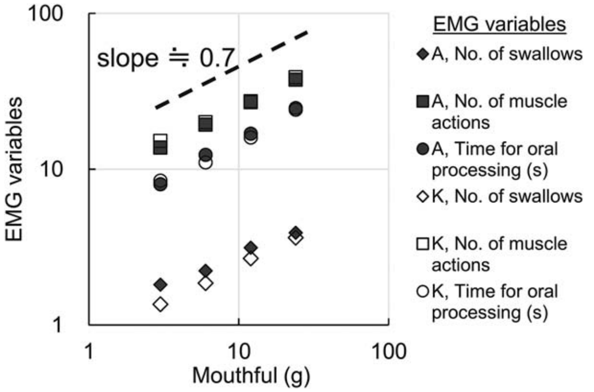

FIGURE 19 Effects of mouthful quantities on numbers of chews and swallows, and times for oral processing for (*A*) agar and (*K*) mixed gels. A slope of 0.7 is indicated with a broken line (Kohyama, Hayakawa, Gao, et al., 2016)

Masseter EMGs in the mastication of 24 g *A* and *K* gels analyzed before the first swallow for the DS and NDSs as well as the entire time for oral processing are shown in Table 3.

As shown in Table 3, muscle activity was larger for *K* gels than for *A* gels. It is expected that *A* gels will be broken down into smaller fragments after some chewing while *K* gels need more chewing to be broken down into similar sizes. Indeed, the time before the first swallow 10.9 s for *A* gel is slightly shorter than 12.3 s for the *K* gel, but the entire processing time 24.7 s for *A* gel is almost the same as 24.1 s for *K* gel. This may mean that *A* gel can be broken down in a shorter time and fewer number of chews, but more time is required to mix saliva with fragments of *A* gel to make a cohesive bolus ready for swallowing than for the *K* gel, and therefore, the entire time for oral processing is nearly the same for both gels. This is in line with a previous report (Ishihara et al., 2011) where the bolus formation was compared for brittle gels (deacylated gellan gels) and deformable gels (gellan/psyllium seed gum composite gels). As is well known (Chen, 2009), food should be broken down into small fragments and mixed with saliva for bolus formation. Ishihara et al. (2011) concluded that gel particulates formed by artificial mastication for gellan single gels are less deformable and less miscible with saliva. On the other hand, the gel particulates for gellan/psyllium composite gels are bound to each other due to the function of psyllium seed gum, which entraps saliva into the structure and swells.

A gels were easily broken into small pieces during the first chew, and the fragments were probably chewed on both sides during subsequent chewing cycles. Usually, the first and later chews of nonfragmented gels are performed on a single side, while fragmented gels may be chewed using both sides.

Brittle *A* gels tended to be broken down with higher probability than *K* gels, and were processed by both sides, leading to a higher NDS/DS ratio. This ratio increased with increasing mouthful size up to 12 g for both *A* gels and *K* gels, and although this ratio for *K* gels increased with increasing serving size, the ratio for *A* gel showed a lower value with further increase of the serving size (Figure 20). The reason for the decrease in the ratio for *A* gels may be attributed to the early swallow of part of 24 g *A* gel following easy fragmentation in one chew.

TABLE 3 Masseter EMGs analyzed for the DS and NDS before the first swallow (rows 1–8) and the entire time for oral processing and number of chews (rows 9–10) for 24 g *A* gel (Middle column) and *K* gel (right column) (Kohyama, Gao, Ishihara, Funami, & Nishinari, 2016)

	24 g *A* gel	**24 g *K* gel**
Amplitude, DS (mV)	1.39	1.78
Amplitude, NDS (mV)	0.86	1.32
Muscle activity per chew, DS (mV)	0.0034	0.0383
Muscle activity per chew, NDS (mV)	0.0226	0.0287
Total muscle activity, DS (mV)	0.679	0.796
Total muscle activity, NDS (mV)	0.403	0.556
Time before the first swallow (s)	10.9	12.3
Number of chews	19.0	20.5
Entire oral processing time (s)	24.7	24.1
Entire number of chews	37.6	39.0

4.3 | Breakdown of soft gels between tongue and palate

The tongue plays important roles in food oral processing: transporting the ingested food to a proper location for biting and mastication, mixing the fragmented foods with saliva and then transporting to the pharyngoesophageal region. The chemoreceptors and mechanoreceptors on the tongue surface act as the most delicate sensation systems for detecting and discriminating the taste and textural properties of foods (Hiiemae & Palmer, 1999; Laguna & Chen, 2016). For a very soft food, the tongue compresses it against the hard palate (Arai & Yamada, 1993; Hori et al., 2015; Morita & Nakazawa, 2000, 2002). Tongue pressure measuring instruments have been used: a polymer balloon or three bulbs are inserted between the tongue and palate, and the compressive pressure is measured (Hewitt et al., 2008; Utanohara et al., 2008; Yoshikawa, Yoshida, Tsuga, Akagawa, & Groher, 2011).

Recently, Alsanei, Chen, and Ding (2015) examined tongue strength and pressure during the breaking of vegetable gels and mashed potatoes combining a conventional compression and a Iowa Oral Performance Instrument. They measured the maximum isometric tongue pressure (MITP) as the maximum pressure exerted for a balloon between the tongue and the hard palate when the balloon was compressed by the possible maximum effort of the subject and found the average value 50 kPa, although the individual differences were quite large. They found a good correlation between threshold hardness at which subject felt it was difficult to crush only by the tongue and the separately measured MITP. They found also a good correlation between the in-mouth measured tongue palate breaking pressure (a balloon was put on a food sample which is set on the tongue) and the instrumental breaking pressure where a balloon was put on the sample which was set on the table of a texture analyser for vegetable gels which show a clear fracture point. While the in-mouth results show smaller values than instrumental values for mashed potato samples which was attributed to the difference between the yielding nature of mashed potato rather than the clear fracture of the vegetable gels, that

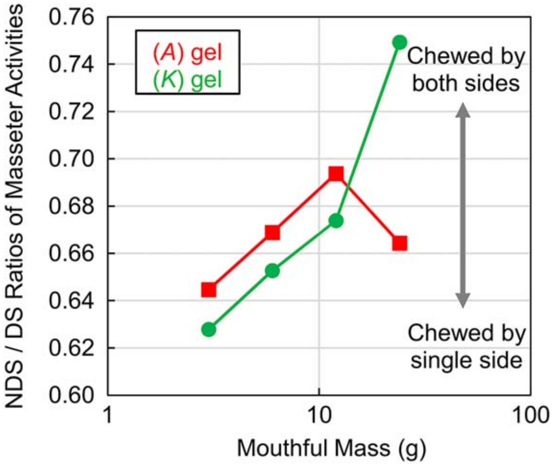

FIGURE 20 Effects of mouthful mass on chewing sides for *A* gels (red square) and *K* gels (green circle). DS = dominant side of chewing; NDS = nondominant side of chewing (Kohyama, Gao, Ishihara, Funami, & Nishinari, 2016)

make the judgement of the breaking point more difficult for mashed potato. It was roughly estimated that subjects can comfortably compress and break up soft gels which have strengths less than half of the tongue strength.

The masseter activity measured by EMG was found very weak for very soft foods which were not chewed using molars as reported by Nakazawa and Togashi (2000) and Ishihara et al. (2011). This is because the suprahyoid muscles also coordinate with tongue movements, involving the compression of the tongue against the hard palate, the protrusion of the tongue and the transportation of the bolus at the beginning or oropharyngeal phase of swallowing (Taniguchi, Tsukada, Ootaki, Yamada, & Inoue, 2008; Vaiman, Eviatar, & Segal, 2004).

To study the tongue-palate squeezing process quantitatively, an artificial tongue was prepared using silicone rubbers and was placed on a metal stage of an Instron type apparatus (Ishihara et al., 2013). The breakdown process was mimicked by the uniaxial compression of a soft gel placed on the artificial tongue, and was compressed by a metal plunger which played the role of the hard palate. Artificial tongue models with different elastic moduli could be prepared by changing the concentration and mixing ratio of silicon rubber, silicone oil, and curing agent. Since the apparent elastic modulus E_a of the human tongue ranged from 20 kPa at a relaxed state to 120 kPa at a tension state, three kinds of artificial tongues S40 ($E_a = 18$ kPa), S50 ($E_a = 55$ kPa), and S60 ($E_a = 115$ kPa) were used in the compression test. Artificial tongue S40 corresponded to the human tongue in a relaxed state, and artificial tongue S60 corresponded to the human tongue in a tension state. Seven kinds of agar gels A1-A7 with different fracture forces ranging from 4 to 51 N (for cylindrical gels of 20 mm diameter and 10 mm height) with equivalent fracture strain (ca. 60%) were prepared by mixing multiple agar sources (Ishihara et al., 2013). The apparent elastic moduli of A1–A7 gels determined from a slope of stress–strain curve between the origin and 20% strain ranged from 5.4 to 140 kPa.

Typical force–strain curves of agar gels A3, A4, A5, and A6 compressed by artificial tongues S40, S50, and S60 are shown in Figure 21. Snapshot images are shown in Figure 22. As shown in Figures 21 and 22, the deformation of the artificial tongue was negligible for soft agar gels A3 and A4 when these agar gels were deformed and broken, while for hard gels A5 and A6, comparable deformation of both agar gels and artificial tongue could be seen. This tendency corresponds well to the selection of human strategy for size reduction; agar gels that fractured through instrumental compression between the artificial rubber tongue and the metal plunger were compressed between the tongue and hard palate for size reduction, whereas agar gels that did not fracture through instrumental compression on the artificial tongue were masticated using teeth for size reduction.

Arai and Yamada (1993) reported that food texture was recognized by initial compression (deformation rate, about 12%) between the tongue and hard palate, around the incisive papilla based on the visual analysis of cineradiography for agar and gelatin gels. In their sensory evaluation, subjects were asked which oral strategy was selected for size reduction using agar gels with different mechanical properties. It was suggested that the decision to select the tongue-palate compression or teeth mastication should be done before fracture of foods. How would the oral strategy be determined at the early stage of oral processing before fracture? A possible reason is that humans may judge from past experience that foods with a larger elastic modulus show a larger fracture stress as in the case of agar. This is also consistent with neural feedback controlling the bite velocity suggested by Dan and Kohyama (2007) as discussed in 3.4.2. However, a food with higher

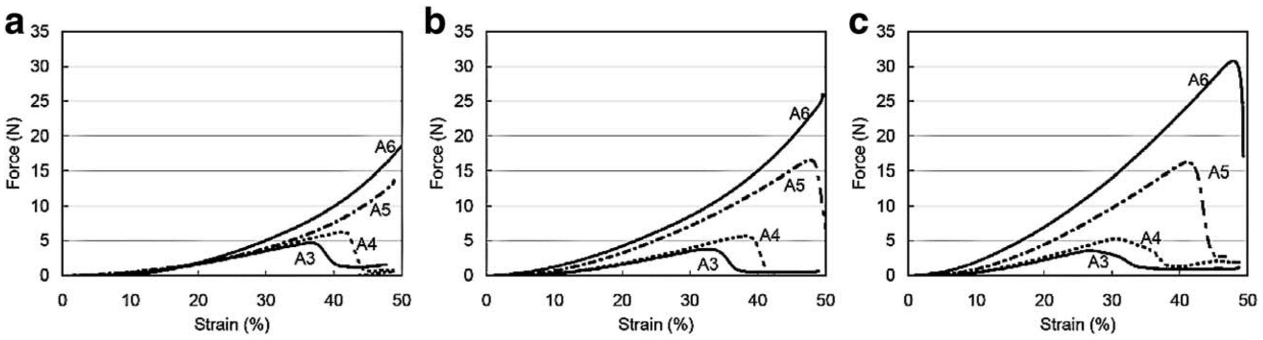

FIGURE 21 Force–strain curves of agar gels on artificial tongues at a crosshead speed of 10 mm/s. Both agar gel and artificial tongue were molded into cylindrical shape of 20 mm in diameter and 10 mm in height. Agar gels A3–A6 were compressed on each artificial tongue (a) S40; (b) S50; or (c) S60 (Ishihara et al., 2013)

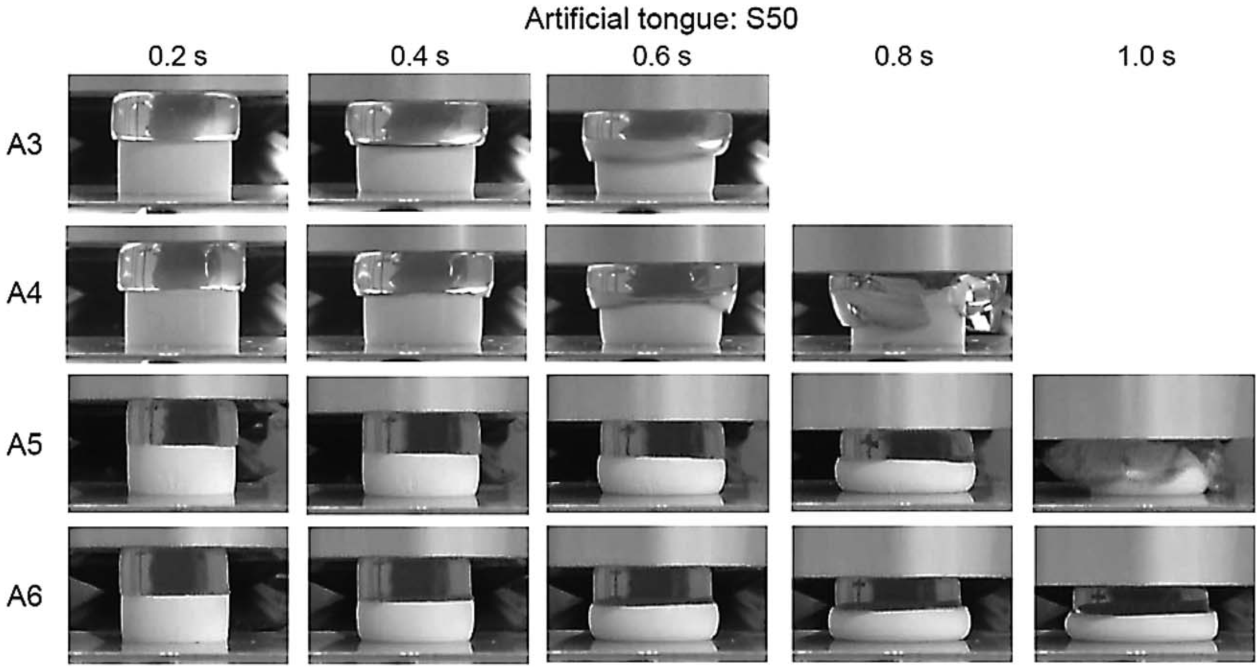

FIGURE 22 Snapshot images representing the deformation behavior of agar gels A3–A6 on an artificial tongue S50 during compression at a crosshead speed of 10 mm/s. Images were captured at a time interval of 1/15 s (Ishihara et al., 2013)

elastic modulus determined at a small deformation range does not always show a higher fracture stress, for example, an agar gel with a larger elastic modulus can show a smaller fracture stress than a gelatin gel which has a smaller elastic modulus but has a larger fracture strain as shown in Figure 1 (Nishinari et al., 1980). Therefore, the determination of oral strategy at an earlier stage before fracture reported in Arai and Yamada (1993) and in Ishihara et al. (2013) stays a difficult problem which should be further studied.

Fracture probability of gels determined by using an artificial tongue S 50 ($E_a = 55$ kPa) was found to correspond to the ratio of subjects who decided to use tongue-palate compression instead of mastication. From a physiological point of view, the oral strategy for size reduction may be determined by sensing the difference in the deformation between a food and the tongue. This was applicable to the gels of which fracture strain was below 65% as in agar gels (Ishihara et al., 2013), but not to the gels of which fracture strain was above 70% as seen in gellan gels (Ishihara et al., 2014). In the examination of the selected oral strategy using gellan gels with different deformability prepared by mixing low and high acyl gellan gums, Ishihara et al. (2014) found that most subjects (equal to or more than 80%) decided to use mastication instead of tongue-palate compression based on resistance to deformation in compressing the gel samples to a relatively smaller degree for comparatively brittle gels, whereas most subjects (equal to or more than 90%) did so by force resistance in compressing of the gel samples to a relatively larger degree when evaluating more deformable gels. This conclusion was based on the answers of subjects to the question about the first size reduction from tongue-palate compression to mastication; resistance of deformation in compressing the gel sample to a relatively smaller degree, resistance of deformation in compressing the gel sample to relatively larger degree, perceived force in compressing the gel sample to relatively smaller degree, and perceived force in compressing the gel sample to relatively larger degree.

4.4 | Eating difficulty and extrusion

Eating difficulty is an ambiguous and difficult attribute to quantify. Since eating capability is related with many factors as recently reviewed by Laguna and Chen (2016). Eating difficulty is caused by various factors: food handling difficulty (e.g., hand gripping, finger gripping, and coordination), oral manipulation difficulty (e.g., lips sealing, biting and mastication, tongue pressing, and swallowing), oral sensing difficulty (e.g., tasting and texture discrimination), and cognitive difficulty (e.g., information seeking and processing, opinion forming, and decision making) (Alsanei & Chen, 2014).

Hayakawa et al. (2014) tried to understand eating difficulty in the mouth by sensory analyses of hydrocolloid gels with different rheological properties. Twenty sample gels of KC, ι-carrageenan, locust bean gum, low- and high- acyl gellan gum, low methoxyl pectin, xanthan gum, agar, mixtures of these polysaccharides, and gelatin were used as food models. Twelve panelists rated the eating difficulty for each gel on a 150-mm unstructured line scale anchored with “extremely easy” at the left end and “extremely difficult” at the right end. Although in some experiments to determine hardness, standard sample foods as were proposed by Szczesniak et al. (1963) may be used, no reference sample was used because eating difficulty is a multidimensional attribute. Subsequently, Hayakawa et al. (2014) also evaluated six texture attributes including firmness (force required for achieving deformation of a sample), cutting effort (force required for achieving fracture of a sample), elasticity (rapidity of recovery from deformation to its original shape after releasing force), extensibility (degree to which the sample

TABLE 4 Five gel samples studied in Hayakawa et al. (2014)

Ingredients (%w/v)	Puncture test F.force	 F.distance	Sensory evaluation difficulty	PCS 1PC	 2PC
κ-CAR 1.0 + LBG1.0	1.391	7.40	74	3.91	−0.95
LBG 0.5 + Xan 0.5	0.677	9.01	65	1.89	1.32
ι-CAR 3.0	0.113	5.49	56	−0.09	1.80
Agar 1.0	0.681	2.65	30	0.17	−1.71
Gelatin 3.0	0.125	6.15	13	−2.15	−0.49

Difficulty, eating difficulty, 0 (easiest), 100 (most difficult).
CAR = carrageenan; F.force = fracture force; F.distance = fracture distance; LBG = locust bean gum; PCS = principal component scores; Xan = xanthan gum.

was extended biaxially on a horizontal plane by the tongue and palate), adhesiveness (degree to which the sample adheres to the tongue and palate or coats the surface of the palate), and melting rate in the mouth (rapidity of change of the sample gel into liquid in the mouth). A principal component analysis characterized the texture attributes of the sample gels on axes of resistance to fracture (principal component 1) and stickiness and flexibility (principal component 2). The contour of the resulting eating difficulty scatter diagram revealed that resistance to fracture and stickiness and flexibility were critical determinants of eating difficulty.

Kohyama et al. (2015) examined the eating difficulty by EMG for five gels with different textures used in Hayakawa et al. (2014) (Table 4).

Kohyama et al. (2015) measured EMG variables of jaw-closing muscles (right and left masseter muscles) and jaw-opening and tongue movement muscles (suprahyoid muscles) taking into account that the eating difficulty comprises several factors such as difficulty in deforming, cutting off, crushing, moving, gathering chewed fragments, flowing, difficulty in chewing, forming a bolus, and swallowing (Hayakawa et al., 2014). They found that the time for oral processing was longest (20.1 s) for the most difficult sample 1% κ-CAR + 1% LBG and the shortest (6.6 s) for the easiest sample 3% gelatin. They also found that total duration and activity of masseter and suprahyoid muscles were also largest for the most difficult gel and smallest for the easiest gel. Thus, they clearly showed that the eating difficulty of these five gels was quantified by EMG variables. This study was carried out for healthy persons because it is difficult to do this for persons with difficulty in mastication and swallowing.

Laguna, Asensio Barrowclough, Chen, and Sarkar (2016) studied the eating difficulty of six products (carrot, banana, mozzarella, potato, soft cheddar, and hard cheddar) and found that the hardest food, carrot required a greater number of chews and the longest processing time in mouth, which they found in accordance with the conclusion by Witt and Stokes (2015). However, hard cheddar was found the most difficult although it resided a shorter time in mouth and the break force was lower than carrot, which led these authors to think that it is not only the force at break but also the structural property of the food that plays an important role in perceived difficulty. They concluded that structured cell-wall or fibrous foods (banana, potato, and carrot), and gel-like foods (mozzarella, mild cheddar, and hard cheddar) cannot be treated in the same way when considering eating difficulty. In addition to the structural aspects, they also pointed out the necessity to take into account food composition (different level of water, fat, protein in vegetables, or cheese); for example, chips with different fat content varied dramatically during mastication although initially their texture was perceived not so differently (Boehm, Baier, & Stokes, 2013).

Using three natural foods (peanuts, cheese, and carrots) and a standardized silicone based test food, Fontijn-Tekamp, van der Bilt, Abbink, and Bosman (2004) examined the relationship between masticatory performance and swallowing threshold. In this study, the size distribution of fragmented foods was used to evaluate masticatory performance. They found that bad chewers did not necessarily chew longer before swallowing than good chewers, indicating that bad chewers tended to swallow larger food particles. The relation between mastication performance and particle size distribution obtained by sieving the bolus just before swallowing was examined using 10 foods of different texture and varying in water or lipid content (peanuts, carrots, gherkins, stoned green olives, mushrooms, egg white, ham, chicken breast, emmental cheese, and coconut) (Jalabert-Malbos, Mishellany-Dutour, Woda, & Peyron, 2007). Jalabert-Malbos et al. (2007) found that the number of cycles, sequence duration, and masticatory frequency varied among subjects and foods, and that the particle size distributions differed among foods but were similar among subjects. They reported that soft and high water content foods were rapidly swallowed (14–20 masticatory cycles) while harder foods needed more cycles and longer mastication before swallowing. Lucas and Luke (1986) reported a significant correlation ($r = .69$) between the number of chewing cycles and masticatory performance for a group of 35 dentate subjects chewing carrots. Therefore, subjects with a less good masticatory performance must continue chewing until the carrot particles are small enough to be safely swallowed. Woda et al. (2010) reported that the upper limit of the median particle size of carrot particles swallowed by a group of young persons with good oral health was 4.0 mm. Because of the intermediary deglutition, the size distribution of the bolus should be interpreted with great caution.

Physiological factors influencing masticatory performance such as loss of teeth, occlusal contact area, malocclusion, bite force, salivary flow, age, gender, sensory feedback have been reviewed (Engelen & van der Bilt, 2008; van der Bilt, 2011).

Brenner et al. (2014) used the same series of polysaccharide gels (without gelatin) used in the study by Hayakawa et al. (2014) and reported on an extrusion test and its correlation with sensory perception.

The extrusion test was implemented on an XT.T2 Texture Analyzer (Stable Micro Systems, Surrey, U.K.). After attaching the piston of the syringe to the texture analyzer with a specialized fixture, the piston was inserted into the syringe, which was held by a stage. Insertion of the piston was done at variable speeds between 0.2 and 15 mm/s, corresponding to volumetric flow rates in the range of 0.4–30 ml/s. The extrusion force was not found to depend strongly on the volumetric flow rate, indicating a predominantly elastic contribution to the force. It was shown that the force (or stress) measured in extrusion correlated highly with the sensory cutting effort of gels; the ratio of the extrusion force (stress) to the Young's modulus correlated highly with the sensory extensibility defined as in Hayakawa et al. (2014); and a logarithmically weighted average of the extrusion force (stress) and the Young's modulus correlated highly with the sensory firmness (Hayakawa et al., 2014). A combination of the Young's modulus and the extrusion force correlated well with perception of firmness. The robust correlations depended weakly on the flow rate in extrusion. Notably, the correlation obtained was higher than that with TPA parameters. Brenner et al. (2014) showed the correlation of several empirical and fundamental large deformation tests with texture, and suggested that the higher correlation with extrusion reflects the closer mixed-mode deformation in mastication.

Gelatin-based gels were perceived as less firm and less hard (Tomczynska-Mleko, Brenner, Nishinari, Mleko, & Kramek, 2014) than expected based on their mechanical properties compared to polysaccharide gels that have the same mechanical properties at room temperature but melt well above body temperature, underlying the importance of the measurement temperature for gels that melt during mastication (Brenner et al., 2017).

4.5 | Flavor release from gels

All foods have both texture and flavor, and it is well known that texture and flavor interact with each other (Koliandris et al., 2010; Nishinari, Takemasa, et al., 2016; Salles et al., 2010; Stieger, 2011). Since the pioneering work of Pangborn, Trabue, and Szczesniak (1973) and Pangborn and Szczesniak (1974), it has been recognized that texture modifies the taste intensity of foods. This problem has been attracting much attention recently because it is expected to give the basic information for the reduction of salt or sugar. It has been generally accepted that sweetness intensity was evaluated higher in softer gels than in firmer gels (Clark, 2002) or in more brittle gels than in more deformable gels (Morris, 1993). Morris interpreted his results that brittle gels fractured at small strains tend to be broken into smaller fragments increasing the surface are which contact with taste buds. Clark found two exceptions to this general tendency; a gelatin gel with the same hardness showed a stronger sweetness and a mixed gel of low acyl gellan/xanthan/locust bean gum showed a weaker sweetness. Since the former melts in the mouth and the latter is cohesive, therefore Clark's finding is not contradictory with Morris's finding but rather complimentary. Bayarri, Izquierdo, and Costell (2007) reported that sweetness was enhanced for weaker gels of kappa-carrageenan and gellan using sucrose and aspartame as sweeteners. Sala, Stieger and van de Felde (2010) emphasized the importance of serum which is exuded upon mechanical compression of gels (Nishinari & Fang, 2016).

Serum release from gels is related to microstructural characteristics of the gels, and can be described by flow through a porous medium and plays a key role in juiciness perception (van Vliet & Walstra, 1994). Since water soluble tastants are contained in the serum, the serum release determines the flavor intensity in gels. The important role of serum release was shown using mixed whey protein isolate/gellan gum gels as model systems and using a method to study permeability. (van den Berg, van Vliet, van der Linden, van Boekel, van de Velde, 2007). They showed that serum release induced by compression is related with the syneresis occurring without compression. Although this is an important phenomenon for gel-like foods, it has not been studied quantitatively except for cheese and related dairy products (van Vliet, van Dijk, Zoon, & Walstra, 1991).

Wang, Yang, Brenner, Kikuzaki, Nishinari (2014) and Yang et al. (2015a, 2015b) studied sucrose release from agar gels and examined the relation between the sucrose release, gel structure, and rheological parameters. It was shown that sucrose release from agar gels by diffusion is much smaller than that induced by compression (Wang et al., 2014). It was shown that inhomogeneous gels were formed when agar was added into sucrose solutions (Method 1) while homogenous gels were formed when sucrose was added after the dissolution of agar (Method 2) beyond the sucrose concentration of 50%. Sucrose release ratio and syneresis from gels prepared by Method 2 decreased with increasing sucrose concentration, while both these decreased up to sucrose concentration 50% and then showed an upturn with increasing sucrose concentration as shown in Figure 23.

The surface area of the fragments produced by compression became a maximum at a compression speed about 1 mm/s. The diffusion of sucrose is not hindered by network chains in these polysaccharide gels although the possibility that local viscosity might hinder sucrose diffusion to some extent could not be ruled out. This is consistent with the reported mesh size of agarose gels which is much larger than the sucrose molecule (Nishinari, Fang, et al., 2016). When a great amount of sucrose is added (>50%) which is often the case in Japanese traditional agar-based sweets, the structural inhomogeneity appears when agar was added together or after dissolution of sucrose as mentioned above, and then syneresis and sucrose release were enhanced (Nishinari, Fang et al., 2016; Yang et al., 2015a, 2015b).

Kohyama, Hayakawa, Kazami, et al. (2016) examined the correlation between the instrumental compression test with time intensity sensory evaluation for agar gels (0.5, 1, and 1.5 w/w%) containing sucrose 10–50 w/w%. Agar was dissolved first and then sucrose was added to prepare homogeneous gels because when agar was added simultaneously with sucrose, it resulted in gels that are inhomogeneous above a sucrose concentration of about 45% (Yang et al., 2015a). In homogeneous gels, fracture stress increased with increasing agar concentration and sucrose concentration as shown below in Figure 24 (left), while the maximum sweetness intensity decreased with increasing concentration of agar (Figure 24 right) which is consistent with previous findings (Clark, 2002; Morris, 1993). The maximum sweetness intensity increased with increasing sucrose concentration, and this increasing rate seems to be saturated above the sucrose concentration about 40 w/w%, indicating that the excessive sucrose addition above 40 w/w% does not contribute to enhanced sweetness intensity.

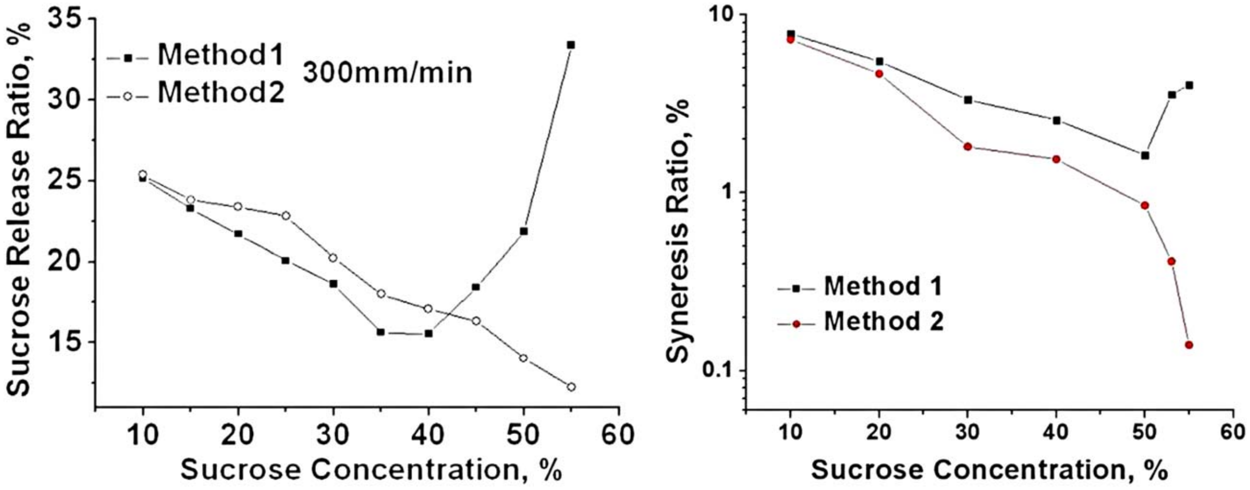

FIGURE 23 (Left) Relationship between sucrose release ratio and sucrose concentration. Sucrose is released from 1% agar gels containing sucrose with various concentrations (10–55%) when compressed at 300 mm/min. (Right) Syneresis observed by centrifugation from 1% agar gels as a function of sucrose concentration (Yang et al., 2015a, 2015b)

Whether this is due to the adaptation or fatigue of the sensation or due to other mechanism should be studied further.

Moritaka, Naito, Nishinari, Ishihara, and Fukuba (1998) examined the release of lemon flavor from lemon jellies consisting of gellan gum solution containing citric acid, Palsweet (aspartame), and 5% lemon powder. Aspartame was chosen as a sweetener because it can sweeten food gels at a very low concentration and not change the texture as sucrose strengthens the gels (Nishinari & Fang, 2016). Jellies with eight different mixing ratios of gellan gum X1, citric acid X2, and Palsweet X3 were prepared. The following equations were obtained:

$$\text{Instrumental hardness}: Y = +26.59XI - 48.42X2 + 12.94X3$$

$$\text{Sensory hardness}: Y = +48.0XI - 12.3X2$$

$$\text{Sensory smoothness}: Y = -122.1XI + 379.9(X1 - 0.1)X2 + 13.9$$

$$\text{Lemon flavor}: Y = -11.8XI + 6.2X2 - 0.4X3$$

$$\text{Sour taste intensity}: Y = -16.6XI + 36.1X2 - 7.3\ X3$$

$$\text{Sweet taste intensity}: Y = -46.2XI - 21.5X2 + 73.5X3$$

A large positive coefficient of X1 for hardness, and the negative coefficient of X1 for sour and sweet intensity were in agreement with previous reports by Morris (1993) and Clark (2002) who found the sweet taste intensity was reduced with increasing hardness of gels. The lemon flavor decreased with increasing hardness (gellan concentration), and the strongest lemon flavor was found in jellies with low gellan concentration and high citric acid concentration suggesting that the sour taste enhanced the lemon flavor. This is caused by the interaction between taste and odor which has also been found in various foods (Lim, Fujimaru, Linscott, 2014; Niimi et al., 2014). Moritaka, Naito, Nishinari, Ishihara, and Fukuba (1999) examined also the milk flavor from milk jellies with various mixing ratios of powdered milk, gellan gum, and Palsweet. For milk jellies, a jelly with the highest aspartame content showed the highest milk flavor although the milk content was lower than the other jellies, which was attributed to the milk flavor enhancement by sweet taste, again the taste–odor interaction.

The relation between texture and flavor perception is not yet understood systematically. Baek, Linforth, Blake, and Taylor (1999)

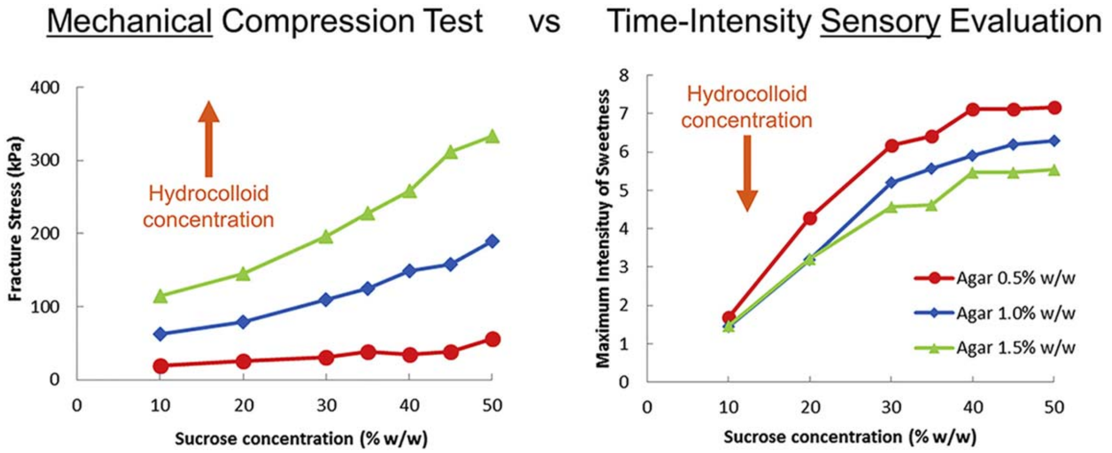

FIGURE 24 Left, fracture stress of agar gels of 0.5% w/w (circle), 1.0% w/w (diamond), and 1.5% w/w (triangle) containing sucrose as a function of sucrose at 20 ± 2C. Right, maximum intensity of sweetness evaluated of 0.5 %w/w (circle), 1.0 %w/w (diamond), and 1.5%w/w (triangle) containing sucrose as a function of sucrose by TI method averaged for values obtained by 12 subjects (Kohyama, Hayakawa, Kazami, et al., 2016)

reported that the in-nose concentration of a volatile aroma furfuryl acetate monitored by atmospheric pressure ionization mass spectrometry and the perceived intensity of the aroma by time intensity method decreased with increasing gelatin matrix concentration. On the other hand, Weel et al. (2002) reported that the perceived intensity of ethylbutyrate or diacetyl in whey protein gels, with different gel hardnesses and water holding capacities decreased with increasing gel hardness while the nose space concentration of these volatiles monitored by the MS-Nose was independent of the gel hardness or water holding capacity. From these observations, Weel et al. (2002) concluded that the texture of gels determines perception of flavor intensity rather than the in-nose flavor concentration. These two conclusions are obviously contradictory. In the study of Baek et al. (1999), panelists chew longer on harder gels. In Weel et al. (2002), the panelists were instructed to swallow the entire bolus after 30 s of chewing, irrespective of the gel hardness. Weel et al. (2002) stated that that the release of flavor from gels might not decrease with firmer gels, but that the flavor perception by panelists could be influenced by the textural properties of the gels in a psychophysical way. This should be studied further.

Knoop, Sala, Smit, and Stieger (2013) studied the combinatorial effect of gel strength and aroma compound on the sweetness intensity of sodium caseinate/gellan gels. An esther, ethyl hexanoate, which is known to enhance sweetness in apple juice was used as an aroma compound. The elastic modulus, fracture stress, and strain were found to decrease, and serum release and sweetness intensity was found increased by adding gellan. Whereas texture weakening by the addition of gellan led to an overall sweetness increase, aroma addition, and sugar concentration were found to have a much smaller impact on sweetness. Knoop et al. (2013) attributed it to the low concentration (15 ppm) of ethyl hexanoate which was known to enhance the sweetness of apple juice at a concentration of 1 ppm. Although in some cases the odor can enhance the taste at a very low concentration which could not be perceived as an odor (Labbe, Rytz, Morgenegg, Ali, Martin, 2007), Knoop et al. (2013) speculated that higher concentrations than 15 ppm might be necessary to enhance the sweetness in gelled system of sodium caseinate/gellan.

Gierczynski, Laboure, and Guichard (2008) examined aroma release from milk gels with three different hardnesses and found that the aroma was perceived as more intense for the firmer gel and for panelists for whom aroma release begins during the chewing of the product, However, the aroma release monitored by atmospheric pressure chemical ionization mass spectrometry was found higher in a softer gel. Therefore, they stated that the release data could not explain the tendency observed on aroma perception between the three gels, and that the modification of the aroma perception resulted from perceptual interactions between the aroma and the texture and/or salt perceptions. They also correlated their results with the report by Peyron et al. (2002) that panelists tend to chew harder foods with more effort. Similar contradictory results have been reported (Gierczynski, Guichard, & Laboure, 2011; Nishinari, 2014, 2015a, 2015b).

The interaction among different sensations taste, odor and texture should be further studied, and the method of sensory evaluation should also be improved, especially the method of cleansing the mouth and nose should be studied although it might be difficult to find a general method applicable for all the foods (Nishinari, 2014, 2015a, 2015b). How to define the terms to express the odor should be also studied. As for the texture terms as mentioned above in Section 2.2, it seems to be comparatively easy, but for odors, it seems to be desperately difficult. The ambiguous usage like “fruity,” ‘mushroom-like” may be terrible without specifying which fruit or mushroom, and “green” which is sometimes used as an odor of freshly cut grass is also ambiguous. Knoop et al. (2013) mentioned about a positive effect of the serum release for the attribute fruity which was lower than the attribute apple flavor. Their definition of the flavor “fruity” is “fruit taste.” This is difficult to understand because an apple is also a fruit.

A further more difficult problem to be clarified is a method of mouth neutralization between the sensory evaluation of different samples. Most papers use a simple oral rinse with water, but some groups use crackers with a bland taste. In a recent paper, a very active French research group (Panouillé, Saint-Eve, Deleris, Le Bleis, & Souchon, 2014) used an apple as palate cleanser in their study of saltiness of bread. Individual differences reported were enormous, for example, amylase activity of saliva was more than eight times different between individuals. Such a huge individual difference discourages us to compare the sensory evaluated values with objectively measured values which might be not so different for processed foods. Since saltiness perception in bread is an important problem as also published from another French group (Tournier, Grass, Septier, Bertrand, & Salles, 2014), these problems should be further studied. The latter group (Tournier et al., 2014) used water while the former group (Panouillé et al., 2014) used apple as palate cleanser.

As mentioned in Sections 2 and 3, ambiguity should be avoided to make the studies more scientific. Although diversity is important in foods and in culture, science and poetry have different goals. Misuzu Kaneko, a wonderful Japanese poet who unfortunately committed suicide, but is loved by many Japanese including myself, chanted “Minna chigatte minna ii.” That is translated by more than 100 persons, as exemplified in that everyone is different. That is what makes humans wonderful. A variety of people have a variety of merits. Everyone has his/her own wonderful personality. Everyone is different from others, and has value for existing. A poet could be and should be different from others and create a new original expression which has not been used before. However, in food science and technology, to advance the understanding the relation between the food property and sensory evaluation, the terminology used in sensory evaluation should have unambiguous significance. If not, it indeed leads again to the disaster of the tower of Babel.

5 | CONCLUDING REMARKS

New measurement methods will be developed further which will shed more light on the complicated oral processing of food. Jaw and teeth movement will be determined with higher precision. Instrumental methods with higher compression speed will also be developed to respond to the requirement of researchers. Further exchange of ideas and close collaboration among different disciplines are required. This review was limited to texture studies on solid and semisolid foods, and still many important recent developments could not be covered such as grittiness sensation, creaminess perception, and the interaction between texture and other sensations especially flavor (Chen & Engelen, 2012; Guichard et al., 2017; Nishinari, 2014, 2015a, 2015b; Parker, Elmore, Methven, & José, 2015). Time dependent behavior such as thixotropy shown by very soft semisolids has been discussed extensively (Barnes, 1997; Mewis & Wagner, 2009) and the textural analysis of yogurt and mayonnaise will be continued. Stirring a hard-type (gel-like) yogurt makes it thinner, but it will recover its initial thickness if left quiescent. Various strategies including the use of microgels provided a better texture modification than a traditional suspending function of xanthan which shows a time dependent behavior (Frith, 2010; Garrec & Norton, 2012). Microgels have been reported to function also as a lubricant (Farres & Norton, 2015). Recent advances in understanding tribological aspects (Chen & Stokes, 2012) help us to better understand products characterized by creaminess.

Application of Scott Blair's springpot model to analyze the rheological behavior of cheese to understand better the relation with sensory evaluation (Faber, Jaishankar, & McKinley, 2017a, 2017b) is a promising approach if large deformations and fractures are further taken into account. The fracture mechanics approach and subsequent fragmentation during oral processing treated by Lucas et al. (2004) should also be developed further. Analysis of large deformation and fracture by wire cutting of cheese (Goh, Charalambides, & Williams, 2005) and starch gels (Gamonpilas, Charalambides, & Williams, 2009) is expected to be further developed to correlate with texture analysis.

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ETHICAL STATEMENTS

Conflict of Interest: The authors declare that they do not have any conflict of interest.

Ethical Review: This study does not involve any human or animal testing.

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