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Review

Approaches to analysis and modeling texture in fresh and processed foods – A review

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ABSTRACT

Texture analysis and modeling are important techniques in food and postharvest research and industrial practice. A wide range of methods have been used to evaluate instrumental results, which provide time-series data of product deformation, thereby allowing a wide range of texture attributes to be calculated from force–time or force–displacement data. Several indices of texture such as the firmness index, crunchiness index and texture index based on "vibration energy density" have been reported, but these are not widely used to quantify food texture. Some modeling and statistical approaches have been adopted to analyze food texture data, including chemical reaction kinetics and the Michaelis–Menton type decay function, mechanistic autocatalytic models based on logistic equation, and the finite element method. However, increasing demand for comprehensive approaches to texture profile analysis, generalized texture indices and fundamental texture models still remain challenges in the food research and industry.

Contents

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1. Introduction

Texture is a key quality attribute used in the fresh and processed food industry to assess product quality and acceptability. Among the texture characteristics, hardness (firmness) is one of the most important parameters of fruit and vegetables, which is often used to determine the freshness of food (Konopacka and Plocharski, 2004). Crispness is the key trait of cellular, brittle and crunchy food (Taniwaki and Kohyama, 2012). Given gelled products such as muscle food, springiness, cohesiveness, adhesiveness and gumminess are significant properties for the texture evaluation (Akwetey and Knipe, 2012; Stejskal et al., 2011). Textural quality attributes of food may be evaluated by descriptive sensory or instrumental analyses. The combination of time and high cost associated with sensory perception has motivated the development and widespread use of empirical mechanical tests which correlate with sensory perceptions of food texture (Costa et al., 2011; Kim et al., 2012; Wang et al., 2007). Over the years, a wide range of instrumental tests have been used in both research and industry to assess food texture, and a great deal of effort has been expended in improving the instruments and measurement techniques for meaningful estimation of textural properties (Oraguzie et al., 2009; Zdunek et al., 2010a, b). Different texture measurement methods may give different results, some expressed as single values such as fruit firmness measured by hand held penetrometer (Ioannides et al., 2007), while others provide more in depth information on the history of deformation, such as time-series data on texture measurement (Derington et al., 2011; Taniwaki et al., 2010). These developments have enabled researchers to further analyze food texture data to provide better understanding of the mechanisms of texture and relevance to sensory perception.

The objective of this article is to provide a review of recent developments in texture analysis and modeling of fresh and processed foods, including approaches to texture profile analysis of instrumental measurements. Various texture indices employed in food analysis and models to predict texture changes during food handling and processing are also discussed.

2. Texture profile analysis

Texture profiles are curves which monitor and record the spatial or temporal characteristic events of samples during food texture measurements. Analysis of the profiles of mechanical and acoustic measurements is an important aspect of food texture research. Texture profile analysis (TPA) sets up a 'bridge' from objective measurement to subjective sensation and makes food texture characteristics more predictable.

The history of food texture measurement and texture profile analysis (TPA) dates back to the late 19th and early 20th centuries when the analysis was based primarily on simple sensory evaluations to detect and eliminate defects (Bourne, 1982). It was during the past 60 years which coincided with boom in food processing that texture measurement and analyses emerged as a subject of research and learning in tertiary education, particularly in food science and technology (Szczesniak, 2002). Given its fundamental importance on food science, several authors have discussed the meaning and historical context of TPA (Bourne 1982, 1978; Brandt et al., 1963). The his seminal textbook on food texture and viscosity Bourne (1982) chronicled the early history of texture measurement and analysis and credited Dr. Alina S. Szczesniak for pioneering our current understanding of the multidimensional nature of texture and its importance to the consumer and for developing the principles of texture profile analysis for both instrumental and sensory methods. Bourne (1982) provides an excellent detailed description of the principle of the TPA, with illustrations of the compression required for TPA test, typical TPA curves generated with specific instruments and a generalized texture profile analysis curve obtained from Instron Universal Testing Machine. With respect to food products, these reviews agree that texture profiling involves compressing the product at least twice and quantifying the mechanical parameters from the recorded force–deformation curves (Szczesniak, 2002) as illustrated in Fig. 2. In this section of the review, we discuss the applications of TPA to the two main of types of tests (mechanical and acoustic) used to measure food texture.

2.1. Profile analysis of mechanical measurements

Mechanical measurements of food texture can be categorized as destructive and non-destructive methods. For example, destructive group includes three-point bending test, single-edge notched bend (SENB) test, puncture and penetration tests and cutting "tooth method" which used an incisor blade (Jiang et al., 2008). This group of methods may link with the micro-structural and molecular mechanisms and imitate the mastication process, but they are destructive and there are no clear relationships with mouth feel. The methods of quasi-static force–deformation (Ruiz-Altisent et al., 2010), impact response (Herrero-Langreo et al., 2012; Molina-Delgado et al., 2009; Ragni et al., 2010), "finger" compression (Jiang et al., 2008), and bioyield detection (Lu and Tipper, 2009; Mendoza et al., 2012) are named as non-destructive measurement as usually no visible damage is found and possible to be applied on line. However, the main disadvantages of mechanical non-destructive methods are that they are still destructive in micro-scale and the information obtained from experiments is not comprehensive.

In both of destructive and non-destructive measurements, force is the key parameter. Therefore, typical texture profiles are force versus time/distance (displacement)/deformation (Chaunier et al., 2007; Farris et al., 2008; Greve et al., 2010; Ragni et al., 2010; Sasikala et al., 2011). De Roeck et al. (2010) compressed carrot cylinder to 70% of its original thickness to obtain the maximum force as the hardness; Sila et al. (2006) described hardness as compression force at 30% strain. In a penetration test, the steep initial slope was treated as the character of stiffness (Nguyen et al., 2010). Takahashi et al. (2009) measured texture properties of cookies and raw radish by puncture test, which showed many peaks and formed a zigzag pattern in the force–strain curves indicating the crispy characteristic. Varela et al. (2008a) compared the texture properties of roasted and raw almonds, which indicated that roasted almond was clearly brittle and crisp with significantly lower first force breakdown (force at first peak) and lower deformation at the point. The probe tensile separation method has been applied for quantitative characterization of the stickiness of fluid foods. During the tensile separation test, the probe is slowly brought downwards to squeeze the fluid sample till the final pre-set gap between the two plates is reached and subsequently pulled back at a set speed (Fig. 1). The force needed for separation is recorded. The maximum tensile force and the work till the maximum force were found to be useful parameters for stickiness prediction (Chen et al., 2008). Tsukakoshi et al. (2007) studied the force–deformation curves recorded by two different testing machines and the results showed that the number of changes in the curves depended on the testing machine. Thus, it is difficult to compare the results by using different instruments.

Warner–Bratzler shear force (WBSF) test is a useful technique that has been used since the 1930s as standard mechanical measurement to estimate the toughness (or tenderness) of raw and cooked meat (Girard et al., 2012; Lorenzen et al., 2010) such as pork (Cai et al., 2011), beef (Destefanis et al., 2008) and rabbit meat (Combes et al., 2004). The profile shows either force exerted over time or force exerted versus the distance that the blade has

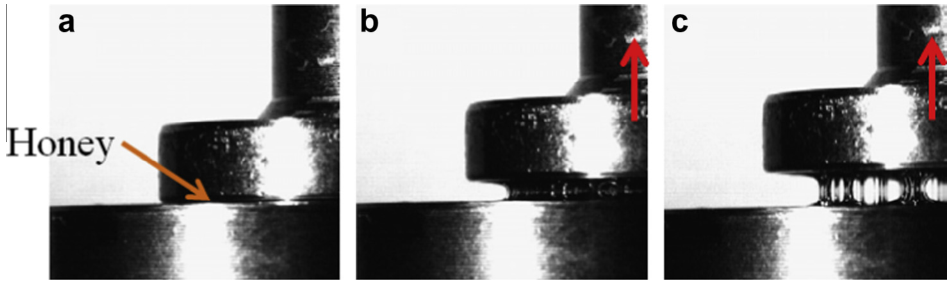

Fig. 1. High speed camera images of honey stretched (arrow pointing north) during a tensile test. The time interval between each image was around 40 ms, and the extension of the honey in *y*-axis was (a) 0.1 mm, (b) 0.9 mm, and (c) 1.7 mm (modified from Chen et al., 2008).

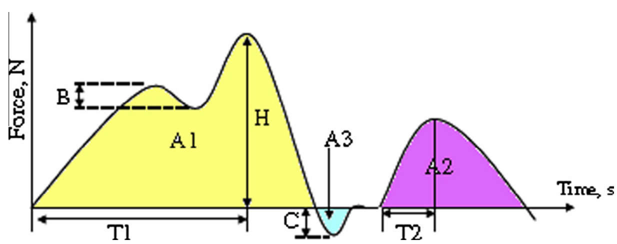

Fig. 2. Texture analysis using Szczesniak mastication profile. Hardness = H, Adhesiveness = A3, Cohesiveness = A2/A1, Brittleness = B, Cohesion Strength = C, Indentation = T1, Elastic Quality = T2/T1, Masticability = H × A2/A1 × T2/T1, Gumminess = H × A2/A1 (modified from Kealy, 2006).

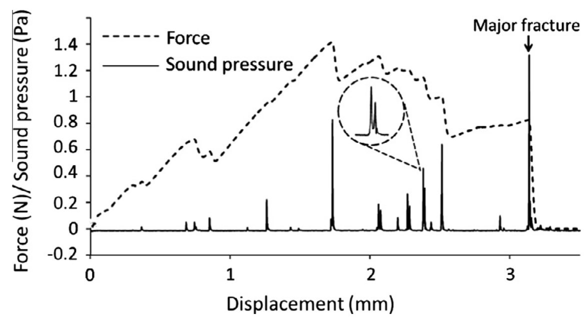

Fig. 3. Examples of the force–displacement curve and acoustic events. The dashed circle indicates an acoustic event cluster (Taniwaki and Kohyama, 2012).

travelled (Girard et al., 2012). Usually, the most considered parameter of the curve is the maximum shear force.

TPA test is based on the imitation of mastication or chewing process with a double compression cycle. The typical profile of TPA test (Fig. 2) can assess a wide range of fresh and processed food texture properties, such as hardness (the maximum force required to compress the sample, H), springiness (the ability of sample to recover its original form after the deforming force is removed), cohesiveness (extent to which the sample could be deformed prior to rupture, A2/A1), adhesiveness (the total negative area between the first and the second peak, A3), gumminess (the force needed to disintegrate a semisolid sample to a steady state of swallowing, hardness × cohesiveness), and chewiness (the work needed to chew a solid sample to a steady state of swallowing, springiness × gumminess) (de Huidobro et al., 2005; Guiné and Barrocab, 2012; Jaworska and Bernas, 2010; Kealy, 2006; Martinez et al. 2004; Wu et al., 2006). The test parameters can be calculated from the compression force versus time (or distance) curves usually using software such as the 'Texture Exponent Lite' developed and supplied by manufacturer (Farahnaky et al., 2012). The TPA method has been successfully used for texture assessment in different foods such as fresh-cut pineapple (Montero-Calderon et al., 2008), date flesh (Rahman and Al-Farsi, 2005), mushroom (Jaworska and Bernas, 2010), root vegetable (Farahnaky et al., 2012), biscuit dough (Sudha et al., 2007), cheese (Ayyash et al., 2011), abalone (Briones-Labarca et al., 2012), meat emulsions (Yilmaz et al., 2012), and sausages (Herrero et al., 2007). Furthermore, researchers have compared TPA with WBSF test in meat texture analysis. For example, hardness (or tenderness) was better predicted by TPA than by WBSF, while springiness was only predicted by WBSF (Caine et al., 2003; de Huidobro et al., 2005).

2.2. Profile analysis of acoustic measurement

Typical characteristic for many hard, crispy and crunchy solid food products is their brittle fracture behavior, mostly accompanied by a sharp sound (acoustic emission or vibration) which is closely related to their texture attributes (Luyten et al., 2004; Maruyama et al., 2008; Taniwaki et al., 2006; van Vliet and Primo-Martin, 2011). Therefore, researchers have combined mechanical tests, such as compression, penetration and three-point bending test with acoustic measurement (Marzec et al., 2010; Saeleaw and Schleining, 2011a,b; Varela et al., 2009).

There are several profiles often used in acoustic measurement such as sound pressure/acoustic emission (also referred to as acoustic module or acoustic pressure level) versus time/strain/displacement/distance (Arimi et al., 2010a; Castro-Prada et al., 2009; Costa et al., 2011, 2012; Salvador et al., 2009; Saeleaw et al., 2012). The important acoustic parameters are the number and magnitude of sound events (Sanz et al., 2007). Varela et al. (2009) described that the number of sound peaks was the best parameter to discriminate texture differences of samples. Usually, mechanical and acoustic profiles are presented in the same figure (e.g. Fig. 3), which could give a clear comparison between them and may help to analyze texture properties. Fig. 3 represents a force–displacement curve and acoustic events when a potato chip sample was bent for a few millimeters before a major fracture. The analysis range was set between the initial point and major fracture point. The study revealed that most of the force drops accompanied acoustic event (Taniwaki and Kohyama, 2012). By studying biscuits, Arimi et al. (2010b) found that the number of force and sound peaks, spatial ruptures, sound curve length and area under the sound curve correlated well ($R^2 > 0.77$) with sensory crispiness data. Zdunek et al. (2010a) also proved that there was a significant correlation of acoustic emission counts with sensory crispness, crunchiness, hardness, juiciness, mealiness and overall apple texture.

2.3. Advantages and limitations of texture profile analysis

The main advantage of texture profile analysis is that the profile records the process phenomena during the mechanical texture

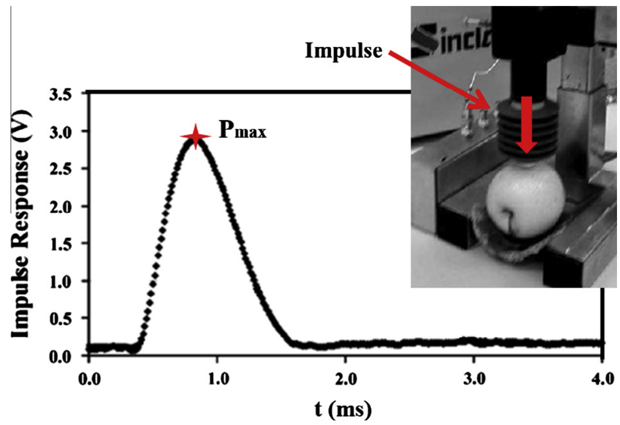

Fig. 4. Schematic of firmness evaluation method by impact test (modified from Shmulevich et al., 2003). P_{max} is the peak amplitude of the impulse response (V).

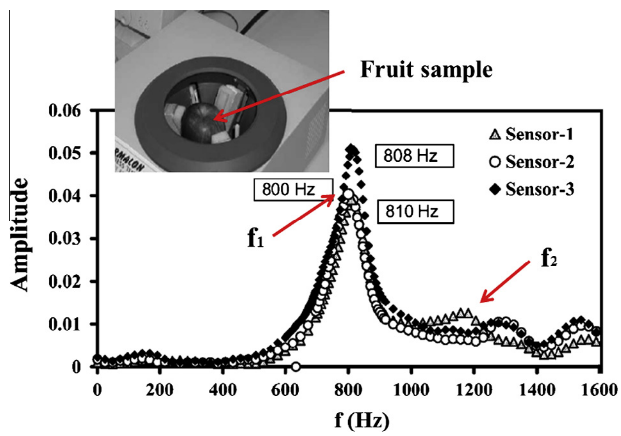

Fig. 5. Schematic of firmness evaluation method by acoustic test (modified from Shmulevich et al., 2003). The f_1 and f_2 of sensor-1 are the first and second natural frequency of the tested fruit, which are shown as an example.

measurement, which may compare quantitively with the 'feel' of human mouth, fingers or ear. However, different equipment and the experimental conditions are just like different people and their eating habits. If there are no strict standards to be complied with, it is hard to compare the results from different researches.

3. Texture indices

3.1. Firmness index

Firmness is an important texture attribute of foods, especially the fresh foods, and has been a criterion for sorting fruit and vegetables for many years (Wang et al., 2006). In engineering terminology, firmness may be interpreted in terms of the modulus of elasticity (E), shear modulus or maximum penetration force (Cherng and Ouyang, 2003; Ragni et al., 2010). Usually firmness is measured by non-destructive methods, such as acoustic, vibration, micro-deformation, impact, and absorption of light (typically short-wave length near-infrared) (Subedi and Walsh, 2009). It is obvious that each of the quality indices is based on one specific measurement method.The most frequently used empirical impact parameters for firmness evaluation, namely firmness indices, are C'_1 and C'_2 (Shmulevich et al., 2003):

$$C'_1 = \left(\frac{P_{max}}{t}\right) \tag{1}$$

$$C'_2 = \left(\frac{P_{max}}{t^2}\right) \tag{2}$$

where P_{max} is the peak amplitude of the impulse response (V) and t, an impact characteristic time (ms) (Fig. 4), such as t_p, time to peak amplitude, t_c, pulse duration, or t_m, width of the impact at half of the peak amplitude. According to the indices, García-Ramos et al. (2003) created an on-line ejection system and fruit was sent to its corresponding outlet. Although C_1 and C_2 sometimes have good correlation with other firmness test results, sometimes they have not, due to their high sensitivities to the variations in fruit form, location and impact angle (Shmulevich et al., 2003).

In acoustical methods (Fig. 5), the most likely used firmness indices, C_1 and C_2, are defined as follows:

$$C_1 = f_1^2 m^{2/3} \rho^{1/3} \tag{3}$$

$$C_2 = f_2^2 m^{2/3} \rho^{1/3} \tag{4}$$

where f is the first or second natural frequency of the tested fruit, m is its mass (kg), and ρ is density (kg/m^3), however ρ is often deleted in a simplified formula (Cherng and Ouyang, 2003; Molina-Delgado et al., 2009; Mendoza et al., 2012; Shmulevich et al., 2003; Taniwaki et al., 2009a, b; Wang et al., 2006). Nevertheless, the limitations of these methods are to evaluate the firmness index of non-spherical fruit, such as avocado or mango. Cherng and Ouyang (2003) created a new firmness index C_3, which is proportional to elasticity, formulated by relating to mass, density and natural frequencies:

$$C_3 = (f_1 f_2^2)^{2/3} m^{2/3} \rho^{1/3} \tag{5}$$

This new index extended the firmness estimation for fruits or vegetables from a spherical to a prolate ellipsoidal shape. At the same time, based on C_3, another firmness index C_4, which is especially for cases from spherical to oblate ellipsoidal shape, could be defined as:

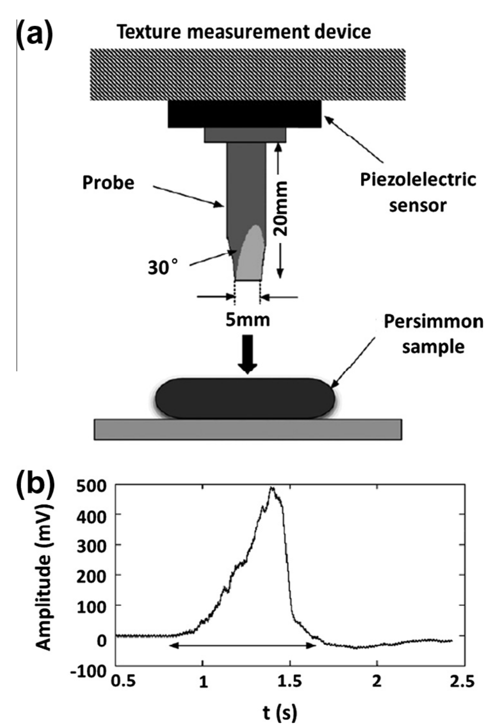

Fig. 6. (a) A schematic of the texture measurement device. A probe was inserted into a fruit sample, and the vibrations produced during penetration were sensed by a piezoelectric sensor. (b) A typical texture signal of a sample (Taniwaki et al., 2009a).

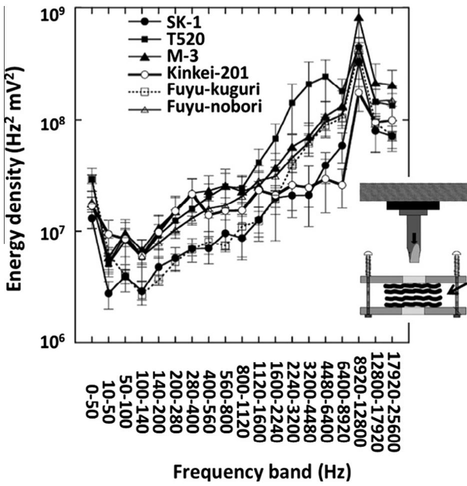

Fig. 7. Texture indices of six cabbage cultivars (SK-1, T520, M-3, Kinkei-201, Fuyu-kuguri and Fuyu-nobori) calculated by Eq. (9) (modified from Taniwaki and Sakurai, 2008). The bars indicate standard error ($n = 24$ for SK-1 and Kinkei-201; $n = 36$ for other cultivars).

$$C_4 = (f_2 f_1^2)^{2/3} m^{2/3} \rho^{1/3} \quad (6)$$

A more general firmness expression was formulated by combining C_3 and C_4 giving:

$$C = ((\min(f_1, f_2)(\max(f_1, f_2))^2)^{2/3} m^{2/3} \rho^{1/3} \quad (7)$$

Eq. (7) is suitable for both prolate and oblate cases and practically useful. In addition, since Poisson's ratio for many fruits is greater than 0.3, the applicable geometry range of ellipsoidal samples for the new firmness index is at least between axis ratio of 0.4 and 2.0 (Cherng et al., 2005).

3.2. Texture index

Based on the characteristics of food mastication process, Sakurai et al. (2005a) and Taniwaki et al. (2006) designed a testing device for food texture measurement which inserts a probe into a food sample and detects the vibration caused by the sample's fracture (Fig. 6). Meanwhile, they created a texture index (TI1) that value was determined according to the "amplitude density" of the obtained signals (Taniwaki et al., 2006, 2009a):

$$\mathrm{TI1} = \frac{\sum |V_i|}{t} \quad (8)$$

where $|V_i|$ is the absolute amplitude of each data point in volts and t is the data length in seconds. The texture index reflects the level of sound generated per second when a sample is masticated. The ripening of persimmon cultivars was evaluated successfully by this TI (Taniwaki et al., 2009a). Still in the same research group and with the similar device, a new TI, "energy density" (Fig. 7), was introduced, which was determined by the integration of squared amplitudes of texture signals multiplied by a factor of a frequency band. This TI enabled evaluation of acoustical signals in the high-frequency region (>1000 Hz). It is more sensitive than the previously used index ("amplitude density"). The new TI is calculated using the following expression (Taniwaki and Sakurai, 2008):

$$\mathrm{TI2} = (f_l \times f_u) \times \frac{1}{n} \sum_{i=1}^{n} V_i^2 \quad (9)$$

where TI2 is the texture index, f_l represents the lowest and f_u the highest limit of each frequency band determined by the half-octave multi-filter, V_i (V) is the amplitude of the texture signal, and n is the number of data points. Using this kind of equipment and the new TI values, researchers evaluated the crispness, crunchiness or firmness of several foods, such as cabbage cultivars and their leaves, pears, potato chips and grape flesh (Iwatani et al., 2011; Taniwaki et al., 2009b,c, 2010).

3.3. Crunchiness index

Crunchiness index (CI) created by Nguyen et al. (2010) and relating product puncture force and stiffness, was able to characterize the severity of the process treatments on various products tested. The CI was presented as:

$$\mathrm{CI} = \frac{F_{\mathrm{treatment}}}{F_{\mathrm{ctrl}}} + \frac{\mathrm{Grad}_{\%\mathrm{treatment}}}{Grad_{\%\mathrm{ctrl}}} \quad (10)$$

where $\mathrm{Grad}_{\%}$ represents the slope of the force–deformation curve of the processed sample at different percentages (10–70%) of maximum puncture force. This value represents the sample stiffness. F is the maximum puncture force (N) of the processed samples and represents the sample hardness. The subscripts 'treatment' and 'ctrl' refer to process treatment and control sample values, respectively. Results reported by Nguyen et al. (2010) showed that instrumental CI results were in agreement with the sensory data of carrot, red radish and jicama, and the authors concluded that CI can be used as an effective tool for comparing the instrumental textural quality of samples subjected to various process treatments.

Another texture index, "Sharpness index", which is based on the acoustic vibration of the probe when the probe is inserted into the tissue, was reported by Sakurai et al. (2005b) and successfully applied in texture analysis of persimmon fruit.

3.4. Advantages and limitations of texture indices

The texture indices, namely firmness index, texture index, crunchiness index and sharpness index, are based on either mechanical or a combination of mechanical and acoustic methods (Table 1). Among these indices, the firmness index was investigated relatively more than others by different researchers. The testing methods of firmness are simple and non-destructive, which may be applied to on-line quality evaluation. However, since the mechanical measurement approaches usually are device-dependent, the texture indices obtained from different equipments are difficult to compare. Additionally, the evaluated food products by these indices discussed above are mainly fresh or processed fruit and vegetables. No studies on gelled products have been reported yet. The firmness index based on low-mass impact method may be adopted to classify muscled food, but this method would not be as comprehensive as TPA and WBSF tests.

4. Texture modeling

Modeling is an efficient approach to predict the texture of foods. Empirical, semi-empirical and statistical models have induced a tremendous impetus on food texture research. With rapid and ongoing progress in modeling techniques, computational simulation modeling approaches such as finite element method (FEM) provide more opportunities to achieve further understanding of food texture.

4.1. First order reaction/kinetic model

Due to its mathematical simplicity and utility, the first order reaction/kinetic model is a widely employed empirical model to predict food texture, especially for studying textural changes of thermally processed foods (Sila et al., 2004). A general reaction rate

Table 1
Texture indices of fresh and processed food.

Index	Based testing method	Food sample	References
Firmness index	Low-mass impact, non-destructive Acoustical response, non-destructive	Fruit and vegetables	Cherng et al. (2005), García-Ramos et al. (2003), Molina-Delgado et al. (2009), Mendoza et al. (2012), and Shmulevich et al. (2003)
Texture index	Fracture vibration, destructive	Cabbage leaves, pears, potato chips, grape flesh	Iwatani et al. (2011), Taniwaki et al. (2006), (2009a,b,c), and 2010)
Crunchiness index	Puncture method, destructive	Carrot, red radish, jicama	Nguyen et al. (2010)
Sharpness index	Acoustic vibration of probe penetration, destructive	Persimmon fruit	Sakurai et al. (2005b)

expression for the degradation kinetics can be written as follows (Nisha et al., 2006):

$$-\frac{d[TR]}{dt} = k[\mathrm{TR}]^y \tag{11}$$

where 'TR' is the quantitative value of the texture of the product under consideration, 'k' is the rate constant for texture development, 'y' is the order of the reaction, and 't' is the time (s). On integration of Eq. (11) with respect to time for the first order reaction ($y = 1$) gives (Nisha et al., 2006; Yu et al., 2011):

$$\ln\left(\frac{\mathrm{TR}}{\mathrm{TR}_0}\right) = -kt \tag{12}$$

where 'TR_0' is the texture reading at time 0, and 'TR' is the texture reading after time 't'. An exponential type of degradation function of time is often discussed (Liu and Scanlon, 2007; Nisha et al., 2006). Usually, the first order model is written as below:

$$\mathrm{TR} = \mathrm{TR}_x + (\mathrm{TR}_0 - \mathrm{TR}_x)e^{-kt} \tag{13}$$

where 'TR_x' can be 'TR_∞' (the 'TR' after a long time) (Le-Bail et al., 2009), and also can be '$\mathrm{TR}_{\mathrm{fix}}$' (the invariable part of 'TR') (Lana et al., 2005), that depends on how you define the equation. By means of this model, some mechanical property changes of foods during processing were predicted including shear modulus, Young's modulus, firmness, hardness and maximum indentation force (Table 2).

Based on the traditional first order model, some other useful empirical models have been used, such as Arrhenius equation combined with fractional conversion factor, to predict the changing kinetics of texture in slices and strips of food products (Troncoso and Pedreschi, 2007; Yu et al., 2011). The Arrhenius equation is one of the most well-known equations in the chemical field and is widely used to describe the temperature dependence of kinetic constants, such as k (Schwaab and Pinto, 2007):

$$k = k_0 \exp\left(-\frac{W}{RT}\right) \tag{14-1}$$

where k is the rate constant (or the specific reaction rate), T is the absolute temperature (K), R is the ideal gas constant, k_0 is the frequency (or pre-exponential) factor and W is the activation energy (J). Both k_0 and W are the parameters of the Arrhenius equation, usually estimated from experimental data. In order to minimize the high correlation between the estimates of two parameters, k_0 and W, another type of Arrhenius equation is adopted (Sila et al., 2004; Schwaab and Pinto 2007):

$$k = k_{\mathrm{ref}} \exp\left[\frac{W}{R}\left(\frac{1}{T_{\mathrm{ref}}} - \frac{1}{T}\right)\right] \tag{14-2}$$

where k_{ref} is the reference reaction rate constant at the reference reaction temperature T_{ref}, while k is the reaction rate constant at temperature T.

The fraction conversion is defined as the fraction of reactant that has been converted to yield a product at a given time. The formula is $(\mathrm{FM}_0 - \mathrm{FM}_t)/(\mathrm{FM}_0 - \mathrm{FM}_\infty)$,where FM_0 is the initial firmness at time zero, FM_t is the firmness at a given time, t, and FM_∞ is the nonzero equilibrium firmness at infinite time. The first-order reaction in terms of the fraction conversion can be simplified as (Corzo et al., 2006):

$$\ln\left(1 - \frac{\mathrm{FM}_0 - \mathrm{FM}_t}{\mathrm{FM}_0 - \mathrm{FM}_\infty}\right) = \ln\left(\frac{\mathrm{FM}_t - \mathrm{FM}_\infty}{\mathrm{FM}_0 - \mathrm{FM}_\infty}\right) = -kt \tag{15}$$

Using the first order kinetic model modified by fractional conversion technique (factor) and combined with Arrhenius equation for the kinetic constant, the changes of food texture properties during processing were investigated, for example, Young's modulus of potato strips during deep frying (Thussu and Datta, 2012), hardness of carrots during thermal processing (Sila et al., 2004), firmness of sardine sheets during vacuum pulse osmotic dehydration (Corzo et al., 2006), etc.

4.2. Gibson–Ashby equation

Gibson–Ashby equation, a macroscopic model, is one of the useful semi-empirical models used in food texture analysis. The equation is written as

$$\frac{E^*}{E} = \left(\frac{\rho^*}{\rho}\right)^2 \tag{16}$$

where E^* represents the Young's modulus of the cellular solid, E represents the Young's modulus of the same solid material without cells, ρ^* and ρ represent the density of the cellular solid and of the same solid material without cells, respectively. This model describes the relationship between the mechanical properties and the porous structure of materials, such as bread crumb (Le-Bail et al., 2009; Zghal et al., 2002).

4.3. Generalized Maxwell model

The generalized Maxwell model with a discrete number of elements is another popular semi-empirical mechanical model for quantification of relaxation behavior of foods and a variety of polymeric materials (Andrés et al., 2008). In the linear viscoelastic range (low deformation), the behavior of foods can be simulated by employing mechanical models consisting of springs and dashpots, which is the mechanism of general Maxwell model (Bhattacharya, 2010; Del Nobile et al., 2007). Originally, it is given by the following expression (Del Nobile et al., 2007):

$$E(t) = \frac{\sigma(t)}{\varepsilon_0} = \int_0^\infty E(\lambda) \cdot \exp\left(-\frac{t}{\lambda}\right) \cdot d\lambda \tag{17}$$

where $E(t)$ (MPa) is the relaxation elastic modulus at time t (s), $\sigma(t)$ (MPa) is the stress at time t (s), ε_0 is the imposed strain, $E(\lambda)$ (MPa) is the continuous distribution function of relaxation times, λ (s) is the relaxation time. During the stress-relaxation test, the viscoelastic behavior of sample material is revealed in a finite, discrete set of

Table 2
Approaches adopted by researchers for modeling texture of fresh and processed foods.

Modeling approach	Modeling principle	Texture/rheological property	Produce	References
First order reaction kinetics (including modified types)	Based on chemical reaction kinetics. The development of texture is directly proportional to the texture property.	Shear modulus; firmness; texture development rate; maximum indentation force; Young's modulus; hardness; Stress relaxation behavior (large deformation)	Rennet casein gelation; fresh cut tomatoes; truss tomatoes; melon; potato cubes, green gram whole, red gram splits; tomatoes; potato strips; potato slices; bread crumb; carrot; root vegetables; litchi; sardine sheets; Moth bean flour (raw and roasted) doughs	Bhattacharya (2010), Corzo et al. (2006), De Roeck et al. (2010), Farahnaky et al. (2012), Lana et al. (2005), Liu and Scanlon (2007), Le-Bail et al. (2009), Nisha et al. (2006), Sila et al. (2004),Schouten et al. (2007), Schouten et al. (2010), Troncoso and Pedreschi (2007), Tijskens et al. (2009), Thussu and Datta (2012), Van Dijk et al. (2006a, b), Yu et al. (2011), and Zhong and Daubert (2004)
Second-order kinetic equation	The rate of change of texture property follows a second order reaction kinetics.	Maximum stress and Young's modulus	Chestnuts	Moreira et al. (2008)
Generalized Maxwell model (including modified type) with 2, 3, 4, 7-element	Mechanical models consisting of springs and dashpots.	Stress relaxation behavior (low deformation), fish skin hardness	Solid-like foods; moth bean flour (raw and roasted) doughs; low-fat chicken sausage, Cape hake, Rohu fish	Andrés et al. (2008), Bhattacharya (2010), Del Nobile et al. (2007), Herrero and Careche (2005), and Jain et al. (2007)
Finite element method (FEM)	Based on fundamental mechanics in microstructure.	Mechanical properties	Single tomato cell; cereal solid foods; two food materials; bread crumb	Dintwa et al. (2011), Guessasma et al. (2011), Kanit et al. (2006), and Liu and Scanlon (2003a,b)
Statistical model	Relationship between texture property and other variables associated with the experimental design.	Firmness, crispiness, crunchiness	Tomatoes, tomato pericarp, mango, banana, peach, cassava crackers, crisps, snack	Pinheiro and Almeida (2008), Rojo and Vincent (2009), Subedi and Walsh (2009), Saeleaw and Schleining (2011a), Saeleaw et al. (2012), and Van Dijk et al. (2006a)
Gibson-Ashby model	Relationship between the mechanical properties and the porous structure of materials. Semi-empirical model in macro-scale.	Young's modulus; compression modulus	Bread crumb; brittle foams	Agbisit et al. (2007), and Zghal et al. (2002)
Michaelis–Menton type decay function	One of the simplest and best-known models of enzyme kinetics	Firmness	Apples	Harker et al. (2006)
Logistic equation (including Boltzman function	Based on the highly simplified autocatalytic mechanism	Firmness; softening	Nectarine, Kiwifruits	Rizzolo et al. (2009), Tijskens et al. (2007), and White et al. (2005)

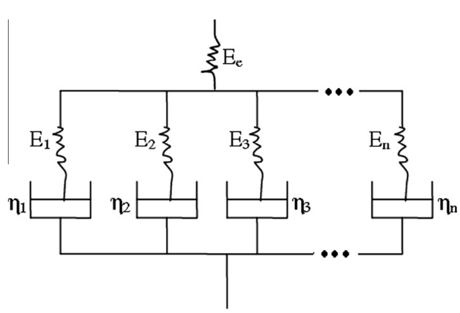

Fig. 8. The generalized Maxwell model with one residual spring element in series (modified from Bhattacharya, 2010). $\eta_1, \eta_2, \eta_3, \ldots, \eta_n$ are the viscosities of the first, second, third … and nth dashpot elements, respectively (Pa s). $E_1, E_2, E_3, \ldots$, and E_n are the modulus of elasticity for the springs in the first, second, third … and nth Maxwell body, respectively (Pa).

response times associated spectral strengths. The generalized Maxwell model consisted of several Maxwell elements in parallel with an independent spring is usually presented as Eq. (18) (Andrés et al., 2008; Bhattacharya, 2010):

$$E(t) = E_e + \sum_i^n E_i \exp(-\frac{t}{\lambda_i}) \tag{18}$$

where E_i and λ_i are the elastic modulus and the relaxation time of the ith Maxwell element, respectively, and E_e represents the modulus of the lone spring (Fig. 8). Literature evidence (Table 2) have shown that the viscoelastic behavior of foods such as low-fat chicken sausage (Andrés et al., 2008) can be described by a generalized Maxwell model; however, the challenge is to determine the number of Maxwell elements to be used in parallel with an independent spring. A modified version of Maxwell model was applied successfully to predict the texture of food products such as fish (Herrero and Careche, 2005; Jain et al., 2007). However, if food exhibits non-linear viscoelastic behavior when subjected to a large deformation, the generalized Maxwell model does not apply (Bhattacharya, 2010).

4.4. Finite element method (FEM)

FEM modeling based on explicit meshing of the material microstructures has proved to be a useful tool for studying the complex mechanical behavior of foods. Several simplified fundamental mechanical models are introduced in this method. It may be roughly summarized by four stages. The first one is to define the geometry and the meshing; the second stage is to include the material properties; the third stage is to determine the stress distribution within the solution domain; the fourth stage is to submit the solution domain to a virtual standard mechanical test (Guessasma et al., 2011). Finally, the FEM results have to be examined by experiments. FEM based on three-dimensional confocal images were performed on two kinds of food materials and the comparison between simulations with different boundary conditions and experiments were carried out by Kanit et al. (2006). For the bread crumb excised from optimal and overproved loaves, the FEM technique gave excellent agreement with the experimental compression stress–strain curves; excellent agreement was also found between the experimental elastic modulus and critical stress (Liu and Scanlon, 2003a,b). Guessasma et al. (2011) reviewed the latest applications of mechanical modeling by FEM to the field of cereal foods, outlined their actual limits and prospected for texture prediction. Furthermore, thanks to the image recording of geometry changes of microstructures, Dintwa et al. (2011) simulated the compression process of single tomato cell by FEM. However, as other modeling methods, FEM also has its own challenges, such as how to choose or decide the material properties and reasonable constants, and how to properly generate meshes on irregular food shapes.

4.5. Statistical modeling approaches

Statistical models are another important group of modeling approaches which are mainly based on mathematics. These approaches are likely to be adopted when the fundamental mechanism of the process or the correlation of parameters is unclear. They are often applied to study the relationship between non-mechanical measuring data and food texture properties. Pinheiro and Almeida (2008) employed the simple linear regression model to analyze the relationships between tomato pericarp firmness and pH and calcium. Partial Least Square Regression model was adopted to correlate the data on firmness of tomato, banana, mango, peach and kiwifruit to the near infrared spectral data (Subedi and Walsh, 2009; Van Dijk et al., 2006a, b) and waveguide spectral data (Ragni et al., 2012). Response surface methodology was applied to analyze the effects of independent variables on the response parameter of snack by matching the response studied with the code factors (Saeleaw et al., 2012). Weibull model was employed to statistically analyze the crispness of crisps by Rojo and Vincent (2009). At the same time, some other statistical methods of data analysis, such as one/two/three-way analysis of variance (ANOVA) and principle component analysis (PCA), are also fairly often used in sensory evaluation and instrumental measurement (Alvarez et al., 2011; Ares et al., 2012; Benedini et al., 2012; Çakır et al., 2012; Varela et al., 2008a, b; Wang et al., 2007; Zdunek et al., 2010b). Furthermore, artificial neural network, a non-linear statistical data modeling tool, was used to correlate the values of fluid mechanical stresses during swallowing to the sensorial texture perception (Rauh et al., 2012).

4.6. Other modeling approaches

Except for the popular modeling approaches described above, there are still some other useful models available: White et al. (2005) used Boltzman function to predict Kiwifruits softening process; Harker et al. (2006) applied Michaelis–Menton type decay function to predict apple firmness during cold storage; using Young's modulus as a measure for texture, Thussu and Datta (2011) built a framework, combining multiphase porous-media based process-model and experimental determined data, for predicting the effective modulus of a solid food material, which had been developed and extended to four moisture removal processes–frying, drying, microwave heating and baking.

In addition, several research groups have offered nice contributions to food texture modeling during the latest twenty years. Besides melon and nectarine (Rizzolo et al., 2009; Tijskens et al., 2007, 2009), tomato is the most important fruit they studied. From truss tomatoes to single tomato suspension cells, they discussed the firmness and the predicting models included first order chemical kinetics (some based on multitude of firmness origins, such as enzyme and pH values) (Lana et al., 2005; Schouten et al., 2007, 2010; Van Dijk et al., 2006a, b), statistical models (such as partial least squares regression relating the data on firmness to the near infrared spectral data) (Van Dijk et al., 2006a, b), and FEM for simulating the force–deformation behavior of tomato cells (Dintwa et al., 2011).

It is paramount to choose or create suitable models for predicting texture properties. Zdunek et al. (2011) used three modeling approaches, the simple linear, multiple linear and the principal component regression (PCR), to investigating the correlation of apple sensory texture to the contact acoustic emission data. PCR models showed the best results among the three models in this study. Troncoso and Pedreschi (2007) compared four models, two irreversible serial chemical reaction, one irreversible chemical reaction, modified first order kinetics (combined with Arrhenius equation and fractional conversion technique) and traditional first order kinetics, in maximum puncture force of potato slices during drying. The comparison revealed that the simplest traditional first order kinetics was not as good as the other three models. Yu et al. (2011) compared modified first order kinetics with Weibull model in the thermal degradation process of litchi firmness. The results indicated Weibull model had better performance than the modified first order equation. Similar foods with different modeling methods were also studied by researchers. For example, Young's modulus and failure stress of bread crumb were successfully fitted ($0.55 \leqslant R^2 \leqslant 0.94$) to the relative density power law model proposed by Gibson and Ashby (Zghal et al., 2002), and with the axisymmetric FEM model, the load–displacement curves of bread crumb generated from cylindrical indentation were well predicted (Liu and Scanlon, 2003b).

Although modeling researches have been carried on for decades, the varieties of foods seem huge. Even the most familiar foods, for instance, an entire dairy process and the final mechanical properties of the end-product, such as firmness, are still poorly modeled (Foucquier et al., 2012). Thus, more efforts should be made in this field.

5. Conclusions

The approaches to analysis of spatial/temporal texture data recorded during experiments are widely employed in research and food industry due to their practicability. However, since food texture is too complicated to be described by only one physical property, more profiles may need to be analyzed together for food texture determination. For example, TPA test combined with acoustic component could be a useful approach to evaluating the texture characteristics. The use of food texture indices is still quite limited, which seems bounded by the definitions of indices themselves because most of them are based on specific measurement methods and corresponding instruments. With computer assistance, modeling is becoming a powerful approach to food texture analysis. The data of both sensory perception and instrumental measurement may be analyzed, while the challenge is the lack of fundamental models for the vast variety of foods. Therefore, multidisciplinary collaboration among food engineers, material researchers, consumer scientists and other professionals is necessary for the texture analysis of food products.

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