ACOUSTIC ENVELOPE DETECTOR FOR CRISPNESS ASSESSMENT OF BISCUITS

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ABSTRACT

The crispness of food materials based on the force/displacement behavior and their acoustic nature was assessed using an Acoustic Envelope Detector (AED) attached to the Texture Analyzer, wherein six kinds of biscuits were used: Carr's Table Water, Crackerbread, Digestive, Dutch Crispbakes, Rich Tea fingers and Shortbread. The force/displacement and acoustic signals were simultaneously recorded during the breakup of biscuits. For each detected acoustic signal, there was a sudden drop in the compression force. The analysis of the force/displacement curve demonstrated the links between the second derivative of force curve and the acoustic event, indicating the energy released through the air of these crack events. The acoustic behavior of the biscuits was assessed in terms of maximum sound pressure level and the number of acoustic events, which were further interpreted as the acoustic events per unit area of newly created surface area and the acoustic event per unit time. The acoustic ranking of biscuits from instrumental assessment was in very good agreement with that from sensory panel tests. The normal integration time (1.25 ms) for the AED was generally effective in detecting acoustic signals for crisp biscuits, but a shorter integration time (0.25 ms) was found advantageous in detecting acoustic signals that occur within a very short time period and gave better differentiation of crisp biscuits.

KEYWORDS

Acoustic Envelope Detector, bending-snapping, biscuits, crispness, sensory, sound

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INTRODUCTION

Crispness is an important sensory attribute in many types of foods, and "crisp" is the most frequently used English word describing a textural attribute. However, its meaning is imprecise and the perception of crispness greatly varies from individual to individual and from country to country (Bourne 2002). The large variation of crispness perception is reflected in various taste panel results and gives food scientists great difficulty in defining a parameter that is scientifically meaningful and easy to measure. Nevertheless, there are two features we all agree about crisp foods: they are mechanically brittle and acoustically noisy.

Extensive researches on food crispness have attempted to establish correlations between crispness and mechanical properties of food materials, in particular, force/displacement. Crisp foods give sequential low-degree fractures once the load exceeds a critical value (Dobraszczyk and Vincent 1999). Such mechanical brittleness was referred as the jaggedness of force/displacement curves of puffed cereal particles (Suwonsichon *et al.* 1997) and was also observed from the force deflection curves of starch-based crisp foods (Vincent 1998). It was believed that a large number of small fracture events suppressed the development of large fracture events by competing for the available energy, thus creating the sensation of crispness (Vincent 1998). Here, we recognize the ambiguity of the English language with regard to "crispness" by referring to it alternatively as crispness or crispy/crunchiness.

The acoustic nature of crispness has also been extensively investigated by two different approaches: one is to measure the perception of air-conducted sounds to establish the contribution of these sounds to the sensation of food crispness, and the other is to record the sounds produced during the application of a force to a crisp food product to obtain quantitative information regarding the crisp, crunchy or crackly sounds (Duizer 2001). The former adopts sensory tests technique (Christensen and Vickers 1981; Vickers 1985) and the latter requires the development of acoustic detection devices (Edmister and Vickers 1985; Seymour and Hamann 1988; Tesch *et al.* 1995; Duizer 2001; Srisawas and Jindal 2003). Although these reports indicated positive correlations between acoustic measurements and the sensation of crispness, the precise interpretation of acoustic data is still difficult.

Little research has been done on the combination of force/displacement measurement and acoustic detection of food materials. This combination possesses the advantages of both techniques and should be able to reveal much more information about the crispness of food than either technique alone. An Acoustic Envelope Detector (AED) has recently been developed by the manufacturer of the Texture Analyzer, Stable Micro Systems (Surrey, U.K.). The device can be easily attached to the Texture Analyzer as an additional fixture

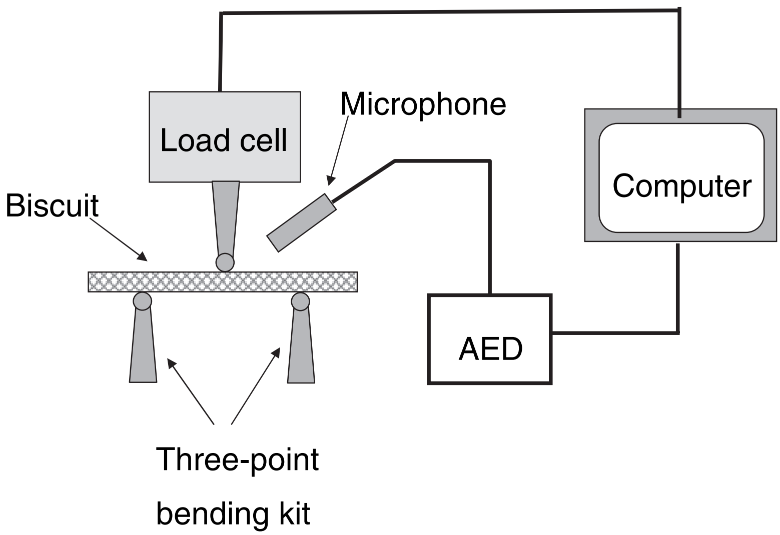

FIG. 1. A SCHEMATIC DIAGRAM OF INSTRUMENTAL SETUP OF THE TEXTURE ANALYZER CAPABLE OF DETECTING FORCE/DISPLACEMENT AND ACOUSTIC SIGNALS
AED, acoustic envelope detector.

(Fig. 1), so that both mechanical force and acoustic signals can be detected at the same time. In this work, we will assess the applicability and reliability of the device in assessing the crispness/crunchiness of food materials. A number of biscuits was assessed for their acoustic characteristics together with the force/displacement information during the breakup of these materials. The instrumental test results were further assessed by comparison with taste panel tests. It is hoped that the results from this work could enhance our understanding of the acoustic and mechanical characteristics of crisp food materials and help us to establish a reliable and simple method for discerning the crispness of food products.

MATERIALS AND METHODS

Testing Materials

Six kinds of biscuits were purchased from supermarkets: Carr's Table Water ([CTW] Carr's of Carlisle, PA), Crackerbread ([CBD] Ryvita Co., Poole, Dorset, U.K.), Digestive ([McD] McVitie's, Ashby-De-La-Zouch, Leicesteshire, U.K.), Dutch Crispbakes ([DCB], Safeway, Hayes, U.K.), Rich Tea fingers ([RTF] Safeway) and Shortbread ([SBD] Safeway). The geometric dimensions of the biscuits are given in Table 1. The samples were unpacked

TABLE 1.
GEOMETRIC DIMENSIONS OF BISCUITS

Biscuit	Shape	Length (mm)	Width (mm)	Thickness (mm)	Diameter (mm)
CTW	Round			4	85
CBD	Brick	150	60	6	
McD	Round			6	71
DCB	Round			10–14	85
RTF	Brick	80	32	4	
SBD	Brick	71	20	11	

CTW, Carr's Table Water; CBD, Crackerbread; McD, Digestive; DCB, Dutch Crispbakes; RTF, Rich Tea fingers; SBD, Shortbread.

and stored in an airtight container and were tested without any further treatment.

Devices and Instrumental Methods

A TA-XT.plus Texture Analyzer (Stable Micro Systems, Surrey, U.K.) was used for force/displacement measurement with a 5-kg load cell. A Reference AED, together with a texture analysis software (Texture Exponent 32), which was also supplied by Stable Micro Systems was also used. The gain of the AED was set at 1. The background noise was screened out by the filter function of the device, removing mechanical noise and acoustic noise below 1 kHz. This gives much enhanced signal/noise ratios because of the preponderance of environmental noise below the chosen cutoff. The Brüel & Kjær free-field microphone (Bruel & Kjaer, Naerum, Denmark) (8-mm diameter) was calibrated using the acoustic calibrator type 4231 (94 and 114 dB sound pressure level [SPL],1000 Hz). A three-point bending device was used for the breakup of biscuits (Fig. 1). The span width was 60 mm for all the biscuits. The motion of the load cell was set at three different speeds: 0.01, 0.1 and 1.0 mm/s. Each test speed was repeated at least eight times and the average of the test results was used for data analysis. The integration time for acoustic signal analysis was set at two different values (1.25 and 0.25 ms) by changing a regulating capacitor connected to the AED. Stable Micro Systems collaborated with us in order to provide the customization of the integration time and some of the software so that the experiments described herein could be performed. The force resolution is 0.1 g and the range resolution is 0.01 mm. The data acquisition rate was 500 points per second for both force and acoustic signals. All tests were performed within a laboratory with no special soundproof facilities and in the open air with a relative humidity of around $25 \pm 1\%$. The room temperature was 22 ± 2C.

Microphone Positioning

The strength of the sound, measured in decibels, depends on the strength of the vibration of the original source, the travel distance and the available sound paths. Therefore, the position of the detecting microphone is important in measuring acoustic signals. Altogether, nine possible positions were tested at three different angles (0, 45 and 90°) and three different distances for each angle (1, 5 and 10 cm). The angles were measured between the load cell probe and the microphone. The recorded acoustic strength at these positions is shown in Fig. 2. The angle of the microphone had a small effect on the acoustic signal, but the signal intensity showed a significant decrease with the increased distance between the microphone and the breaking point (more than 15% intensity reduction of recorded acoustic signal for the increase of distance from 1 to 10 cm). The sound pressure reduction had no correlation with the square of the distance. A possible reason for this is that in our experimental setup, the microphone was placed in the near-field of the sound source (less than the radius squared, r^2, of the microphone aperture divided by the wavelength, λ) because the correlation between the sound intensity reduction and the square of the distance is only true in the far-field (greater than r^2/λ) (Povey 1997). Assuming a speed of 350 m/s for sound traveling in air, the wavelength for 1–12 kHz would be between 35 and 3 cm. A 1-cm probe–biscuit separation would therefore be within the far-field of the microphone detector, but if we

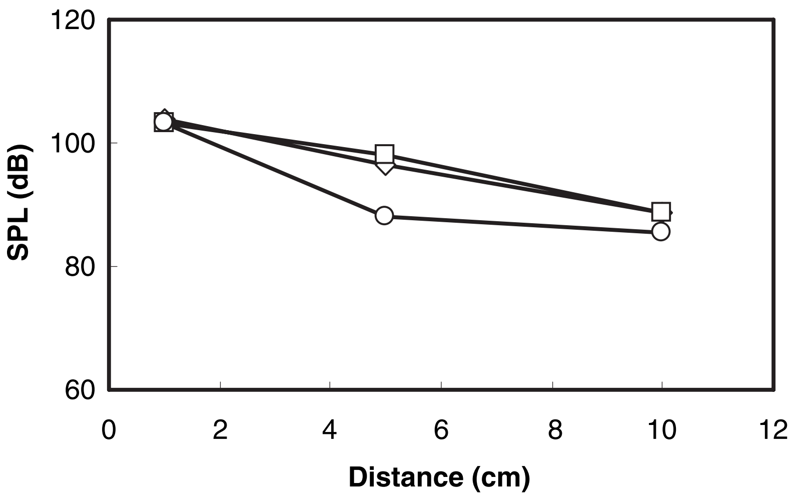

FIG. 2. THE ACOUSTIC PRESSURE LEVEL AT VARIOUS DISTANCES AND ANGLES FROM THE SOUND-BREAKING SOURCE

◇, 0°; □, 45°; ○, 90°. SPL, sound pressure level.

assume that an entire biscuit acts as a source of sound, then the detector is within the near-field (e.g., ~$7 \times 7/3 = 16$ cm for McD) and the free-field microphone characteristic makes it less sensitive to the direction from which the sound is arriving.

The variation of the acoustic signal was smallest when the microphone was set 1 cm from the breaking point, regardless of the angle. Therefore, 1-cm distance and 45° angle were used as the standard position for this work, while 45° is also the angle recommended by the manufacturers of free-field microphones.

Sensory Tests

Two sensory taste panel tests were carried out for a quantitative assessment of the crispness of six kinds of biscuits. Eleven untrained participants were involved in the first taste panel tests. The panelists were asked to consume the biscuits and grade the samples by plotting them on a scale from "highly crisp" (1) to "least crisp" (5) based on the perception from whole oral process. Out of the 11, five people were subsequently invited for a second sensory test. Each panelist was blindfolded this time so that no visual interference was involved in the perception of crispness. The panelists were only allowed to make a single bite using their front teeth and then grade the biscuits from 1 (for highly crisp) to 5 (for least crisp). In this test, a microphone was also positioned in front of each panelist within a distance of 3 ± 2 cm away from the corner of the mouth, and the acoustic signals were recorded. Each sample was tested for five times. We regard our sensory tests as preliminary.

RESULTS AND DISCUSSION

Correlation Between Acoustic Events and Force/Displacement Curve

The addition of AED to the Texture Analyzer made it possible to simultaneously record two sets of information: force/displacement and acoustic signals. Figure 3 shows a typical test result for a CTW biscuit, where the force/displacement is represented by a continuous curve and bars/lines indicate individual acoustic events. Figure 3 is reproduced as it appears to the instrument operator on the controlling computer screen. The annotations a–g refer to parts of the data which were subsequently analyzed in greater detail. The time shown in Fig. 3 is linearly related to the displacement of the probe that traveled at a constant speed of 0.01 mm/s. The force/displacement graph has three distinctive regions. The first is the force increase region, starting from the first contact between the probe and the biscuit until the first major drop

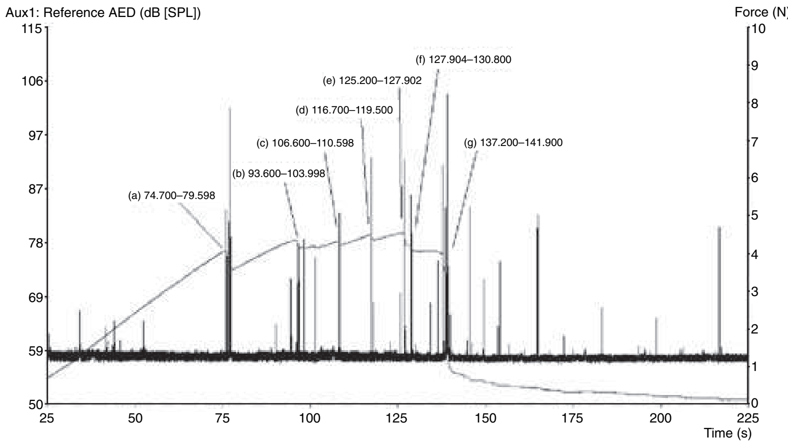

FIG. 3. A TYPICAL GRAPH SHOWING THE FORCE AND ACOUSTIC PRESSURE LEVEL DURING THE BREAKING OF CTW AT A TESTING SPEED OF 0.01 mm/s
AED, acoustic envelope detector; SPL, sound pressure level; CTW, Carr's Table Water.

of the force (at around 76 s). Within this regime, the compression force increased almost linearly with the displacement, while acoustically very quiet. This suggests that the biscuit undergoes deformation, but no major structural destruction. The slope of the force increase at this stage can be used for the calculation of the elastic modulus of each biscuit (Dobraszczyk and Vincent 1999; van Vliet 1999), but the enormous irregularity of biscuit geometry (Table 1) made the calculation less meaningful, and therefore, no further attempt was made in this respect.

The major structural breakdown occurs in the second regime, where the compression force appeared to be jagged and many acoustic events were recorded within a very short period of time. There was no further increase in the compression force after the first crack, but the ups and downs of the measured force were clearly observable. The frequency and extent of force drop varied between individual samples. For this particular test, there were about seven major drops of recorded force (indicated by a–g in Fig. 3). The recorded force appeared not as jagged and small, nor as frequently as had been previously seen (Vincent 1998; Dobraszczyk and Vincent 1999), but these force decreases certainly reflect the continuing minor structural breakup within the test material. The major structural failure occurred at around 139 s where a sharp drop of the force was recorded, and this could be regarded as the third regime of deformation test. After this major event, the biscuit still steadily remained on the testing rig and a further push was needed before the broken biscuit finally dropped to the instrument base. The compression force was very small at this stage and reached zero when the broken biscuit dropped off the testing rig.

Abundant acoustic signals were detected across the whole testing process. The acoustic signals recorded during the linear regime of force/displacement are the result of surface contact between the probe and the biscuit, and therefore, were not taken into consideration. Similarly, the acoustic signals recorded after the major structural breakup at around 139 s were also considered to be less relevant. Attention has been mainly focused on acoustic signals in the second deformation region or the jagged part of the force/displacement curve, such as the acoustic signal bands in the range between 76 and 139 s in Fig. 3, where the cracking of the biscuit took place. It appears from Fig. 3 that a group of acoustic events occurs for each major force drop. The fact that acoustic events were not in periodic pattern and there was no gradual decrease in intensity suggests that the series of acoustic events for each major force drop is not because of echo or resonance of the sound. The acoustic bunch is highly likely a series of breaking events of structural elements captured within one major mechanical peak. During the deformation of a material, stress will build up inside the material and crack will start at the weakest point once the stress exceeds its yield point. It is reasonable to hypothesize that the energy dissipated from a structural failure will spread out (probably in the form of sound) and could trigger cracks of nearby structural elements that are close to the yield point. After a series of cracks and release of energy, the material is in a status of much lower stress. Further deformation will then be needed before the next series of structural elements fracture.

Further analysis of the force/acoustic data supports this hypothesis. Figure 4 highlights the data group (a) in Fig. 3. There are five acoustic events recorded in less than 1.5 s. The major mechanical peak seen in Fig. 3 is actually composed of a series of minor force drops. There is almost one-to-one correspondence between each minor force drop and an acoustic event. The 500 points per second digitalized force/displacement curve was smoothed using an 11-point Savitzky–Golay routine that also computed the second derivative (shown as a dotted line in Fig. 4). Savitzky–Golay is a powerful mathematical technique for data analysis and smoothing and is available as part of the Origin graphics software package. The 11-point smoothing was chosen as a compromise between minimizing digitization noise and maximizing time resolution. The correlation between the acoustic event and the second derivative of force/displacement curve is also evident. However, there was a small delay between the second derivative peaks and the associated acoustic events/force drops. This delay is an artifact of the 11-point smoothing process.

An acoustic event may not necessarily be linked to a drop in compression force, considering the fact that a sound wave is the result of the sudden release of the energy in a short period of time, while the force curve is an

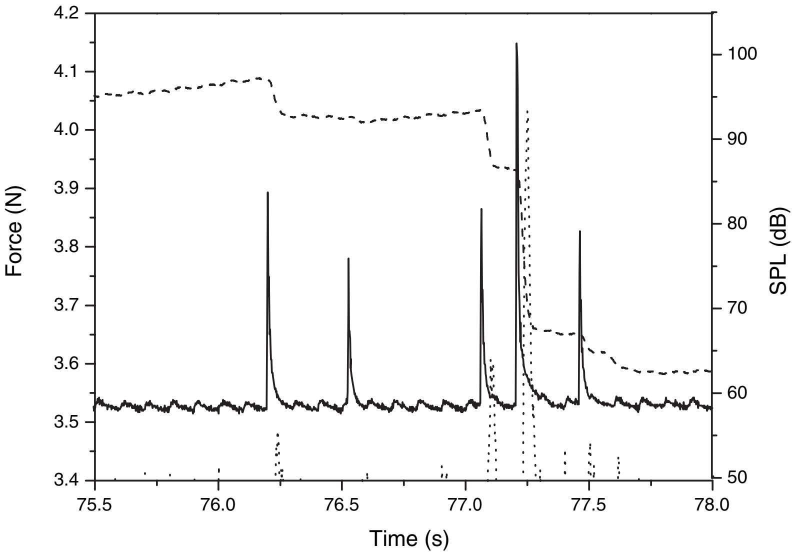

FIG. 4. THE CORRELATION BETWEEN THE SPL AND THE SECOND DERIVATIVE OF FORCE/DISPLACEMENT CURVE FOR THE BREAKING OF CTW

The raw data set was chosen from the section (a) in FIG. 3. The solid line represents the acoustic events, the dash line is the force curve and the dotted line gives the second derivative of the force curve. SPL, sound pressure level; CTW, Carr's Table Water.

indication of the energy applied to the material. In theory, it is the second derivative of the force curve that gives the rate of energy release of the breaking materials. Therefore, we would expect a direct link between the second derivative of the force curve and the acoustic events in a crisp food. There is an excellent correlation between the force drop and the acoustic events observed here because these force drops occur in a very short period of time with its energy mainly released through the sound wave. But this may not be the case for many soft food materials. Assuming that the ratio of detectable sound pressure to the whole energy released is the same for all cracking events, the maximum SPL should theoretically correspond to the energy released by an individual crack event, and there should be a correlation between the amplitude of the force derivative and the amplitude of the SPL. This seems not the case in Fig. 4. One possible reason for this could be due to the complications of the sound propagation path in the test. For example, the sound from the front surface and from the back of the test sample will have completely different propagation paths and consequent signal attenuation.

Acoustic Assessment of the Crispness of the Biscuits

The advantages of using the total events of acoustic emission in correlation with the sensory perception of crispness have been demonstrated by Attenburrow *et al.* (1989). In addition to the number of acoustic events, this work also used the amplitude of acoustic signal to characterize biscuit acoustic behavior. While the total number of acoustic events reflects the frequency of acoustic emission, the amplitude gives information about the SPL. Figure 5 plots the maximum peak value of the acoustic signal against the total number of acoustic events for six kinds of biscuits tested at three different speeds (0.01, 0.1 and 1.0 mm/s). The SPL varies between 70 and 110 dB, and the total number of acoustic events varies across almost three orders of magnitude (from single unit to close to 1000). On the left-hand side of the graph, SBD, McD, RTF, CTW and CBD give an almost linear correlation at three test speeds. DCB distinguished itself by its frequency of acoustic events, its maximum peak value starts to level off at around 110 dB and showed no difference from that of CBD and CTW. The saturation of the acoustic detecting device could be the reason for the leveling off of SPL, and further improvement of the device is currently underway to avoid such saturation. If a high SPL and a large number of acoustic events suggest a very crisp biscuit,

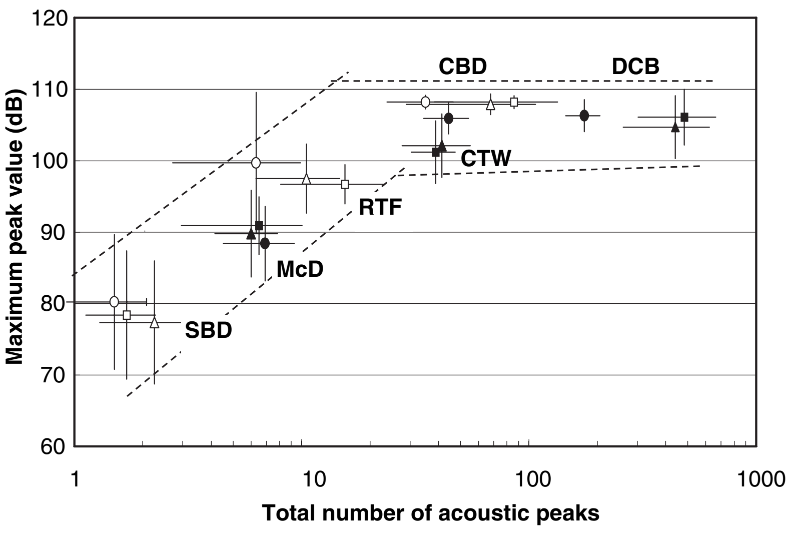

FIG. 5. THE CORRELATION OF MAXIMUM ACOUSTIC PEAK VALUE AND THE TOTAL NUMBER OF ACOUSTIC EVENTS FOR BISCUITS TESTED AT THREE DIFFERENT SPEEDS
Circle, 1.0 mm/s; triangle, 0.1 mm/s; square, 0.01 mm/s. SBD, Shortbread; McD, Digestive; RTF, Rich Tea fingers; CBD, Crackerbread; CTW, Carr's Table Water; DCB, Dutch Crispbakes.

the results shown in Fig. 5 would rank the crispness of biscuits from low to high in the following order: SBD, McD, RTF, CTW, CBD and DCB. This crispness ranking agrees well with the ranking from sensory test results (see later).

One particular difficulty in comparing the acoustic characteristics of commercial products is the difference in geometry (Table 1) of the tested samples (size, thickness, shape, etc.). Although crispness is an intensive property of the food material and should be independent of its geometry or size, the total number of acoustic events received by the acoustic detector depends on the size (thickness, width, etc.) of the tested sample. Vickers (1985, 1988) concluded that the number of emitted sounds per unit biting distance together with the loudness of the sounds changed with perceived crispness. Figure 6 gives the acoustic events as the number of acoustic peaks per unit of newly created cross-section area, which was approximated to be the product of width and thickness of the sample. SBD, McD and RTF are easily distinguishable in this way, but the other three products became more closely ranged as compared to Fig. 5. The overall acoustic ranking remained the same as in Fig. 5. The newly created surface area based on width and thickness was a rough estimation. Many biscuits did not have a neat breakup and could have a much larger newly created surface area than the estimation.

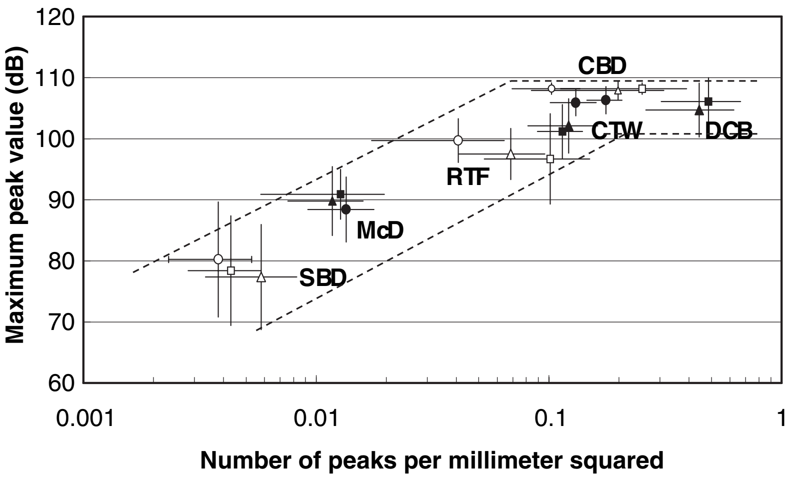

FIG. 6. THE CORRELATION OF MAXIMUM ACOUSTIC PEAK VALUE AND THE ACOUSTIC EVENTS PER UNIT OF NEWLY CREATED SURFACE AREA FOR BISCUITS TESTED AT THREE DIFFERENT SPEEDS

Circle, 1.0 mm/s; triangle, 0.1 mm/s; square, 0.01 mm/s. SBD, Shortbread; McD, Digestive; RTF, Rich Tea fingers; CBD, Crackerbread; CTW, Carr's Table Water; DCB, Dutch Crispbakes.

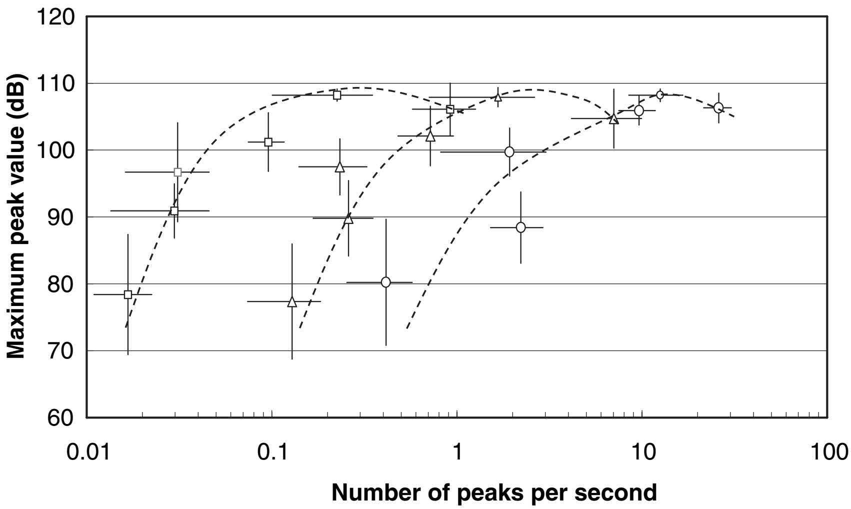

FIG. 7. THE CORRELATION OF MAXIMUM ACOUSTIC PEAK VALUE AND THE ACOUSTIC EVENTS PER SECOND FOR BISCUITS TESTED AT THREE DIFFERENT SPEEDS FOR THE SIX BISCUITS SHOWN IN FIG. 5
○, 1.0 mm/s; △, 0.1 mm/s; □, 0.01 mm/s.

It seems likely that the frequency of acoustic events has a very important role in influencing human perception of crispness. Figure 7 shows the correlation between SPL and acoustic events per unit time for five biscuit products at three different testing speeds (0.01, 0.1 and 1.0 mm/s). The lower the testing speed, the longer it takes for a biscuit to break up, and therefore, the lower the frequency of acoustic events. Despite different test speeds, the acoustic rankings of the biscuits in Fig. 7 show almost the same pattern and ranking order. Although the ranking order of the biscuits is exactly the same in Figs. 5–7, it appears that the results in Fig. 7 show a better differentiation of the acoustic nature of the biscuits, particularly at low testing speeds (0.01 and 0.1 mm/s). This suggests that the frequency of acoustic events could be more effective in discerning the acoustic nature (or crispness) of biscuits than using the acoustic events per unit biting distance per area as suggested by Vickers (1985, 1988).

Figure 7 also shows that one magnitude increase of testing speed leads to almost one magnitude increase in the frequency of acoustic events. This is true for CBD, CTW, RTF and McD at all three test speeds, and true for DCB and SBD at low testing speeds (0.01 and 0.1 mm/s). This demonstrates the reliability of AED in detecting acoustic signals during biscuit breakup at low speeds. The device probably fails to pick up all individual acoustic events at high testing speed (1 mm/s) for some products because of a too large integration time of the AED that makes the device unable to distinguish two sequential acoustic events. The current default integration time (1.25 ms) works well for the majority of crisp foods at a reasonably low test speed, but a shorter integration time should be considered for acoustic-rich products.

Different Integration Time

Integration time has a strong influence on the sensitivity of AED in detecting acoustic events. A shorter integration time, in theory, should give the device a quicker response to acoustic events. The integration time was therefore reduced from 1.25 to only 0.25 ms by switching to a different integration capacitor. Figure 8 gives the total acoustic events for five different biscuits at the new integration time. The acoustic differences between the five samples can be easily identified through the amplitude and/or the total acoustic events. The acoustic ranking in Fig. 8 agrees in general with that revealed in Figs. 5–7, where a longer integration time was applied.

The acoustic behavior detected by the AED with two different integration time settings showed an obvious difference. Firstly, more acoustic signals

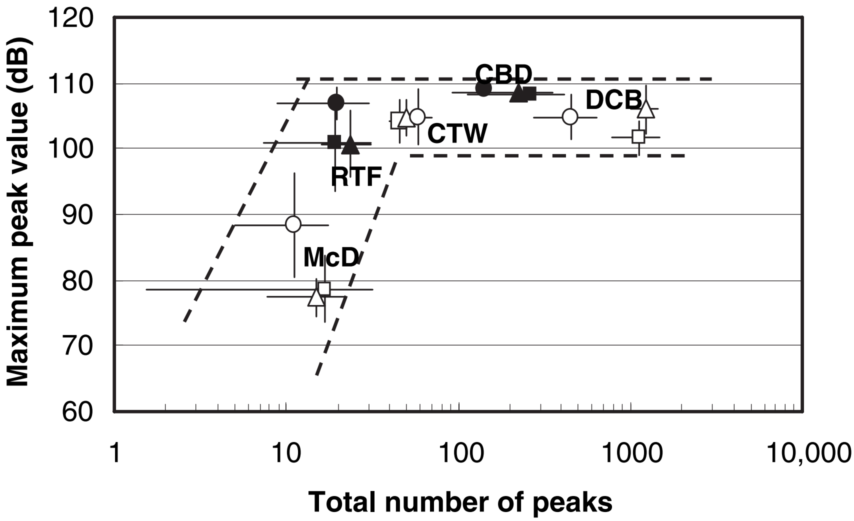

FIG. 8. THE CORRELATION OF MAXIMUM ACOUSTIC PEAK VALUE AND THE TOTAL NUMBER OF ACOUSTIC EVENTS FOR THE BISCUITS TESTED AT THREE DIFFERENT SPEEDS AT AN INTEGRATION TIME OF 0.25 ms

Circle, 1.0 mm/s; triangle, 0.1 mm/s; square, 0.01 mm/s. McD, Digestive; RTF, Rich Tea fingers; CTW, Carr’s Table Water; CBD, Crackerbread; DCB, Dutch Crispbakes.

were recorded at a short integration time (0.25 ms) for all five tested products. The recorded acoustic events were two or three times higher than those detected at a longer integration time (1.25 ms). The detected acoustic events for the two most acoustic-rich biscuits, CBD and DCB, are more than two times higher at low test speeds (0.01 and 0.1 mm/s) and three times higher at a higher test speed (1.0 mm/s) as a result of integration time reduction from 1.25 to 0.25 ms. This is consistent with the increased ability of the shorter integration time to distinguish sequential acoustic events. Secondly, a short integration time seems to have the advantage of improved sensitivity in detecting SPL, at least for the case of RTF, whose maximum SPL was increased from 90 to 100 dB at a longer integration time to close to 110 dB at a shorter integration time. Although the overall ranking revealed in Fig. 8 is not different from that shown in Fig. 5, the differentiation between the biscuits in Fig. 8 is obviously much clearer. We speculate that, at a longer integration time (1.25 ms in this case), the AED could not distinguish two or more sequential acoustic events that occur within a very short time period and will probably record them as a merged one. Therefore, a short integration time could be beneficial to better distinguish highly crisp materials.

Sensory Taste Panel Tests

Two sensory taste panel tests were organized to assess consumers' perception of the crispness of the tested biscuits. The first one involved 11 untrained panelists and was carried out using a normal quantitative descriptive technique. The major advantages of this discrimination test are the relative simplicity of the setup and operation and its high sensitivity (Kilcast 1999). The panelists were asked to grade the biscuits in crispness order after the consumption of the biscuits using an *ordinal scale* (1 for the highest to 5 for the lowest). Information from visual assessment, previous knowledge about the product and whole oral processing could all be used for the assessment. Figure 9 summarizes the testing results and shows that the grading from this taste panel test is consistent with the ranking from the acoustic assessment: the DCB comes at the top followed by CBD, while RTF and McD are the two with the lowest crispness ranking. CTW appeared to be very controversial in terms of its crispness, with a similar percentage across the whole range of ranking. We are not sure of the exact reasons for this discrepancy, but it seems that different criteria were used by individual panelists in assessing the crispness of this product.

The second sensory tests were performed in a more restrictive way, with five blindfolded panelists positioned in front of the acoustic detector. The panelists were fed with a biscuit and required to only make one bite using their front teeth. The broken biscuit was immediately spat out after the first

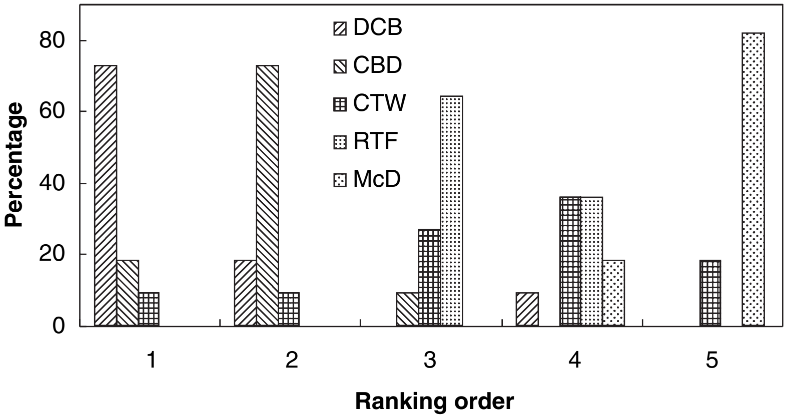

FIG. 9. THE CRISP GRADING OF BISCUITS FROM FULL ORAL PROCESSING SENSORY TASTE PANEL (FROM 1 FOR THE HIGHEST CRISP TO 5 FOR THE LEAST CRISP)
DCB, Dutch Crispbakes; CBD, Crackerbread; CTW, Carr's Table Water; RTF, Rich Tea fingers; McD, Digestive.

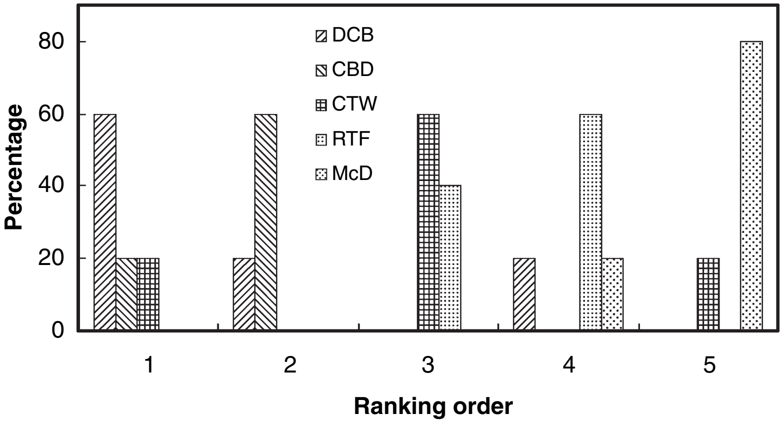

FIG. 10. THE CRISP GRADING OF BISCUITS FROM FIRST BITE SENSORY TASTE PANEL (FROM 1 FOR THE HIGHEST CRISP TO 5 FOR THE LEAST CRISP)
DCB, Dutch Crispbakes; CBD, Crackerbread; CTW, Carr's Table Water; RTF, Rich Tea fingers; McD, Digestive.

bite. The grading was therefore made on the basis of hearing and teeth sensing of the first bite. Figure 10 shows that the overall grading was consistent with the grading from the full oral processing and with those from instrumental acoustic assessments.

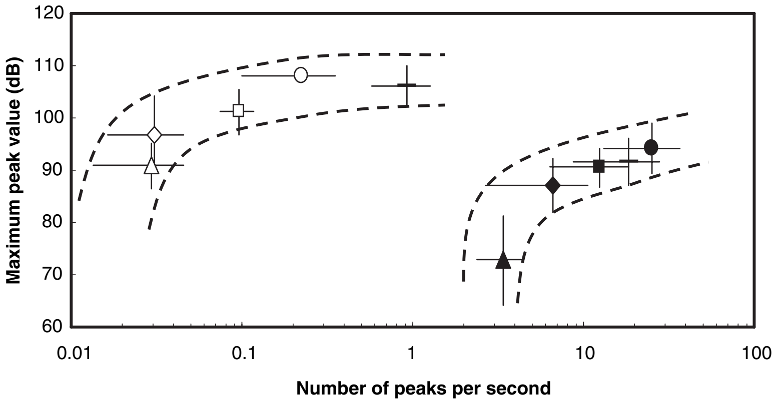

FIG. 11. COMPARISON OF ACOUSTIC EVENTS BETWEEN THE HUMAN FIRST BITING AND THE INSTRUMENTAL BREAKING (AT A SPEED OF 0.01 mm/s) OF BISCUITS
Triangle, McD; diamond, RTF; square, CTW; circle, CBD; bar, DCB. Open symbols are from instrumental tests and the solid symbols are from the sensory test. McD, Digestive; RTF, Rich Tea fingers; CTW, Carr's Table Water; CBD, Crackerbread; DCB, Dutch Crispbakes.

The acoustic signals during the first bite were also recorded using the AED, and the results are shown in Fig. 11 together with those recorded during an instrumental breakup at a speed of 0.01 mm/s. The sound produced by the panelists was not as loud as that produced from the instrumental tests. This is understandable if we consider the damping effect from the soft tissue of the human mouth. The biscuits appeared to be in the same ranking order except for the two most crisp ones (DCB and CBD). The reason for the discrepancy of the two most crisp biscuits is not yet clear, but merged acoustic signals of highly acoustic-rich product could be a possible explanation. The frequency of acoustic events for the first bite is almost 100 times higher than that of the instrumental breakup at 0.01 mm/s. Compared with the first bite curve with the instrumental test results in Fig. 5 at an instrumental speed of 1 mm/s, we find a displacement of the curve to a higher *x*-axis value. This indicates that the human biting speed of biscuits is faster than 1 mm/s, or comparable to the biting speed of 20 mm/s measured for cheese products (Meullenet and Finney 2002).

Summary

The results suggest that the AED device effectively works in detecting the acoustic characteristics of biscuits. The acoustic events showed excellent correspondence with the sudden drop of the compression force and also the second derivative of force curve, confirming that each acoustic event correlates with, not only the force decrease of individual crack event, but also its rate of energy release. The normal integration time (1.25 ms) was found to be efficient for discerning low-crisp biscuits, where the breaking up of biscuit relatively produces less acoustic events. However, a shorter integration time (0.25 ms) for acoustic data acquisition would be advantageous for highly crisp materials, where the acoustic signals occur within a very short time frame. The instrumental acoustic assessments based on the total acoustic events, on the acoustic events per unit area of newly created surface or on the acoustic events per unit time all showed very good correlation with the sensory tests results, although the frequency of acoustic events seemed to be more effective in distinguishing the biscuits. Another great advantage of the AED device and the peak counting technique is the open-air test with no requirement for a soundproof environment. This makes the technique practically applicable.

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REFERENCES

ATTENBURROW, G.E., TAYLOR, L.J., GOODBAND, R.M. and LILLFORD, P.J. 1989. Structure, mechanics and texture of a food sponge. J. Cereal Sci. *9*, 61–70.

BOURNE, M. 2002. *Food Texture and Viscosity, Concept and Measurement*, 2nd Ed., Academic Press, San Diego, CA.

CHRISTENSEN, C.M. and VICKERS, Z.M. 1981. Relationships of chewing sounds to judgements of food crispness. J. Food Sci. *41*, 1158–1164.

DOBRASZCZYK, B.J. and VINCENT, J.F.V. 1999. Measurement of mechanical properties of food materials in relation to texture: The materials approach. In *Food Texture: Measurement and Perception* (A.J. Rosenthal, ed.) pp. 99–151, Aspen, Gaithersburg, MD.

DUIZER, L. 2001. A review of acoustic research for studying the sensory perception of crisp, crunchy and crackly textures. Trends Food Sci. Technol. *12*, 17–24.

EDMISTER, J.A. and VICKERS, Z.M. 1985. Instrumental acoustical measures of crispness. J. Texture Studies *16*, 153–167.

KILCAST, D. 1999. Sensory techniques to study food texture. In *Food Texture: Measurement and Perception* (A.J. Rosenthal, ed.) pp. 30–64, Aspen, Gaithersburg, MD.

MEULLENET, J.-F. and FINNEY, M.L. 2002. Measurement of biting velocities, and predetermined and individual crosshead speed instrumental imitative tests for predicting cheese hardness. J. Texture Studies *33*, 45–58.

POVEY, M.J.W. 1997. *Ultrasonic Techniques for Fluids Characterization*. Academic Press, San Diego, CA.

SEYMOUR, S. and HAMANN, D. 1988. Crispness and crunchiness of selected low moisture foods. J. Texture Studies *19*, 79–95.

SRISAWAS, W. and JINDAL, V.K. 2003. Acoustic testing of snack food crispness using neural network. J. Texture Studies *34*, 401–420.

SUWONSICHON, T., NORMAND, M.D. and PELEG, M. 1997. Estimation of the mechanical properties of individual brittle particles from their bulk compressibility. J. Texture Studies *28*, 673–686.

TESCH, R., NORMAND, M.D. and PELEG, M. 1995. On the apparent fractal dimension of sound bursts in acoustic signatures of two crunchy foods. J. Texture Studies *26*, 685–694.

VAN VLIET, T. 1999. Rheological classification of foods and instrumental techniques for their study. In *Food Texture: Measurement and Perception* (A.J. Rosenthal, ed.) pp. 65–98, Aspen, Gaithersburg, MD.

VICKERS, Z.M. 1985. The relationships of pitch loudness and eating technique to judgements of the crispness and crunchiness of food sounds. J. Texture Studies *16*, 85–95.

VICKERS, Z.M. 1988. Evaluation of crispness. In *Food Structure: Its Creation and Evaluation* (J.M.V. Blanshard and J.R. Mitchell, eds.) pp. 433–448, Butterworths, London, England.

VINCENT, J.F.V. 1998. The quantification of crispness. J. Sci. Food Agric. *78*, 162–168.