An Acoustic Study on the Texture of Cellular Brittle Foods

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ABSTRACT

Crispness, crunchiness and crackliness are the essential qualities for food that is cellularly brittle. The relationship between acoustic sensations and perception of texture has been studied in cellular brittle foods. This article aims to review the progress of measuring acoustics in brittle food to predict human perception of sound/vibration. In doing so, the techniques used for sound/vibration recording, acoustic parameters related to food sensory properties, and the stimulus test of acoustic/vibration on human perception of food texture will be reviewed. Lastly, the mainstream direction of this field of research will be summarized. Additionally, prospective research for the future in this area of study is provided.

Keywords

acoustic study, cellular brittle food, food texture, sensory perception, sound/vibration

1. Introduction

Cellular brittle foods are the foods that have properties including crispness, crunchiness and crackliness. Szczesniak and Kahn (1971, 1984) had found that consumers considered crispy and crunchy foods to be appealing and enjoyable. Crispness, crunchiness and crackliness are textural attributes often associated with the freshness and firmness of natural produce and manufactured foods. For example, crispness has been described as one of the most versatile single texture parameters of food products because it is universally liked, as it enhances or contrasts texture, and was the prominent texture attribute related to top-quality cooking. However, the definitions described by dictionaries, consumers, and researchers varies greatly (Michael et al., 2013). The sounds described the overall quality of a food product better than any other sensory feature (Gondek and Marzec, 2008). The information obtained in acoustic studies of foods has been useful for developing definitions of crisp, crunchy and crackly products and to provide a point of conflict between the terms. Michael et al. (2013) stated that crispness was one sound event perceived as a sharp, clean, fast, high pitched sound and evaluated with the incisors and lips open; crunchiness was multiple lower pitched sounds perceived as a series of small events and evaluated with the molars and lips closed; crackliness was one sudden low pitched sound event that brittle products produce when pressure is applied and evaluated with the molars and lips closed. Table 1 shows the definitions of terms used to describe the textural attributes of cellular brittle foods that produce sounds when they are crushed or bitten/chewed by humans.

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Table 1: Literature citations of crispness, crunchiness and crackliness

| Texture       | Definition                                                                 | References                          |
|---------------|-----------------------------------------------------------------------------|-------------------------------------|
| Crispness     | A high pitched sound                                                        | Dacremont, 1995                     |
|               | A light and thin texture producing a sharp clean break with a high-pitch sound when force is applied, mainly during the first bite with front teeth | Fillion and Kilcast, 2002             |
|               | Soft sound, more airy than crackling                                        | Dijksterhuis et al., 2007           |
|               | One sound event perceived as a sharp, clean, fast and high-pitched sound     | Chauvin et al., 2008                |
| Crunchiness   | Degree of low pitched noise (with respect to crisp sounds)                  | Seymour and Hamann, 1988            |
|               | Pitched sound, light sound, longer sounding                                 | Dijksterhuis et al., 2007           |
|               | Multiple lower pitched sounds perceived as a series of small events         | Chauvin et al., 2008                |
| Crackliness   | To make small, sharp, sudden and repeated noises                            | Vickers, 1984                       |
|               | Low pitched sounds with a high level of bone conduction                    | Dacremont, 1995                     |
|               | Combination of sound and bite force                                         | Dijksterhuis et al., 2007           |

Acoustic methods for evaluating the quality of cellular brittle foods have gained worldwide traction due to their rapid and cost-friendly nature. Furthermore, the relationship between acoustic sensations and the perception of texture has been studied around cellular brittle products for over the past few decades (Drake, 1963; Vickers, 1987; Al Chakra et al., 1996; Luyten and Van Vliet, 2006; Spence and Shankar, 2010). This has fueled an increased interest in the acoustic method’s utilization for quality evaluation of cellular brittle foods. The current work aims to highlight the acoustic method's technical development of quality evaluation with a primary emphasis on the use of stimuli methods.

The primary purpose of this review is to summarize the mechanisms and principles by which the acoustics of cellular brittle food affects human perception. This review seeks to offer a better understanding of the physiological and rheological principles of food texture and sensory perception, as well as how to interpret textural results from acoustics more effectively. This review is organized as follows: Section 1 provides a brief description of the significant achievements of acoustical studies about food texture in the last half-century. Additionally, the acoustic properties relate to sensory words, as well as the texture quality relate to acoustic properties of crisp food and the human perception mechanism of sound/vibration are introduced. Section 2 summarizes the methods of sound/vibration recording, including the type of sound/vibration recording devices used, the crushing method of vibration emission, and the effect factors on sound/vibration recording. Section 3 describes the acoustic/vibration parameters that relate to crisp quality. Section 4 focuses on the stimuli test and gives perspective of acoustic research for the brittle cellular food.

1.1 Sound/vibration as critical cues for perception of food texture and producing of sound/vibration

The auditory enhancement of food texture perception may be especially important, given the consumer’s high regard for crispness in foods (Szczesniak and Kleyn, 1963). Drake (1963) as a means of advancing texture research, first introduced the idea that auditory sensations are essential for texture perception. Vickers and Bourne (1976) demonstrated that auditory cues were essential for the accurate judgment of crispness. Moreover, Vickers (1981) revealed no difference between humans’ perception of a food crispness as determined by biting/chewing sounds and
from the estimation of crispness, which is achieved by using both oral-tactile and auditory cues. Christensen and Vickers (1981) demonstrated that the perception of crispness could be unaffected by masking the sound of the biting action with a loud noise, revealing that auditory sensations and their measurements are essential for evaluating crispness. Subsequently, it has been reported that auditory cues play an essential role in texture perception (Lee et al., 1990; Al Chakra et al., 1996; Srisawas and Jindal, 2003; Zampini and Spence, 2004; Chaunier et al., 2005; Courcoux et al., 2005; Luyten and Van Vliet, 2006; Varela et al., 2008; Spence and Shankar, 2010). If a crisp product did not produce the expected sound upon biting, it was considered stale or of poor quality (Duizer, 2001). The sounds described the overall quality of a food product better than any other sensory feature (Gondek and Marzec, 2008). De Liz Pocztaruk et al. (2011) showed that auditory masking led to significantly lower scores on the attributes of sound and snapping. Zampini and Spence (2010) reported that the perception of crispness and staleness of potato chips could be altered by varying the loudness or frequency in composition of the first bite sound. The effect of sound modulation on crispness perception has been subsequently replicated by Masuda et al. (2008), Masuda and Okajima (2011), Koizumi et al. (2013), and Demattè et al. (2014). The principle of cross-modal integration has explained the effect of auditory modification on crispness perception in previous studies by Deneve and Pouget (2004) and Ernst and Bülthoff (2004), whereby oral sensation and chewing sounds are said to be integrated unconsciously (Spence, 2015). Endo et al. (2016) demonstrated that the "crunchy" pseudo-chewing sound has a significant influence on the perception of food texture under the condition of when actual "crunchy" oral sensation is lacking. The masking of sounds that foods make during eating can impair the ability to discriminate textural attributes of foods. Even the sounds emitted were not usually paid attention to, but chewing sounds could influence the perception of food texture, especially the perception of crispness and crunchiness (Zampini and Spence, 2010; Saeleaw and Schleining, 2011; Spence, 2013).

Numerous research investigations have studied the mechanism of the acoustic property which indicates the texture quality of cellular brittle foods. The sound emitted by crisp foods depends on several macroscopic and microscopic factors within said food. The breakdown of particles and moistening of crispy food during mastication result in lower sound levels (Lee et al., 1990). Al Chakra et al. (1996) indicated that structure has a significant impact on the sounds produced when biting into products with crisp, crunchy, and crackly textures. Microscopically, within a noisy product, the arrangement of cells, chemical bonds, impurities, and existing cracks all affect sound production. The sound wave is the product of the movement of individual air molecules around their equilibrium. As one molecule is displaced from its equilibrium, it displaces other molecules around it, causing the surrounding molecules to vibrate. As the movement spreads from molecule to molecule, a sound wave is propagated (Speaks, 1999). Luyten et al. (2004) demonstrated that the morphology of cellular material could be characterized by the porosity or the relative density of the material. Porosity is related to the volume fraction of air in the material; the size and shape of the cells, and the distribution in these properties; the local absence of cell walls caused by gas cell coalescence causing the cellular structure to open. This multiple determination was an effective way of predicting sensory results. The sound produced was due to the rupture of the cell walls, and variations in the number of cells being crushed gave rise to the irregular sounds.

1.2 Perception mechanism of sound/vibration

The perception of acoustic sound wave produced upon the breakage of cell walls can be detected by air conduction to the ear (air-conduction mechanism), bone conduction through the mandible, teeth, jaws, and through the soft tissue of the cheeks and tongue (bone-conduction mechanism, see Vickers and Bourne, 1976). Upon entering the inner ear, the wave is divided into component frequencies by the basilar membrane. The composition of these
frequencies contributes to the subjective perception of loudness and pitch of the sound (Kinsler and Frey, 1962). The breakage behavior of food and the corresponding sound is essential for sensory sensation. In order to research the effect of sound emitted on cellular brittle food, acoustic measures of both bone- and air-conducted noises must be collected (Kapur, 1971; Dacremont et al., 1991; Dacremont, 1995). Guest et al. (2002), by utilizing the skin-parchment illusion, found a similar result; the crackliness from chewing chips was significantly affected by the attenuation of the overall sounds recorded near the subjects’ mouth and fed to them via headphones.

There is still an argument whether the bone-conduction vibration is prior to the air-conduction sound. They observed that during biting, both systems contributed to the sensation of food texture equally. However, Dacremont (1995) demonstrated that air-conducted sounds are more important than bone-conducted sounds for the determination of the crispness of foods due to soft tissues, which strongly dampened the bone-conducted sound. Zampini et al. (2003) indicated the cross-modal fusion between vibrotactile oral and auditory input at the subjective conscious level, via the (pre-attentive) pairing of both congruent inputs. Moreover, the sound transmitted through air-conduction or the bone-conduction sensory effect is determined by the crispness of cellular brittle food. Future neuroscientific studies are necessary to assess the impact of air- and bone-conduction on the human perception of sound.

Even though the effect of sound on the human perception of food texture has been widely investigated, very few reports have focused on the vibration effect on the perception of food texture. The vibration received by mechanoreceptors located in the mouth also has a significant role in the perception of food sensory. Watanabe (2004) described the fine structures of lamellated mechanoreceptive corpuscles, Merkel cell-neurite complexes, and free nerve endings in the oral mucosae of mammals, with special attention paid to the axon terminals and lamellar cells. The organized mechanoreceptive corpuscles are present in the mucosae of the gingiva, cheek, tongue, and soft and hard palate. The mechanoreceptor is the neurological center for sensing the chewing vibration. Typically, these corpuscles receive one to three myelinated nerve fibers and are surrounded by a capsule, as observed in the gingiva of the tufted capuchin monkey (Cebus apella) (Watanabe, 1982). De Liz Pocztaruk et al. (2011) concluded that bone-conduction of the vibrations from food breakage, proprioception, and tactile sensors may supply sufficient information to the brain in order to control the chewing process when auditory information is lacking. However, these are a few examples regarding how mammals discriminate vibrations through tactile sound in the mucosae.

2. Method of sound/vibration recording

The recording method is critical to the evaluation of food texture in crunchiness. As showed in Figure 1, all recording methods are accomplished through sound/vibration emission, sensing of sound/vibration, recording/data acquisition and data analysis. For example, sound emission by the instrument crushing to the crisp samples and were sensed by the microphone, then the sound was recorded in digital data on a computer.

![Procedure of sound/vibration recording](image)

Figure 1: Procedure of sound/vibration recording

This section summarizes the development of sound recording devices, and production method of sound/vibration. Furthermore, previous research has also found some factors that affect the recording of
sound/vibration, which helps to avoid the unnecessary sound/vibration disturbance in the study of cellular brittle foods.

2.1 Recording device of sound/vibration

The sound recording device had progressed from a microphone with tape medium (Drake, 1963) or directly into a computer (Gondek et al., 2013), to a contact sensor (Zdunek and Konstankiewicz, 2004), and to piezo film (Taniwaki et al., 2010). As technology progressed, the quality of sound/vibration recording has become more accurate. As far as the microphone is concerned, condenser microphone was often utilized because it is much more sensitive than dynamic microphone or ribbon microphone. Recording the chewing sounds is accomplished by placing a microphone over the ear canal on the side of mouth that the test subject uses to eat with (Drake, 1963; Mohamed et al., 1982; De Belie et al., 2000; De Belie et al., 2002). Most of these studies used a microphone to detect the sound/vibration of the sample breaking (Lewicki et al., 2009; Taniwaki et al., 2010; Saeleaw et al., 2012).

Zdunek et al. (2010a), Herremans et al. (2013), Chanvrier et al. (2014), and Akimoto et al. (2017) registered acoustic signal generated during deformation of different food products by the piezoelectric contact sensor. The vibrations induced by stress affected the output voltage and phase of the element. Taniwaki and Sakurai (2008) confirmed that the output voltage from a piezoelectric element was proportional to the displacement of the element in study of acoustic vibration for brittle foods. Contact methods of acoustic emission measurement have been applied for texture evaluation of breakfast cereals (Gondek et al., 2006), extruded bread (Marzec et al., 2007), apples (Zdunek et al., 2011) and sugar gels (Herremans et al., 2013). A contact acoustic emission detector uses a puncture probe, an accelerometer that detects vibrations, and processors that count so-called acoustic emission counts. Concertedly, a similar idea was used by Sakurai et al. (2005). Akimoto et al. (2017) used a new device that consists of a free-running truck with a probe and vibration sensor, a slightly slanted track on which the truck moves, and a velocity sensor.

The use of the contact sensor has several advantages. First, the contact sensor has a high sensitivity, which allows for the detection of small signals which are not visible on the force-deformation curve (Zdunek and Konstankiewicz, 2004). Secondly, the method is nearly impervious to background noise; thus, no special acoustic isolation is required. Additionally, contact measurements during mechanical breakdown simulate chewing and sense the bone-conducted vibrations, which are important for texture perception (Vickers, 1987; Taniwaki et al., 2010).

2.2 Crushing method

Sound wave propagation is made of alternating regions of compression (increased density of molecules) and rarefaction (decreased density of molecules) moving through the air (Speaks, 1999). Piazza et al. (2007) elucidated that when a force is applied to a crisp item, and its structure is stressed until a critical point is reached, the action of the external force causes the brittle walls of the cellular structure to rupture, which begins to vibrate. Compression done by an instrument or physiological biting and chewing are the most used methods for producing a sound emission from crushing crisp foods.

Texture analyzer and breaking with simulated chewing/biting are the most used to crushing cellular brittle foods to get the acoustic emission. This approach has been used in several mechanical tests evaluating plant tissues: compression (Moskowitz et al., 1974; Guraya and Toledo, 1996), puncture (Brown et al., 1998; Harker et al., 2002; Zdunek et al., 2010a), and bending (Zdunek and Konstankiewicz, 2004; Zdunek and Bednarczyk, 2006). Several studies have used a texture analyzer for simultaneous measurement of force-displacement and sound pressure that are generated by the fracture of a crisp food sample (Mohamed et al., 1982; Chaunier et al., 2005; Chen et al., 2005;
Varela et al., 2006; Castro-Prada et al., 2007; Marzec et al., 2007; Primo-Martín et al., 2008; Salvador et al., 2009; Arimi et al., 2010; Marzec et al., 2010; Zdunek et al., 2010a; Taniwaki and Kohyama 2012). Besides, some research groups have attempted to crush the food samples by a self-made device, but the working mechanism of the device imitates the texture analysis meter. Regardless of the sensor used, acoustic methods demonstrate a good correlation with the quality and sensory texture attributes of food.

Biting uses the incisors while chewing/mastication uses the molars and premolars. Although more than one chew was evaluated, the first chew was shown to provide the highest amount of acoustic information for crisp foods (Lee et al., 1988). De Belie et al. (2002) recorded that by separating the sound from each chew into its frequency components, more information could be obtained if the total sound is analyzed as a function of time. The acoustic study used for cellular brittle foods by biting method (Sherman and Deghaidy, 1978; Vickers, 1984; Seymour and Hamann, 1988; Dacremont, 1995; Al Chakra et al., 1996; Duizer et al., 1998; Jousmäki and Hari, 1998; Fillion and Kilcast, 2002; Guest et al., 2002; Zampini and Spence, 2004; Chen et al., 2005; Suzuki et al., 2006), also by the chewing method (Lee et al., 1988; Dacremont et al., 1991; De Belie et al., 2000; Zdunek, et al., 2010b). The biting method has been widely used rather than the chewing/mastication method in food texture acoustic studies. Two factors primarily contribute to the biting method. One is the biting action, which generates simple and clear sound emission as compared to the chewing action. While, the chewing action generates unclear sound emission when samples were mixed with saliva and part of the sound was absorbed by the soft tissues in the mouth and jaw. The other reason is that the sound emission of food crushing is convenient and effective in recording near and out of the mouth, while it is extremely difficult to set the recorder in the mouth when food is being chewed.

2.3 Effect on sound/vibration recording

Firstly, the recording of sound/vibration in instrument method may be affected by the size of the sample and the distance of the sound recorder from the sound emission. Sound emission during biting appears to change as the sample dimension (length, width, and thickness) of the product changes (Al Chakra et al., 1996).

Secondly, the microphone method for recording sounds from instrument method or mastication sounds from participants has several drawbacks for quantitative and reproducible evaluation of food texture, such as variations in the microphone performance (Chen et al., 2005), the conditions of the experiment (room size, arrangement of auditory equipment, and environmental noise). To allow for the collection of acoustic information with minimum machine noise, Seymour and Hamann (1988) enclosed the compression cell in an anechoic chamber and used the voltage signal from a microphone placed near their sample in an anechoic chamber to obtain acoustic pressure information. However, the influence of recording environmental noise on sound or vibration recording depends on the recording method used. The contact sensor appeared to be a better anti-noise method than the sound recorded by a microphone.

Thirdly and the last of all, individual factors, such as the force generated by using teeth, bite speed of the jawbone, volume of the oral cavity, size of the human head cavity and mandible (Taniwaki et al., 2010), and the area of contact surface between the teeth and the food (Chauvin et al., 2008) will vary from person to person in generating sound emission. Additionally, chewing sounds depends on the mouth’s configuration and whether the mouth is closed or open (Fillion and Kilcast, 2002; Chauvin et al., 2008). They are typical of low frequency due to the absorption of sound by the soft tissue of the mouth and jaw. The resonance frequency of the mandible is 160 Hz, and sounds generated at this frequency are amplified when chewing with a closed mouth (Kapur, 1971; Vickers and Bourne, 1976). The resonant frequencies of the mouth cavity and the skull bone connected to the mouth (Van Der
Bilt et al., 2006), and the quantity and rate of saliva during mastication (Szczesniak, 2002) has been confirmed to be difference between participants affect the sound/vibration recording.

3. Acoustic components as an index

A sound wave is made of a series of sinusoidal waves differing in amplitude, frequency, and phase. Research studies have attempted to predict food texture by one or more parameters of sounds/vibrations. Early studies focused on analyzing acoustic data in the frequency-domain (Seymour and Hamann, 1988; Dacremont, 1995). However, several recent studies have attempted to analyze acoustic data in the time-domain (Giacosa et al., 2016; Jakubczyk et al., 2017).

3.1 Frequency domain

Frequency is defined as the rate at which sound vibrates and is measured as the number of cycles of vibration completed per second (cps) or as hertz (Hz), where 1 Hz = 1 cps (Speaks, 1999). An earlier study completed by Jesteadt et al. (1977) summarized that the data for intensity discrimination of pulsed sinusoids at various frequencies and sensation levels are markedly different from the data for the detection of amplitude modulation that is often used in evaluating models of discrimination. Therefore, for several years, food research focused on the frequency of sound when studying the sound effect on food texture. Fast Fourier Transform (FFT) has been used as a method for determining the frequencies most evident during biting and chewing crisp, crunchy, and crackly food products. Using FFT has allowed for the comparison of the predominant frequencies exhibited by crisp, crunchy, and crackly products. Techniques that have been used in spectrographic or speech analysis can provide an analysis of the frequency over time. The sound spectrograph is a wave analyzer, which produces a permanent visual recording showing the distribution of energy in both frequency and time (Koenig et al., 1946). The analysis used in a sound spectrograph is similar to FFT, but produces three-dimensional recordings of frequency, amplitude, and time (Brochetti et al., 1992). The main research studies regarding the frequency range of sound/vibration producing from foods crushing dominantly in cellular brittle foods are illustrated in Table 2. As Table 2 showed, the frequency character of sound/vibration in cellular brittle foods varied from sample to sample and from study to study. The collective conclusion is that high frequency significantly proportioned to crispness.

| Samples                        | Frequency range (kHz) | References                   |
|--------------------------------|-----------------------|------------------------------|
| Potato chips, tortilla chips   | 3–4, 6                | Lee et al., 1988             |
| Potato chips, crackers         | 0.5–3.3               | Seymour and Hamann, 1988     |
| Almond, carrots, biscuits      | 1.25–2, 5–12.8        | Dacremont, 1995             |
| Pasta samples                  | 10–12                 | Al Chakra et al., 1996      |
| Cereal based foods             | 2–8                   | Roudaut et al., 1998        |
| Extruded corn puffs            | 1–2, 6–7              | Duizer et al., 1998         |
| Potato chips                   | 2–20                  | Zampini and Spence, 2004    |
| Wheat breakfast cereals        | 7–9, 14–15            | Gondek et al., 2006         |
| Crisp bread                    | 1–3, 7–15             | Marzec et al., 2007         |
| Potato chips                   | 1.6–25.6              | Taniwaki et al., 2010       |
Another analysis method in frequency domain was fractal analysis. Some of the measures of the amplitude-time curve can be used to characterize the jaggedness of the curve (such as number of peaks and mean height of the peaks). Fractal analysis is a technique that characterizes the jaggedness of peaks, and has recently been applied to food research (Barrett et al., 1992; Rohde et al., 1993; Barrett and Peleg, 1995; Duizer et al., 1998). Kilcast (2004) demonstrated that Fractal analysis involves the use of mathematical algorithms to determine the degree of jaggedness of a line in order to give a fractal dimension of the line. The fractal concept was proposed as a means of describing dimensions between the conventional dimensions of 1, 2, and 3 and structures that are neither Euclidean lines, surfaces, nor solids. Tesch et al. (1995) concluded that it was possible to use the fractal dimension of the bursts in sound emitted by chewing the crunchy foods as an objective measure of the plasticizing effect of moisture. Acoustic signatures of cheese balls and croutons through fractal dimensions could be useful in equations to determine the relative roles of mechanical and acoustic stimuli in the perception of crunchy products. Duizer et al. (1998) used fractal analysis on the acoustics of chewing and related this to sensory properties of extruded snacks. The apparent fractal dimension was significantly correlated to crispness, pitch, and crumbliness.

### 3.2 Time-domain

The acoustic data in time-domain is usually treated as acoustic emission (AE), which refers to the generation of transient elastic waves produced by a sudden redistribution of stress in a material (Vahaviolos, 1999). The AE is a sound clip including multiple acoustic events (Figure 2), after envelope detection by half-wave rectification, the AE characterized by determining the maximum amplitude, number of peaks, height of the peaks and duration of the sound, sound energy. Also, the sound/vibration pressure and sound/vibration intensity were studied.

![Figure 2: Illustration of acoustic emission’s parameters in time-domain](image)

#### 3.2.1 Amplitude of sound wave and vibration

Drake (1963) showed that the amplitude of the sound produced during biting of toasted bread increased as the degree of toast increased, lately, this tendency also indicated by Vickers and Bourne (1976). Zampini and Spence (2004) reported that increasing the amplitude and high-frequency components of auditory feedback during biting on
potato chips systematically enhanced the perception of crispness. Nearly all research on the amplitude of sound to food texture concluded that the higher the amplitude of the sound, the crispness increases in a given sample.

3.2.2 Peaks in amplitude of sound wave’s and vibration’s signal

Edmister and Vickers (1985) found that a combination of the mean height of the peaks in voltage of sensor output and the number of sound peaks (NSP) were most highly correlated with the auditory crispness of crisp products \((r = 0.89)\). Vickers (1987) determined that the number of peaks produced while biting a potato chip is a positive predictor of chip crispness \((r = 0.92)\). Varela et al. (2006) reported that the sensory crispness of roasted almonds is highly correlated with the size of acoustic peaks emitted by crackling. Moreover, Varela et al. (2008) found that NSP was superior in discriminating precooked chicken nuggets and were directly related to food crispness. Primo-Martín et al. (2009) investigated bread crust and suggested that a high NSP determined the crust crispness. Salvador et al. (2009) stated that the sensory crispness of potato chips was positively related to the NSP. Saeleaw et al. (2012) showed that the NSP could be used to determine the crispness of rye-based extrudates and cassava crackers produced in different process conditions, such as extrusion conditions and frying parameters, respectively. The NSP was also used to characterize crispness of extruded cereals (Chanvrier et al., 2014), biscuits (Blöiska et al., 2014), apples (Cybulska et al., 2012; Piazza and Giovenzana, 2015), and hazelnut kernels (Giacosa et al., 2016) as well. Furthermore, Jakubczyk et al. (2017) studied coextruded snacks by using the NSP parameters and explained that milk-filled extrudates were crisper than jelly-filled extrudates since milk-filled extrudates had the highest values of these acoustic parameters. Some studies have also associated high values of the maximum acoustic peak and mean of sound response with crispness (Salvador et al., 2009; Saeleaw et al., 2012; Piazza and Giovenzana, 2015; Giacosa et al., 2016; Jakubczyk et al., 2017).

3.2.3 Acoustic events

The acoustic events per unit area, or acoustic events per unit time, showed an excellent correlation with the sensory results. Varela et al. (2006) reported that the sensory crispness of roasted almonds is highly correlated with the rate of emission emitted by crackling. Salvador et al. (2009) indicated that the sensory crispness of potato chips is positively related to the number of fracture and acoustic events. Primo-Martín et al. (2009) stated that the crispness of the crust model was characterized by a low work of fracture and a high number of sound and force events. Recently, the sound emitted during fracture of the crust of crispy foods was studied as an indicator of crispness (Arimi et al., 2010; Primo-Martín et al., 2010; Taniwaki et al., 2010; Saeleaw and Schleining, 2011). Acoustic signals expressed in terms of acoustic events was found to be better correlated with crispness and crunchiness than firmness with these attributes such as AE events, mean AE amplitude (Zdunek et al., 2010b).

3.2.4 Sound pressure/loudness/acoustic intensity/sound and vibration energy

Luyten and Van Vliet (2006) demonstrated the amount of damage is related to the amount of sound energy and loudness. The pitch of the emitted sound (frequency) is related to the type of fracturing process and the behavior of the material involved. Additionally, the size of broken pieces most likely affects both the amount of sound and the pitch. Given that sound pressure is proportional to the voltage output of the microphone, sound pressure is the most readily measurable variable in a sound field (Kinsler and Frey, 1962; Seymour and Hamann, 1988). Sound pressure can be defined as the amount of force per unit area of a sound wave (measured in N/m²) (Speaks, 1999) and is used in the calculation of the sound pressure level. The sound pressure level is a factor in the psychophysical perception of the loudness of crisp samples (Ross, 1990). When studying potato chips at various water activities, Seymour and Hamann (1988) found that potato chips with a low water activity had a higher mean sound pressure. Chen et al.
(2005) demonstrated that maximum sound pressure \((S_{\text{max}})\) could be used to range biscuit crispness. They demonstrated that the highest \(S_{\text{max}}\) was highest in foods with the highest crispness. Latterly, Çaşanba et al. (2018) indicated that the \(S_{\text{max}}\) \((r = 0.89)\) positively correlates to sensory descriptor crispness in the cursing test.

Several other studies have claimed that crisp sounds are typically both louder and higher in pitch. Zampini and Spence (2004) demonstrated that the perception of both the crispness and staleness was systematically altered by varying the loudness and/or frequency composition of the auditory feedback elicited during the biting action.

The acoustic intensity level is related to sound pressure, with sound pressure being proportional to the square root of acoustic intensity \((W/m^2, \text{Speaks, 1999})\). Acoustic intensity has been shown to differ between potato chip samples of different water activities, with intensity level decreasing as water activity increased. However, this is less important for characterizing crispness than the mean sound pressure and the sound pressure level (Seymour and Hamann, 1988). To calculate the equivalent continuous sound level, Mohamed et al. (1982) analyzed the recorded sounds produced from various crisp products through a statistical distribution analyzer. Tesch et al. (1996) and Roudaut et al. (1998) investigated the effect of water content on acoustic properties of products and showed that the intensity of emitted sound was strongly related to the moistness of the materials.

Sound power is the total sound energy emitted by a source per unit time. Guirao and Stevens (1964) have demonstrated that auditory density increases as the sound frequency and sound intensity increases. Furthermore, auditory density refers to the penetrating quality of a sound, its apparent compactness, and concentration of hardness. This occurrence was interpreted as an energy release in the form of sound as a result of material fracturing (Zdunek et al., 2010a; 2010b). Sound energy has been used to calculate the acoustic intensity level (Seymour and Hamann, 1988) and the equivalent continuous sound level \((\text{Leq})\) (Mohamed et al., 1982). \(\text{Leq}\) is the equivalent continuous sound level in decibels, which is equivalent to the total sound energy measured over a stated period of time and is also known as the time-average sound level. Correlation analysis showed that as the crispness of various samples stored at different water activities increases, the \(\text{Leq}\) also increases \((r = 0.701)\) (Mohamed et al., 1982). Vickers (1985) suggested that the relationship between the crispness of a product and the auditory density of the sound produced should be studied. Iwatani et al. (2013) demonstrated that a new energy texture index, which expresses the vibration energy per unit time of a wedge-type probe inserted into a food sample, was a better index to the texture of cellular brittle. The sound emission is the result of a sudden release of energy, while the force curve is a reflection of the energy applied to the material (Varela et al., 2008). Moreover, Taniwaki and Kohyama (2012) explained that the magnitudes of the force drop at the fracture point releases stored strain energy during the deformation of potato chips, and some of this energy is released as sound energy.

4. Stimuli test of sound/vibration

Research in this field is not only limited to analyzing the relationship between statistical data and food sensory. Currently, given the advancements in neuroscience, the brain-machine interface as well as human sensory perception of food texture is gradually being clarified. The initial stage in exploring the interface of human perception of food sensory is the stimuli experiment.

In previous research, piezoelectric materials that generate electricity in response to mechanical stimuli were suggested as a source to replace hair cells in the hopes of creating an artificial cochlear epithelium. The cochlear amplifies and filters sound vibration using structural elements, especially the basilar membrane, through an energy-dependent active process of fine-tuning that is mostly dependent on the function of the outer hair cells. The location of the largest vibration in the basilar membrane depends on the frequency of the traveling wave (Békésy, 1960; 1970). Zampini and Spence (2004) carried out a stimuli test by varying the loudness and/or frequency composition.
of the auditory feedback elicited during the biting action. Their results highlight the significant role that auditory cues can play in modulating the perception and evaluation of food. Inaoka et al. (2011) developed a prototype artificial cochlear epithelium using a piezoelectric membrane response in deafened guinea pigs, which functions as a sensor with the capability for acoustic/electric conversion without a battery. Additionally, sound stimuli were transmitted through the external auditory canal to a piezoelectric membrane implanted in the cochlea, inducing it to vibrate. These findings suggest a possibility for testing the sound/vibration stimuli on human participants. Currently, there is no sensorial stimuli test of vibration directly on the human being’s oral, however, some research groups have attempted vibration tests on the skin to assess human sensory perception. Bensmala and Hollins (2003) demonstrated that the Pacinian channel has been implicated in the perception of fine textures, though the stimuli test was carried on the index finger. Kuroki et al. (2017) indicated that when participants touched two sinusoidal vibrations of differing frequency (which activates separate channels with neighboring fingers or the different hand and judges the frequency of one vibration), the perceived frequency shifted toward the other (assimilation effect). Furthermore, when the participants judged the frequency of the pair as a whole, they consistently reported an intensity-based interpolation of the two vibrations (averaging effect). Though research of Kuroki et al. (2017) was not a stimuli test on the human mouth, he suggested that the vibration effect on human perception should be considered as the assimilation effect and averaging effect.

Vibrations can be perceived up to several hundred hertz through the tactile sense (mechanoreceptors in the skin). The tactile of the skin can discriminate against vibrations with a different frequency. However, no vibration stimuli test on the oral mechanonociceptor has been attempted. Future studies are required that assess tactile perception in humans regarding vibrations on the mouth. There are several arguments, or rather conflicting points, regarding how people perceive food sensory through vibration that need to be clarified. As the development of neuroscience in human perception of vibration and technology of instruments, it looks forward to discrete the essential information of vibration to excite the human perception of food sensory. As this review summarized, several assumptions about the preformation of the sound/vibration, such as frequency, peaks number, and energy were used to explore human perception of food sensory. However, an effective method in determining the effect of vibration on human perception of food texture is needed. Additionally, future studies exploring the principles of vibration, such as the assimilation effect, averaging effect, cross-modal interaction of human acoustics, and haptic within the mouth is required.

5. Conclusion

As sound/vibration detection technology continues to improve, the vibration information of food chewing or crushing will be more precisely collected. The frequency-domain has its limitations given that the frequency varies from device to device and from sample to sample. The time-domain of vibration such as the energy of burst and the peaks of the burst have been given much attention. As the continually improving of the analysis technology of the vibration, as well as neuroscience development gradually uncover the human perception of the auditory and the vibration, the stimuli experiments of the effect of vibration on human perception would be given much attention, the relation between the human perception of food sensory and the vibration is expected to be revealed.

6. Perspective

It might be possible to alter people's experience of food texture via altered auditory feedback of chewing sounds, thereby ameliorating dissatisfaction with food texture in individuals who are obliged to follow restricted diets. The investigation of human sensory concerning the crispness is influenced by chewing sound, even if the actual oral sensation is lacking, will be of great benefit for the satisfaction and pleasantness of the diet for people who may have
a decline in auditory or chewing ability. Firstly, satisfaction and pleasantness come from chewing sound/vibration. Such information may help the cracker industry to fine-tune foods that certain consumer requires. The food that creates a more intense sound/acute will please the consumer and provide an increase in sales. On the other hand, the detection technology of the dominant vibration for crispness could help the cracker industry by improving quality control. For example, quality check of crisp food on the industry line would have obvious advantage than the physical and precise than sensory evaluation for individual difference. Secondly, international trade and globalization require a shared understanding of texture terms of different countries. Therefore, it would be simpler if there were some instrumental standards of measuring the quality of crisp food.

This review helps to clarify the interface between the human sensory system and sound/vibration. A substantial amount of focus has been given to research in artificial intelligence on the interface between the human perception of sensory and the information transfer from the mouth to the human brain. In other words, the code of crispness is writeable bases on the corresponding relationship between the food sensory of food texture and the present type of sound/vibration.

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