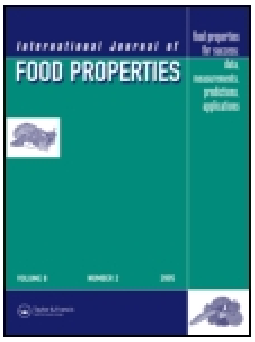

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# CRITICAL EVALUATION OF CRISPY AND CRUNCHY TEXTURES: A REVIEW

**Michael H. Tunick, Charles I. Onwulata, Audrey E. Thomas, John G. Phillips, Sudarsan Mukhopadhyay, Shiowshuh Sheen, Cheng-Kung Liu, Nicholas Latona, Mariana R. Pimentel*, and Peter H. Cooke****

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***Crispness and crunchiness are important factors in the enjoyment of many foods, but they are defined differently among dictionaries, consumers, and researchers. Sensory, mechanical, and acoustic methods have been used to provide data on crispness and crunchiness. Sensory measurements include biting force and sound intensity. Mechanical techniques resemble mastication and include flex, shear, and compression. Acoustical techniques measure frequency, intensity, and number of sound events. Water and oil content contribute to crispness and crunchiness, which also have temporal aspects. Information in the literature is compared in this article to develop definitions of crispness and crunchiness.***

**Keywords:** ***Crisp, Crunch, Sensory, Texture.***

## INTRODUCTION

Crispness and crunchiness are textural attributes often associated with the freshness and firmness of natural produce and manufactured foods. In consumer interviews, Szczesniak and Kahn[1,2] found that Americans considered crispy and crunchy foods to be appealing and enjoyable. Crispness was described as the most versatile single texture parameter of a product because it was universally liked, it enhanced or contrasted texture, and was the prominent texture attribute related to top-quality cooking. Crunchiness was found to be highly noticeable, associated with pleasure and fun, regarded with warmth, and described as active, energetic, and appealing. Sounds made during eating can modulate people's perceptions of moistness, texture, and other aspects of food, and may influence taste perception.[3]

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Vickers had 52 subjects judge food sounds, and found that crisp and crunchy exhibited the largest positive correlations with pleasantness.[4] In word association tests of texture terms with 150 participants, 47% recognized crispness and 29% recognized crunchiness; none of the other 60 terms mentioned were cited by more than 37 respondents.[5] Crispness and crunchiness are important when discussing food texture, but researchers agree that they are poorly defined quantities.[6,7]

"Crispy" is sometimes used to characterize attributes described by others as "crunchy"[6] and some researchers consider the terms interchangeable (for example, Chen et al.[8]). Crispness and crunchiness have been found to have a strong correlation by many researchers,[9–12] though others suggest they refer to different parameters.[13–15] Chaunier et al.[16] did not use the attribute crispy during sensory panel testing of corn flakes because they felt it did not reflect a unique sensory concept.

Crispness and crunchiness have traditionally been associated with the mechanical force required to compress food until it fractures into small pieces, but these relate to the ease of fracture or fracturability brittleness of a structure. Also, there are audible aspects to crispness and crunchiness that suggest that they are due to a combination of acoustic output and rigidity of the structure or its mechanical strength.[17] Acoustic and mechanical data are subject to large variations due to the heterogeneous nature of food structure.[18] Moreover, changes with time and environment are felt to be important when characterizing crunchy foods, which have a more intricate failure mechanism (repetitive deformation and subsequent fracture events) than crispy foods.[19]

The goal of this article is to provide empirical definitions of crispness and crunchiness in one continuum that may be used when describing food texture. These definitions may then be used as a starting point by making adjustments relating to cultural differences, test conditions, and state attributes of a structure.

## SEMANTICS

*Crisp* was derived from the Latin *crispus*, meaning "curled." This adjective meant "wrinkled" or "rippled" in 14th century English and the meaning changed to "brittle but hard or firm" in the 16th century.[20] Dictionary definitions of crispness include "firm, dry, and brittle, especially in a way considered pleasing;"[21] "firm but easily broken or crumbled; brittle;"[22] and "easily crumbled, brittle, desirably firm and crunchy."[23] A compromise definition could be "desirably firm and brittle, and easily crumbled."

*Crunch* has been an English verb since the 19th century and was derived from *cranch*, a 17th century word that was probably imitative.[20] Definitions include "crush (a hard or brittle foodstuff) with the teeth, making a loud grinding sound;"[21] "chew with a noisy crackling sound;"[22] and "chew or press with a crushing noise."[23] A consensus of these definitions could be "chew with a crushing noise." Vickers noted that the vowel "i" and the ending "sp" in *crisp* have higher-pitched sounds than the "u" and "ch" in *crunch*, which may convey part of their meanings.[10]

Textural terms vary because of language and culture. People often use crispy, crunchy, and brittle interchangeably though they are not synonymous.[24] For example, the Chinese and the Japanese each have about a dozen words dealing with these three attributes, including words translating as "rustling" and "sprinkling."[25] Measurable descriptors are needed to limit the boundary of what is termed crispy or crunchy.

## CONSUMER PERCEPTIONS AND SENSORY PANELS

An essential aspect of food texture is consumer perception. Szczesniak polled 200 consumers at New York's Grand Central Station and asked them to give three examples of crisp foods along with descriptions of crispness.[25] Lettuce, crackers, celery, and potato chips were the most frequently cited foods. The definition that emerged of a crisp food was one that is firm or stiff and snaps easily when deformed, emitting a crunchy/crackly sound. Snap was characterized by a very sudden, clean, and total fracture. Szczesniak concluded that potato chips are crisp, ice is crunchy, and fresh celery, which snaps cleanly and has a series of fractures when chewed, is both crispy and crunchy.

Varela et al.[26] found that the perception of crispness and crunchiness depends on the background of the consumer. About three-quarters of respondents from both Uruguay and Spain defined crispy foods as making a characteristic sound, but their opinions of crunchy foods varied widely. The leading definition of a crunchy food among Uruguayan consumers (mentioned by 38% of respondents) was "hard, resistant, solid;" only 6% of Spanish consumers used those terms. The top definition among Spanish consumers was "heterogeneous texture," cited by 21% of the respondents. The different responses among people who spoke the same language were obviously due to contrasting cultures and experiences.

Sensory tests with trained and untrained panels show that techniques for determining crispness (Table 1) and crunchiness (Table 2) also vary greatly. Crispness is usually evaluated by biting with incisors and crunchiness is generally determined by chewing with molars. Force and sound levels are commonly mentioned, but not always quantified.

Sensory panel judgments for crispness and crunchiness can be adjusted to 100-point scales for comparison. A 100-point scale is shown in Table 3, which combines data from four papers: one from 28 years ago,[11] another from 6 years ago,[27] and two from the past

**Table 1** Selected sensory measurements of crispness.

| Product | Technique | Measurement | Reference |
|---|---|---|---|
| Pickles | Bite through with incisors | Relative force | [62] |
| Biscuits, malted milk balls, wafers | Bite evenly with molars | Score on 1–100 scale | [29] |
| Crackers, potato chips | Bite through once with incisors | Level of higher-pitched noise | [12] |
| Extruded corn puffs | Bite once with incisors, abrupt and complete failure required | Perceived horizontal force | [55] |
| Extruded corn puffs | Crunch in mouth | Perceived relative force | [63] |
| Extruded corn puffs | Bite entirely through with back molars | Combination of breakdown and noise produced | [64] |
| Hazelnuts | Bite through with incisors | Force to bite through and level of high-pitched noise, score on scale | [65] |
| Apples, vegetables | First bite with incisors, second bite with molars, abrupt fracture | Score on 16-cm line scale | [28] |
| Cake with deep-fried batter, bread | First bite, force teeth through slowly, chewing | Score on 0–100 line scale | [66] |
| Extruded corn puffs | First bite | Force to bite and chew, score on 10-cm line scale | [67] |
| Apples | Bite with incisors | Sound intensity, score on 100-point scale | [68] |

**Table 2** Selected sensory measurements of crunchiness.

| Product | Technique | Measurement | Reference |
|---|---|---|---|
| "Space cubes" of cookie, cracker, strawberry | Chew 2 or 3 times with molars after initial bite | Force to crush and grind | [69] |
| Crackers, potato chips | Bite with molars | Degree of low-pitched noise but above threshold pitch, score on 14-point scale | [12] |
| Extruded corn puffs | Single complete bite through with molars | Perceived intensity of repeated incremental failure | [55] |
| Extruded or dried snacks | Chew up to five times with molars | Perceived cumulative intensity of force required for repeated incremental failures | [58] |
| Apples, vegetables | First bite with incisors, second bite with molars, higher force than crispness | Score on 16-cm line scale | [28] |
| Apples | Bite | Force required for first bite plus resulting noise, score on 10-point scale | [70] |
| Bread, cake coated with deep-fried batter | First bite | High pitched and light sound, longer than snap, score on 100-point line scale | [66] |
| Apples | Chew | Sound intensity, score on 100-point scale | [68] |

11 years.[6,28] Such a comparison is not statistically valid because of the various techniques used, but does provide an idea of what people have considered to be crispy and crunchy foods. Note that Meilgaard et al.[27] used one-half of a Melba toast cracker (a very dry and thinly sliced piece of toasted bread) as the top of the scale for crispness and Chauvin et al.[6] used the same as their highest level for crunchiness. The condition of the food is important—the crunchiness of a celery rib decreased from 50 to 20 after it was blanched for 3 min.[11] Size appears to be significant, though many researchers have not reported the size of the specimens they used, making normalization of data difficult. Vickers[11] and Vincent et al.[28] scored regular carrots at 45–50 for crispness and 65–70 for crunchiness, but Chauvin et al.[6] have mini carrots at 100 for crispness.

## MOISTURE

Some researchers have divided foods into wet crisp and dry crisp based on moisture content.[6,29,30] The most common wet crisp foods are raw fruits and vegetables, whose texture depends on the size, strength, and stiffness of their water-filled cellular structures and the manner in which the cell walls rupture during eating.[7] Fresh fruits and vegetables have water activity ($a_w$) levels between 0.960 and 0.999.[31] The force required to bite and chew and the sound produced are responsible for crispness.[11,32] Dry crisp products are basically those that contain cells or cavities filled with air instead of water. Products, such as crackers, potato chips, and popcorn, are dry crisp and can have $a_w < 0.1$.[33] Vickers and Christensen[30] determined that wet crisp and dry crisp were not different sensations and were not based on different auditory cues, but Chauvin et al.[6] found that panelists could

**Table 3** Intensity data for crispness and crunchiness, converted to scale from 0 to 100 and rounded to nearest 5.*

| Crispness value | Crunchiness value | Product | Size | Reference |
|---|---|---|---|---|
| 0 | 0 | Banana | 1.3 cm slice | [6] |
| 10 | — | Granola bar | 1/3 bar | [27] |
| 15 | 0 | Cereal-marshmallow bar | 1/6 bar | [6] |
| 20 | 30 | Braeburn apple | 1/8 apple | [28] |
| 25 | 25 | Gala apple | 1.3 cm slice | [6] |
| 25 | 25 | Golden Delicious apple | 1/8 apple | [28] |
| 30 | 35 | Turnip | 1.2 × 1.2 cm | [11] |
| 30 | 40 | Cucumber | 1 cm slice | [28] |
| 35 | — | Club cracker | 1/2 cracker | [27] |
| 45 | — | Oat cereal | 28 g | [27] |
| 45 | 45 | Granny Smith apple | 1/8 apple | [28] |
| 45 | 70 | Carrot | 7 mm slice | [28] |
| 50 | 25 | Water chestnut | 1 whole | [11] |
| 50 | 30 | White radish | 0.6 × 1.2 cm | [11] |
| 50 | 45 | Saltine cracker | 0.4 × 2.4 cm | [11] |
| 50 | 65 | Carrot | 1.5 × 2.5 cm | [11] |
| 55 | — | Bran flake cereal | 28 g | [27] |
| 55 | — | Mini rice cake | 1 cake | [6] |
| 65 | 30 | Peanut | 1 peanut | [11] |
| 65 | — | Goldfish cheese crackers | 28 g | [6] |
| 65 | 60 | Tortilla chip | 1 chip | [6] |
| 65 | 60 | Celery | 1 cm curl | [28] |
| 65 | 65 | Jicama (Mexican turnip) | 1.3 cm slice | [6] |
| 70 | 20 | Celery, blanched 3 min | Rib | [11] |
| 75 | — | Corn flake cereal | 28 g | [27] |
| 75 | 50 | Celery | Rib | [11] |
| 75 | 65 | Graham cracker | 0.4 × 3.0 cm | [11] |
| 75 | 70 | Shredded wheat cereal | 1 piece | [11] |
| 75 | 70 | Ginger snap cookie | 0.5 × 1.2 cm | [11] |
| 75 | 75 | Ruffled potato chip | 1 chip | [11] |
| — | 80 | Graham cracker stick | 1 stick | [6] |
| — | 85 | Dill pickle | 1.3 cm slice | [6] |
| 90 | 80 | Peanut brittle | 0.7 × 1.0 cm | [11] |
| 100 | — | Mini carrots | 1 carrot | [6] |
| — | 100 | Green pepper | 1.3 cm slice | [6] |
| 100 | 100 | Melba toast | 1/2 cracker | [6, 27] |

*Data from first bite is used for crispness scores and from chewing with molars for crunchiness scores.

clearly distinguish between wet and dry foods. Therefore, the same auditory cues differed only by the means of sound propagation in air or water.

Not surprisingly, crispness and crunchiness are related to $a_w$. Increasing the water content of food breaks macromolecular interactions and enhances the mobility of side chains and of sections of the backbone of macromolecules. The ability of macromolecules to slide against each other decreases the glass transition temperature, stiffness, and viscosity of the food.[19] Katz and Labuza[33] and Srisawas and Jindal[34] found that sensory scores of crispness for crackers, extruded snacks, and potato chips decreased with moisture content in a straight-line relationship with $r^2$ values $> 0.9$. Force-deformation curves and acoustic spectra of crunchy dry foods lose their jaggedness when moisture is added.[35] Peleg[36] reinterpreted data for breakfast cereals from Sauveageot and Blond[37] and found considerable variations in the range of $a_w$ corresponding to most of the crispness and crunchiness. The speed of deformation in conjunction with $a_w$ is also related to crispness. Castro-Prada et al.[38] defined a critical $a_w$ at which crispness is first lost, and found that as the speed of deformation increased from 10 to 40 mm/s the critical $a_w$ increased from 0.40 to 0.5–0.6.

By using the data in Table 3, plots of crispness and crunchiness of dry crisp (Fig. 1) and wet crisp (Fig. 2) foods were obtained. A curve showing all of the points with each food labeled is also shown (Fig. 3). The crispness of dry crisp foods had a strong linear relationship with their crunchiness ($r^2 = 0.986$), which shows that consumers correlate these parameters in dry food products. In contrast, the relationship between crispness and crunchiness in wet crisp foods was not significant ($r^2 = 0.313$), an indication that variations in $a_w$ are an important factor in wet crisp food.

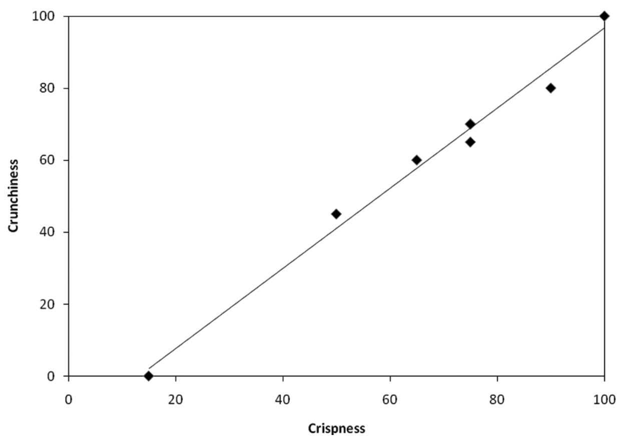


**Figure 1** Crispness and crunchiness of dry crisp foods. Data from Chauvin et al.,[6] Meilgaard et al.,[27] Vickers,[11] and Vincent et al.[28] Linear regression equation: crunchiness = 1.11(crispness) – 14.64, $r^2 = 0.986$.

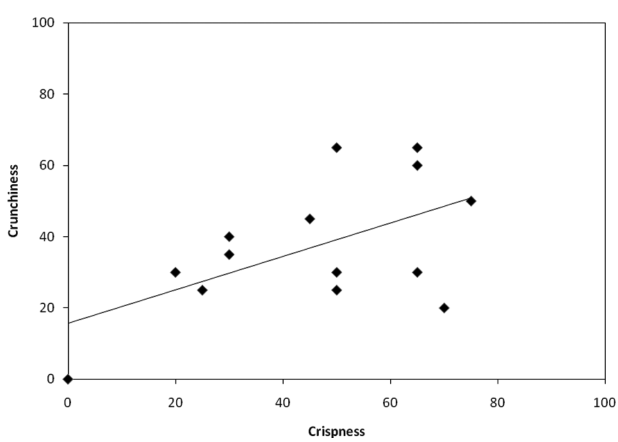


**Figure 2** Crispness and crunchiness of wet crisp foods. Data from Chauvin et al.,[6] Meilgaard et al.,[27] Vickers,[11] and Vincent et al.[28] Linear regression equation: crunchiness = 0.47(crispness) + 15.69, $r^2 = 0.313$.

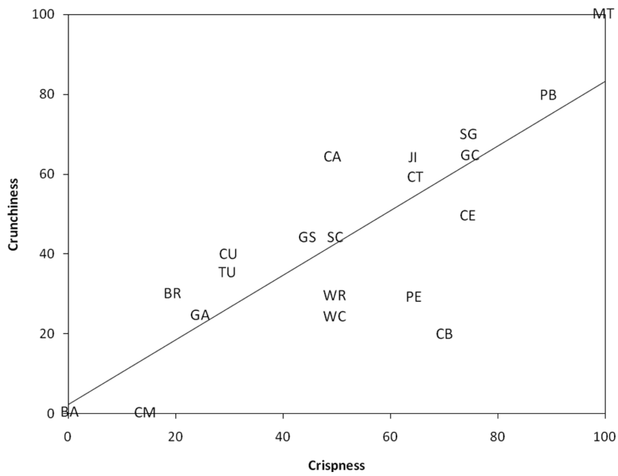


**Figure 3** Crispness and crunchiness of dry crisp and wet crisp foods. Data from Chauvin et al.,[6] Meilgaard et al.,[27] Vickers,[11] and Vincent et al.[28] Linear regression equation: crunchiness = 0.80(crispness) + 4.4, $r^2 = 0.634$. Legend: BA = banana, BR = Braeburn apple, CA = carrot, CB = celery blanched, CE = celery, CM = cereal-marshmallow bar, CT = celery and tortilla chip, CU = cucumber, GA = Gala apple, GC = Graham cracker, GS = Granny Smith apple, JI = jicama, MT = Melba toast, PB = peanut brittle, PE = peanut, SC = Saltine cracker, SG = shredded wheat and ginger snap, TU = turnip, WC = water chestnut, and WR = white radish.

## OIL

Crispness and crunchiness of food, especially of fried food, also depends on its oil content. The crispness of French fries, for example, is highly significantly correlated with frying time. The oil uptake increases as moisture is lost and levels off around 29% as the moisture content drops below 35%.[39] The use of a dip to decrease oil absorption results in higher crunchiness values because of increased moisture retention.[40] Voids in the food are created by water evaporation during frying, and the condensation of water vapor while the product is allowed to cool decreases the internal pressure, causing oil adhering to the food surface to be sucked in.[41] Oil uptake does not lead to significant changes in the mechanical properties of crispy cellular food, but the number of acoustic events and the acoustic energy are greatly reduced upon fracture.[42] This effect appears to be due to reflection of sound at the oil-air interface and increases within 20 min of frying, resulting in loss of crispness.[42]

## MECHANICAL ASPECTS

Fracture events take place when a crispy or crunchy food is bitten and chewed. When an initial bite is taken, the structure is ruptured and a crack sound is produced simultaneously as the force drops. The fracture propagates until the piece fragments, the bite is stopped, or the crack encounters a hole or some other inhomogeneity.[19] Physical parameters obtained by mechanical tests are therefore indicators of crisp and crunch properties of rigid foods. The molecular basis of these attributes may be obtained by small deformation tests,[15] but large deformation and fracture testing are the most suitable techniques for mimicking eating. Flex, shear, and compression techniques have all been used, with the latter most closely resembling mastication.[7] Some mechanical techniques used for

**Table 4** Representative mechanical techniques for determining crispness.

| Product | Technique | Conditions | Measurement | Reference |
|---|---|---|---|---|
| Pickles | Texture profile analysis | 50 mm/min | Brittleness, hardness, total work | [62] |
| Biscuits | Constant loading rate | 1.23 kg/s for 5 s | Fracture force and rate, work done | [29] |
| Extruded corn puffs | Compression | 50 mm/s, 67% compression | Time to reach maximum force | [64] |
| Hazelnuts | Compression | 10 mm/min | Force and deformation through second fracture point | [65] |
| Apples | Puncture | Penetrate 8 mm at 240 mm/min | Puncture force | [71] |
| Extruded corn puffs | Bite force apparatus inside mouth | Panelists bite sample in half | Maximum force, stress, area under curve | [67] |

determining crispness are shown in Table 4. Compression may involve puncture (which simulates biting with incisors) and is easily characterized by a peak force, but squeezing the sample between parallel plates or with a piston inside a cylinder does not yield a break point for a rigid structure.[43] Peleg has shown that the jaggedness of the force-deformation curve is related to sensory crispness and crunchiness,[36] and Vincent showed that sensory crispness is related to large fracture events.[44]

The number and size of the pieces produced when a food is fractured may also give an indication of crispness and crunchiness. In this technique, Varela et al.[45,46] photographed almonds fractured under compression to obtain image analysis of the pieces. The breakdown pattern was compared with microstructure, fracture properties such as number of force curve peaks, and sensory testing at low and high compression speeds.

## ACOUSTICAL ASPECTS

Food textural properties, such as crispness or crunchiness, are largely auditory sensations, and the product acceptability is often judged by the acceptable or expected sound level.[47] Hence, analyzing the pitch of sound released during chewing or biting a certain food often reveals these key sensory characteristics. Once the sound has been created by eating or chewing a solid food, it can be sensed by the conduction of air to the ear, via soft tissues in the mouth, and also through conduction via the jawbone.[47] Bone-mediated noises require propagation at a frequency of 160 Hz for clear perception of the nature and intensity of sound released during food mastication, while air-mediated noises need to be propagated at 160 Hz and amplified at 3.5 kHz. These two sounds have different natures in sound contribution and need to be combined and equalized for accurate acoustic sensations to be experienced while eating food.[13]

When a food is deformed during biting, the work performed by the external forces is stored as elastic potential energy, which is liberated as acoustical energy when the applied stress reaches a critical value and interatomic bonds are ruptured.[48] Pioneering research on noises made while chewing food was conducted by Drake, who had volunteers chew various foods while recording sounds picked up by microphones.[49,50] Vickers and Bourne reviewed the literature on crisp foods[51] and concluded that it is primarily an acoustical sensation.[52] Luyten and van Vliet determined that a high crack speed and the sound that accompanies it are prerequisites for crispy and crunchy foods.[53] The loudness of sounds generated by biting and chewing are highly correlated with crispness, but the ability to

**Table 5** Frequency measurements of crispness and crunchiness.

| | Frequency (kHz) | | | |
|---|---|---|---|---|
| Product | Range measured | Crispy food | Crunchy food | Reference |
| Crackers, potato chips | 0.5–3.3 | 1.9–3.3 | Not determined | [12] |
| Potato chips | 0–20 | 6 | 3–4 | [57] |
| Almonds, carrots, biscuits, bread, pastry | 0.06–12.8 | 5–12.8 | 1.25–2 | [14] |
| Extruded corn puffs | 1–20 | 1–2, 6–7 | Not determined | [64] |
| Corn flakes | 0–22 | Around 7.5 | Not determined | [16] |
| Potato chips | 0–25.6 | >1.6 | Not determined | [72] |

detect this sensation is not impaired by the absence of sound.[54] Vickers recorded herself biting and chewing 23 food products and asked 20 volunteers to listen and then judge crispness and crunchiness on scales that she set at 176 mm.[11] She found that as the pitch and loudness increased, the sound associated with crispness increased, confirming her earlier study in which the panelists bit and chewed the food themselves.[10]

Some researchers have found that crunchiness corresponds to emission of lower frequency noises and crispness to higher frequency noises. The information in Table 5 shows that these frequencies vary depending on the food tested. Dacremont et al. showed that sounds conducted through the air outside the body and through the mandible are generated differently.[13] Air conduction is predominant when biting with incisors and with lips opened, while bone conduction is predominant when chewing with molars and with the mouth closed. Bone-conducted sounds are typically of lower frequencies because some sound is absorbed by soft mouth tissue and by the jaw.[47]

The acoustic outputs of disintegrating crispy and crunchy foods are jagged, with number and amplitudes of peaks varying greatly. Fast Fourier transforms may be used to interpret the data,[55] but the results are in terms of stress whereas the mouth detects force.[44] Acoustic signatures lend themselves to fractal analysis using the box-counting method.[56] In acoustic tests of compressing cheese balls and croutons, Tesch et al. found sigmoidal relationships between the apparent fractal dimension and water activity.[56]

Other parameters examined from acoustic data include amplitude of sound produced,[48,50] maximum sound level,[8] mean peak height,[32,34] number of sound events,[32,34,52] sound duration and energy,[48] and sound pressure and intensity.[12] However, it appears that pitch, as manifested by frequency observed, is a determining factor of the sensation of crispness and crunchiness.

## TEMPORAL ASPECTS

Crunchiness has been related to elapsed time of chewing. Such evaluations fall under compression or multiple break forces. Lee et al. noted that analyzing a series of chews provides more information than just the first chew,[57] but the amount of time to be considered when determining crunchiness is subject to debate: Barrett et al. defined crunchiness as "perceived intensity of repeated incremental failure during a single complete bite with the molar teeth;"[55] Guraya and Toledo used "perceived cumulative intensity of force required for repeated incremental failures of the product by chewing up to five times with molars;"[58] and Brown et al. noted a relationship between crunchiness and chewing effort between the fifth and tenth chew.[59]

## SENSORY AND MECHANICAL

Statistically significant relationships between acoustic, mechanical, and sensory measurements of crispy and crunchy foods have been reported (Tables 6 and 7). Force/work data and acoustic events appear to be related to sensory results for both crispness and crunchiness. Consumers in taste panels use loudness to judge intensity of crispness and crunchiness.[49,52,60] Some regression equations relating acoustic and mechanical results to crispness and crunchiness for a few foods are shown in Table 8. Variations in the parameters used are due to differing mechanical properties, structural properties, and mechanisms of producing and transmitting sound in the products.[61] It appears that one equation would not be suitable for all products or even a class of products because of these differences.

## CRISP-CRUNCH DEFINITIONS

We may use the consumer characterization of a crisp food as one that snaps easily, with snap being a very sudden, clean, and total fracture.[25] This description implies a single sound event, which Chauvin et al. further described as high-pitched.[6] Fillion and Kilcast[60] found that consumers considered crispy foods to have light and thin textures. A proposed definition of a crisp aspect is:

*A dry rigid food which, when bitten with the incisors, fractures quickly, easily, and totally while emitting a relatively loud, high-pitched sound.*

**Table 6** Studies reporting significant correlations between sensory, acoustic, and mechanical measurements of crispness.

| Product | Method | Measurement | Reference |
|---|---|---|---|
| Sensory and mechanical | | | |
| Pickles | Texture profile analysis | Total work | [62] |
| Biscuits, malted milk balls, wafers | Constant loading rate | Ratio of work during fracture to total work | [29] |
| French fries | Pendulum hammer impact | Impact strength, flexural strength | [39] |
| Hazelnuts | Compression | Fracture point, slope area under curve | [65] |
| Apples | Puncture | Force, work required for rupture | [70] |
| Extruded corn-based snacks | Bite force apparatus | Maximum force, stress, area under curve | [67] |
| Sensory and acoustic | | | |
| Extruded corn-based snacks | Microphone on cheek | Acoustic fractal dimension | [64] |
| Various wet and dry foods | Microphone above ear | Root mean square of 5-s audio waveform | [6] |
| Sensory, mechanical, and acoustic | | | |
| Potato chips | Force-displacement with microphone | Number of fracture and acoustic events; maximum sound pressure | [73] |
| Apples | Puncture; recording of puncture test | Maximum puncture force; acoustic emission events and mean amplitude | [68] |

**Table 7** Studies reporting significant correlations between sensory, acoustic, and mechanical measurements of crunchiness.

| Product | Method | Measurement | Reference |
|---|---|---|---|
| Sensory and mechanical | | | |
| "Space cubes" of cookie, cracker, strawberry | Compression | Stress at rupture, modulus of elasticity | [69] |
| Starchy snack | Compression | Compressive force | [58] |
| Biscuits | Cylindrical punch | Shear coefficient | [59] |
| Hazelnuts | Compression | Fracture point, slope, area under curve | [65] |
| Apples | Puncture | Puncture force | [71] |
| Sensory and acoustic | | | |
| Various wet and dry foods | Microphone above ear | Root mean square of 5-s audio waveform | [6] |
| Sensory, mechanical, and acoustic | | | |
| Apples | Puncture; recording of puncture test | Maximum puncture force; acoustic emission events and mean amplitude | [68] |

**Table 8** Regression equations relating mechanical and acoustic tests with crispness and crunchiness (all $R^2$ values > 0.85).

| Product | Regression equation | Reference |
|---|---|---|
| Biscuits, malted milk balls, wafers | log crispness = 0.59 + 0.49 log (equivalent sound level) + 0.50 (work done during fracture/total work) | [29] |
| Eight vegetables | log wet crispness = 1.722 – 0.090 (log food thickness) + 0.340 log (sound duration) + 0.226 log (number of sound peaks) + 0.817 log (mean peak height) | [34] |
| Almonds and seven baked goods | log dry crispness = 1.531 – 0.184 (log food thickness) + 0.177 log (sound duration) + 0.677 log (number of sound peaks) + 0.800 log (mean peak height) | [34] |
| Potato chips | Oral crisp = 5.35 (number of sound peaks) + 133 (mean peak height) – 6.21 (peak force) – 15.6 | [32] |
| Potato chips | Crispness = 9.904 - 0.134 (work) + 0.025 (mean sound pressure at 2.6-3.3 kHz) Crunchiness = 3.43 -0.15 (work) + 0.19 (sound pressure level at 1.9–3.3 kHz) | [12] |
| Twisted cheese flavored snack | Crispness = 16.47 – 0.064 (maximum force at failure) - 0.110 (mean sound pressure at 0.5–1.2 kHz) Crunchiness = 10.94 – 0.60 (maximum force at failure) - 0.10 (mean sound pressure at 1.9–3.3 kHz) | [12] |

On the other end of the spectrum, a relatively wet crunchy food, when bitten with the incisors, fractures quickly, easily, and totally while emitting an audible low-pitched sound. These foods can be hard and dense. A proposed definition of a crunchy food is:

> *A dense-textured food which, when chewed with the molars, undergoes a series of fractures while emitting relatively loud, low-pitched sounds.*

## CONCLUSIONS

Further work on differentiating and defining crispy and crunchy textures is needed so that universal standards can be obtained. Such definitions could be translated into any language and would be applicable to fruits, vegetables, baked foods, extruded foods, etc. Research in our laboratory, described in a subsequent article,[74] represents a step in that direction.

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