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DEVELOPMENT OF AN ACOUSTIC MEASUREMENT SYSTEM FOR ANALYZING CRISPINESS DURING MECHANICAL AND SENSORY TESTING

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ABSTRACT

The objective of this study was to develop an acoustic measurement system for analyzing crispiness and correlate its results with sensory evaluation. Four biscuits (Crackerbread, Table Water, Rich Tea and Shortbread) were punctured using an Instron Universal Testing Machine. The force–displacement and sound amplitude–time signals were simultaneously recorded during puncturing. The acoustic recording system was also used to capture sound emitted during sensory evaluation. From the force–displacement signal, the number of peaks, maximum force, curve length, work, crispiness work and initial slope were extracted. From the sound data, the maximum sound pressure, number of sound peaks, sound curve length and area under amplitude–time curve were obtained. The number of force and sound peaks, spatial ruptures, sound curve length and area under the sound curve correlated well ($R^2 > 0.77$*) with sensory crispiness data. An acoustic measurement system for analyzing crispiness was developed which can be used with most food texture-analyzing instruments and during sensory evaluation.*

PRACTICAL APPLICATIONS

The method proposed in this study provides an acoustic system for capturing and analyzing sound data during mechanical testing of crispy foods using Instron Universal Testing Machine. The system is designed in such a way that it can be used as an attachment with any food texture-analyzing system. In addition, the acoustic system can be used independently from texture-analyzing instrument especially during sensory evaluation.

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KEYWORDS

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INTRODUCTION

Crispiness is an important and a desirable textural attribute of either wet crisp foods such as carrots, celery (Edmister and Vickers 1985) and apples (De Belie *et al*. 2002) or dry crisp foods such as breakfast cereals (Sauvageot and Blond 1991). Dry crispy products can be defined as brittle materials that abruptly fracture following the application of a low force (Vincent 1998). The fracture of crispy products is accompanied by sound bursts (Drake 1963). Therefore, crispiness is perceived through a combination of tactile, kinesthetic and auditory sensations (Szczesniak 1990; Dacremont and Colas 1993).

Methods used for determining crispiness are based on sensory evaluation, mechanical testing or a combination of both (Roudaut *et al*. 2002). Sensory evaluation gives a direct measure of crispiness but is not convenient for routine tests (Liu and Tan 1999). Therefore, where routine crispiness tests are necessary (e.g., in industries), mechanical methods are preferred.

Mechanical testing based on the force–displacement testing during fracture of a material has been widely used in analyzing crispiness (Roudaut *et al*. 2002). However, force–displacement testing has the limitation of not capturing the sound generated by crispy products during fracture. To overcome this limitation, acoustic testing is used (Duizer 2001).

Acoustic testing is based on capturing the sound produced from crispy products during the fracture process (Drake 1963; Duizer 2001). The main technique used in acoustic testing involves recording the sound during actual biting and chewing (Christensen and Vickers 1981; Vickers 1982) or during a mechanical fracturing of a material (Drake 1963; Edmister and Vickers 1985; Salvador *et al*. 2009). The recorded sound is subjected to various analyses to relate it to crispiness. Combining both force–displacement and acoustic testing generates more information to aid in the objective determination of crispiness (Vickers 1987).

Although crispiness has been widely studied using the above-mentioned techniques, there is no standard device and method for objectively determining crispiness (Castro-Prada *et al*. 2007). The two instruments that are widely used for analysis of crispiness from force–displacement data are the texture analyzer (TA) (Stable Microsystems, Surrey, U.K.) and the Universal Testing Machine (UTM) (Instron Corporation, High Wycombe, U.K.). A method combining both force–displacement and acoustic analysis of crispiness using TA was developed (Chen *et al*. 2005) and has been applied by a number of researchers (Varela *et al.* 2006; Salvador *et al.* 2009). The method developed by Chen *et al.* (2005) is proprietary to TA. This limits its use with other texture-analyzing instruments such as Instron instruments. In addition, the sampling rate of the sound data was relatively low (0.5 kHz.). Crispy products are known to generate sounds of high frequencies (Lee *et al.* 1988; Al Chakra *et al.* 1996). Therefore, such a low sampling rate may not be satisfactory when analyzing the frequency of sound data covering the entire audible frequency range (20 Hz–20 kHz). According to the Nyquist criterion, the sound sampling rate should be at least twice the range of frequency of the sound data analyzed (Hartmann 1998).

Chaunier *et al.* (2005) studied crispiness of breakfast cereals by combining force–displacement and acoustic testing using an Instron UTM. In their method, a computer sound card in a desktop computer was used to capture the sound data. This way, the acoustic system may not be suitable as a portable sound data-capturing device. A portable acoustic device is preferable for use during sensory analysis. Based on proposed acoustic and mechanical test conditions for crispiness, such a device requires a software that can acquire data at very high rates (>50 kHz) and is suitable for analyzing the complex data associated with crispiness (Castro-Prada *et al.* 2007).

The objective of this study was to source devices and software that allow very high rates of data acquisition and capacity for analysis of complex acoustic and force data sampled at very high frequencies from a texture-analyzing instrument. In this study, an Instron UTM was used as an instrumental TA. The acquired acoustic and force data were synchronized to ensure correlation between acoustic and force–displacement data. Several parameters are derived from both mechanical and acoustic data. The derived parameters were correlated for all the three texture-analyzing methods used, i.e., acoustic, mechanical and sensory. From the correlations, the parameters derived from force–displacement data and acoustic data that best describe crispiness are determined.

MATERIALS AND METHODS

Testing Materials

Four types of commercial biscuits brands were purchased locally: Table Water (CTW) (Carr's of Carlisle, Cumbria, U.K.), Crackerbread (CB) (Ryvita Co. Leicesteshire, U.K.), Classic Rich Tea (RT) (McVitie's, Ashby-De-La-Zouch, Leichesteshire, U.K.) and Shortbread (SB) (Scottish shortbread, Cheshunt, U.K.). These biscuit types were selected as they were previously used to develop an acoustic envelope detector to analyze crispiness using a TA

TABLE 1.
GEOMETRIC DIMENSIONS OF THE BISCUITS STUDIED AND COMPOSITION (%) OF THE BISCUITS EVALUATED IN THE PRESENT STUDY

a

Biscuit	Shape	Length (mm)	Width (mm)	Thickness (mm)	Diameter (mm)
CB	Brick	115	60	6	–
CTW	Round	–	–	3	60
RT	Round	–	–	6	65
SB	Brick	80	250	11	–

b

Biscuit	Moisture*	Protein†	Fat†	Carbohydrates†	Sodium†	Fiber†	Water activity*
CB	3.9	10.3	3.5	76.9	0.4	3.5	0.153
CTW	2.8	10.1	7.6	74.2	0.6	4.2	0.098
RT	3.1	7.1	15.5	71.2	0.3	2.9	0.072
SB	3.5	5	28.2	62.5	0.3	1.5	0.270

* Values experimentally determined.
† Values as presented on package by manufacturer.
CB, Crackerbread; CTW, Table Water; RT, Rich Tea; SB, Shortbread.

(Chen *et al.* 2005). Therefore, the selection of these biscuits meant that the results of the present study could be compared and correlated with those published by Chen *et al.* (2005). The geometric dimensions and composition (protein, fat, carbohydrates, sodium and fiber) of the biscuits as presented by the manufacturer on the package are given in Table 1a,b respectively. Ten samples of each biscuit type were tested immediately following the opening of the packaging material and the testing was done before the expiry date printed on the package.

Determination of Moisture Content and Water Activity of the Biscuits

Moisture content was determined by oven drying at 100C for 24 h. The water activity of the four biscuits was measured using a Novasina Labmaster-A_w (Novatron, Horsham, England). A biscuit from each brand named in the Testing Materials section was broken into small peaces by hand, fitted and sealed in airtight container and allowed to equilibrate to 25C. Duplicates of each biscuits brand were analyzed.

Mechanical Texture Analysis

Individual biscuits were punctured using a UTM (Instron Model No. 5544, Instron Corporation) fitted with a 500 N load cell (Serial No. UK

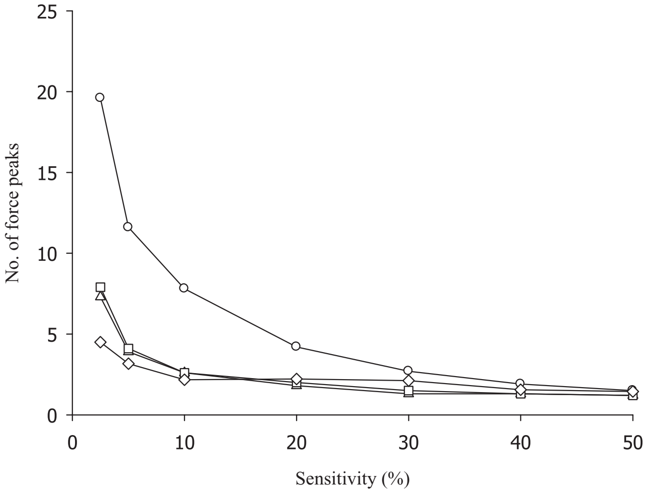

FIG. 1. EFFECT OF SENSITIVITY (%) SETTING ON BLUEHILL 2 SOFTWARE ON THE NUMBER OF FORCE PEAKS RECORDED DURING PUNCTURING OF EACH TYPE OF BISCUITS: CRACKERBREAD (○), TABLE WATER (△), RICH TEA (□) OR SHORTBREAD (◇)

196). The puncturing probe (5-mm diameter cylindrical probe) was fixed to a Jacobs chuck (Model No. 6B, The Jacobs Manufacturing Co. Sheffield, England) which was attached to the load cell. The load cell travelled at a crosshead speed of 60 mm/min. In this study, a single compression profiler was used which allowed the Bluehill 2 software to calculate the number of force peaks during the puncture test. All samples were punctured for a distance of 32 mm and the data were acquired with a maximum possible resolution of 500 Hz.

The number of peaks was acquired at a sensitivity of 2.5% of the maximum force. This sensitivity was determined as optimal in reducing noise and differentiating between the samples (Fig. 1). A minimum of 10 biscuits for each brand were analyzed.

Several parameters were derived from the force–displacement data acquired at 500 Hz to enable determination of crispiness of the biscuits. The parameters were: work (area under the curve), maximum force (N), initial slope (N/mm), number of peaks and average force of peaks (N). From the data, crispiness was determined using three approaches; first, crispiness work was calculated as defined by Van Hecke *et al.* (1998) according to the following equations:

$$\text{Number of spatial ruptures}\,(N_{\mathrm{sr}})\left(\mathrm{mm}^{-1}\right)=\frac{N_{\mathrm{o}}}{d} \tag{1}$$

$$\text{Average puncturing force}\,(F_{\mathrm{m}})(\mathrm{N})=\frac{A_1}{d} \tag{2}$$

$$\text{Crispiness work}\,(W_{\mathrm{c}})(\mathrm{N\ mm})=\frac{F_m}{N_{sr}} \tag{3}$$

where N_{o} is the total number of peaks, d is the sample thickness (mm) and A_1 is the area (mJ) under the force–displacement curve.

The second approach was to calculate the curve length (N) as was used in the determination of the texture of crispy and crackly products by (Norton *et al.* 1998). The method is analogous to placing a piece of string along force–displacement curves, following every peak and trough. The length of the string is then measured to find the length of the curve. The measured length of the line was calculated by summing only the absolute vertical movements (change in force at the highest resolution) instead of calculating the correct distances by Pythagoras' theorem between the points. In algebraic terms, the length was measured as:

$$\text{Curve length}\,(\mathrm{N})=\sum|\Delta force| \tag{4}$$

The curve length was normalized by dividing by the maximum force (N) since hard samples generally give longer curves without necessarily being crispy.

The third approach was to use a crispness index (*Ci*) (Heidenreich *et al.* 2004) defined as:

$$Ci=\text{Curve length}/(A\times F_{mean}) \tag{5}$$

where curve length is as determined by Eq. (4); A is the area under the curve (J) and F_{mean} (N) is the average force of the number of peaks from the force–displacement curve.

Acoustic Recordings and Signal Processing

All measurements were performed on samples held inside an anechoic box measuring 460 × 380 × 280 mm lined inside with sound-absorbing foam. The emitted sound during puncturing of the sample was recorded using a prepolarized, free-field, half-inch GRAS microphone (3.15 Hz–20 kHz) (Model No. 40AE) in combination with a preamplifier (Model No. 26A, G.R.A.S Sound & Vibration, Holte, Denmark). A free-field microphone is preferred for such studies since it is less directionally dependent than other types of microphones (Chen *et al.* 2005; Castro-Prada *et al.* 2007). The acoustic signal was acquired at a sampling rate of 50 kHz. To enable such a high sampling rate, the microphone was connected to a NI USB card (Model No. 9233, National Instruments Corporation, Austin, TX) which was connected to a computer via a USB connection. The data were captured by virtual instrument (VI) program code written by the author using Labview 8.2 (National Instruments Corporation). The captured sound data were filtered by a 3rd-order Butterworth high-pass filter set to 1.5 kHz to cut off sound frequencies less than 1.5 kHz as it has been previously reported that the motor of a texture measurement instrument generates sounds with frequencies of 0–1 kHz (Chaunier *et al.* 2005; Chen *et al.* 2005; Gondek *et al.* 2006). The Labview program can be set to capture a wide range of parameters, but in this study, it was only set to capture maximum sound pressure (Pa), number of sound peaks as well as maximum force (N) data from the load cell of Instron UTM. The microphone was positioned perpendicular to the direction of puncturing probe and 50 mm from the probe. To assess the sound level of background noise, blank trials (10 replicates) without any sample were performed. The mean of the maximum "blank" sound pressure recorded (1.0 Pa) was subsequently used as the threshold in calculating sound peaks.

Another VI code was written to analyze the frequency of the sound data in the amplitude–frequency domain from the amplitude–time domain. The code was written to read and extract the saved sound data for each second and perform fast Fourier transformation (FFT). The FFT was performed on the sound data collected for only the first 5 s during puncturing of the biscuit as this period is when most of the biscuit fracture occurred. The mean of frequencies that recorded the highest amplitude is presented.

Other parameters – curve length (Pa) and the area (Pa·s) under the sound amplitude–time curve – were obtained by analyzing the amplitude–time data using a custom written equation in Sigmaplot 10 (Systats Software Inc., Chicago, IL). The sound data in the amplitude–time domain were first transposed, and then the sum of absolute differences of sound pressure was calculated. The sound curve length was based on the principle of Norton *et al.* (1998), as given in Eq. (4), but in this case, the sum of changes in the absolute sound pressure was used (instead of changes in force) as described in Eq. (6):

$$\text{Sound curve length (Pa)} = \sum |\Delta \text{Sound pressure}| \tag{6}$$

Synchronizing of Mechanical and Acoustic Data

The sound amplitude–time signal at 50 kHz and the force–displacement signal at 25 kHz were acquired simultaneously, synchronized and plotted using Labview 8.2 software (National Instruments Corporation). The force–displacement signal captured at 25 kHz was not used for any analysis but for synchronization with sound signal only. Two computers were used, one

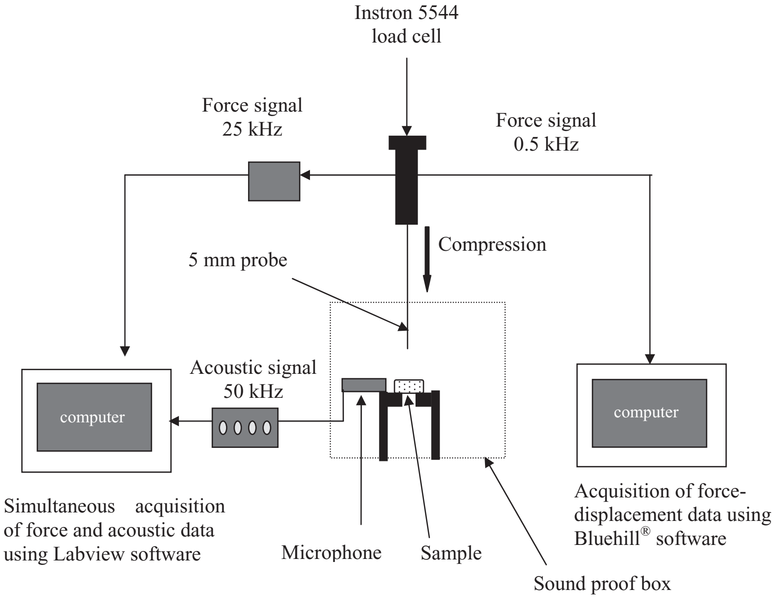

FIG. 2. SCHEMATIC DIAGRAM OF MECHANICAL AND ACOUSTIC DATA ACQUISITION SYSTEM

computer was the standard setup running Bluehill 2 software that was used to control and acquire the force–displacement data from the UTM (Fig. 2). The other computer was running the Labview software and was used to synchronize both sound amplitude–time and force–displacement data (Fig. 2). The sound data were acquired as described in the Acoustic Recordings and Signal Processing section, while force data were acquired through a NI USB card Model No. 6009 (National Instruments Corporation). Both signals were passed to the same computer through USB ports. The acquisition of acoustic and force signals was started in the computer running Labview followed by initiation of acquisition of force–displacement data using Bluehill 2 software on the second computer. The simultaneous acquisition of both the acoustic and force signals was carried out for 35 s to ensure that it covered the entire period (32 s) during which the sample was punctured.

Sensory Evaluation

The sensory crispiness of the four biscuit types was evaluated by 10 untrained panelists. The sensory evaluation was carried out in a specially designed sensory room with booths equipped with special lights. The panelists

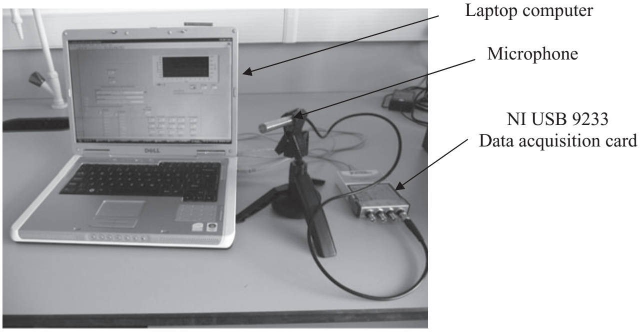

FIG. 3. THE ACOUSTIC SETUP USED TO CAPTURE SOUND DATA DURING SENSORY EVALUATION

were provided with entire biscuit of each brand from freshly opened package and asked to bite it once with their incisors and spit the sample with no further mastication. After evaluating all the four samples, the panelists ranked them in terms of crispiness on a scale of 1 (least crispy) to 5 (most crispy).

A GRAS microphone described in the Acoustic Recordings and Signal Processing section was attached to a laptop computer and positioned 5 mm in front of each panelist to capture the sound generated during biting (Fig. 3). The sound was captured and plotted using only the acoustic setup devices and software described in the Acoustic Recordings and Signal Processing section. The acquisition of sound data was initiated ~2 s prior to the panelists biting the biscuit. The entire test was recorded for 10 s to ensure complete capture of all sound data generated during the biting. From the sound amplitude–time data, the number of sound peaks, maximum sound pressure (Pa), area under amplitude–time curve (Pa·s) and sound curve length (Pa) were determined.

Statistical Analysis

All correlations, the curve lengths and area under sound amplitude–time curves were calculated using Sigmaplot 10 (Systat Software Inc.). PROC GLM of SAS (SAS Institute, Cary, NC, USA) was used to determine the differences between treatment means which were considered significantly different at $P \leq 0.05$ unless stated differently.

RESULTS AND DISCUSSION

Acquisition of Mechanical and Acoustic Data

Initial tests were performed and showed that it was necessary to use an anechoic box to eliminate external sound artifacts in the acoustic data. A typical plot of synchronized force–displacement and sound amplitude–time signal during puncturing of CB is presented in Fig. 4. During puncturing, the probe comes into contact with the biscuit after a displacement of ~2 mm. From that point, the recorded force starts to increase, as the stress builds up a local yield point occurs after ~2.5 mm. At this yield point, a force drop occurs which is accompanied by sound peaks on the sound signal plot. After that point, the force continues to build up with increasing displacement. Another force drop occurs at ~3.25 mm accompanied by a slightly bigger peak on the sound signal plot. The force continues to build and a big force drop occurs after ~3.6 mm of displacement. The force drop is bigger than the preceding recorded drops and is accompanied by a correspondingly larger peak on the sound pressure curve. The rate of change in force (Nmm^{-1}) in the displacement region ~2 mm to ~2.5 mm was used to determine initial slope of the biscuit. The major force drop occurring after ~3.6 mm of displacement may be as a result of a major structural breakdown of the biscuit and was accompanied by a high sound amplitude. Between displacements of ~3.6 and 5.75 mm, regions with many force drops accompanied by an equally high number of sound peaks on the sound signal plot are evident. Although there are several force drops in this region, the force does not completely drop to zero. This may suggest that there is no complete failure of the biscuit structure but rather continuous minor structural/cellular fractures. At a displacement just over ~5.75 mm, the force dropped sharply to almost zero indicating a substantial structural breakdown of the CB. After this big force drop, small sound peaks appear on the sound signal plot, but there is no change in force up to displacement of 8 mm. This may indicate that the capturing of sound pressure was more sensitive than that of force data. This could be partly due to the high sampling frequency of sound (50 kHz) compared to 25 kHz of force signal. After 8 mm of displacement, the force dropped to zero indicating that the CB was completely punctured.

Mechanical and Acoustical Texture Properties of the Biscuits

The profiles of the typical force–displacement curves obtained during puncturing of the biscuits differed according to biscuit type (Fig. 5). CB required ~9 N to puncture which was significantly lower than the force (12 and 15 N) required to puncture the other biscuits (Table 2). CB recorded a significantly higher number of force peaks, longer curve lengths and lower average force than the other biscuits (Table 2). RT biscuit exhibited the highest initial slope 48 N/mm (more than twice that of the other biscuits), indicating it was the stiffest of the biscuits studied, while the other biscuits had lower but similar values. No clear trend between work values and biscuit type was evident. This is attributed to fact that they were of different geometries. The number of spatial ruptures and the crispiness index of the biscuit types followed the

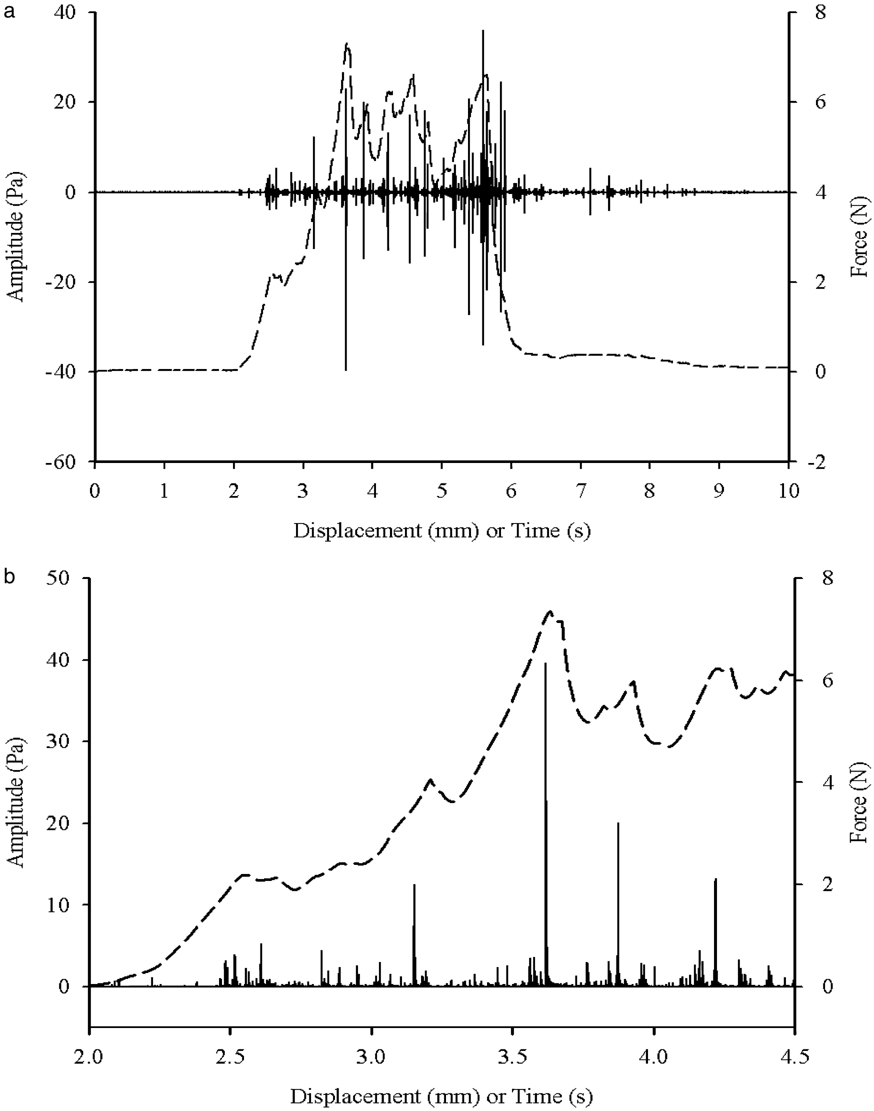

FIG. 4. (a) AN EXAMPLE OF A TYPICAL SYNCHRONISED FORCE–DISPLACEMENT (DASHED LINE) AND SOUND AMPLITUDE–TIME (SOLID LINE) SIGNALS RECORDED DURING PUNCTURING OF CRACKERBREAD. (b) A PLOT OF SELECTED PORTION OF FIG. 4a FROM DISPLACEMENT OF 2–4.5 MM WITH THE SOUND SIGNAL TRANSPOSED

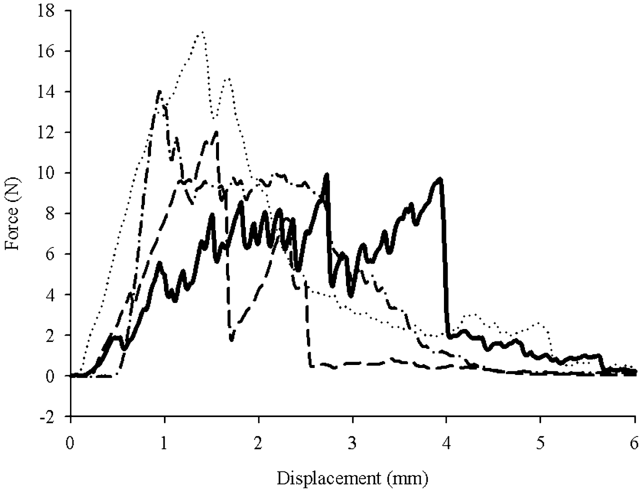

FIG. 5. TYPICAL FORCE–DISPLACEMENT CURVES RECORDED DURING PUNCTURING OF: CRACKERBREAD (—), TABLE WATER (---), RICH TEA (-·-·-) OR SHORT BREAD (······) BISCUITS

following order: CB > CTW > RT > SB, while crispiness work increased in reverse order (Table 2). A high number of force peaks (with low force) are associated with a high degree of crispiness (Vincent 1998). This suggests that CB is the most crispy since it had highest number of peaks with lowest average force and that SB is the least crispy biscuit (few number of peaks with high average force) (Table 2).

The maximum sound pressure recorded during the puncturing of the biscuits decreased as follows: CTW ≥ CB > RT > SB (Table 3). This trend of maximum sound pressure with biscuit type correlated well ($R^2 = 0.82$) with that reported by Chen *et al.* (2005) for similar products.

The number of sound peaks emitted on puncturing CB was approximately three times greater (~1300) than that recorded for CTW (~456), with RT (~125) approximately three times less that of CTW (Table 3). SB emitted a sound signal with peaks below the threshold value, so no peaks were recorded (Table 3). The curve length and area under amplitude–time curve decreased as follows CB > CTW > RT > SB, while sound frequency was as follows CTW > CB > RT > SB (Table 3). Based on the number of sound peaks, CB is the most crispy while SB the least crispy.

The mechanical and acoustic crispiness parameters, particularly the number of force peaks, spatial raptures, sound pressure and number of sound peaks, were more strongly influenced by the fat and carbohydrate content of the biscuits than the moisture content or A_w. The fat content influenced

TABLE 2.
TEXTURE PARAMETERS DERIVED FROM FORCE–DISPLACEMENT DATA DURING PUNCTURING OF THE BISCUITS STUDIED

Biscuit type	Max force (N)	No. of peaks	Curve length (N)	Average force (N)	Initial slope (N/mm)	Work (mJ)	N_{sr} (mm^{-1})	*Ci*	Crispiness work (W_c) (N mm)
CB	9.1 ± 1.2^a	20 ± 3^b	7.3 ± 1.0^b	5.24 ± 0.8^a	15.1 ± 3.3^a	27.54 ± 3.3^c	3^d	50.9 ± 4.2^c	1.4 ± 0.2^a
CTW	12.3 ± 2.2^b	8 ± 3^a	4.12 ± 1.1^a	6.40 ± 1.7^{ab}	17.8 ± 3.7^a	14.82 ± 3.3^a	2^c	38.9 ± 2.5^b	2.0 ± 0.1^b
RT	14.4 ± 1.0^b	7 ± 2^a	4.05 ± 0.6^a	8.81 ± 2.8^b	48.1 ± 5.5^b	21.06 ± 2.9^b	1^b	21.9 ± 2.0^a	2.7 ± 0.1^c
SB	15.1 ± 4.1^b	5 ± 1^a	4.01 ± 0.4^a	8.18 ± 1.9^b	21.2 ± 3.4^a	28.29 ± 8.5^c	0^a	20.0 ± 2.0^a	6.3 ± 0.1^d

Values in each column represent mean ($n = 10$) ± standard deviation.

[a–d] Means in the same column with unlike letters are different ($P < 0.05$).

CB, Crackerbread; CTW, Table Water; RT, Rich Tea; SB, Shortbread; Nsr, number of spatial ruptures; *Ci*, crispiness index.

TABLE 3.
ACOUSTIC PARAMETERS DERIVED FROM SOUND AMPLITUDE–TIME DATA DURING PUNCTURING OF THE BISCUITS STUDIED

Biscuit type	Max sound pressure (Pa)	No. of sound peaks	Curve length (Pa)	Area under amplitude–time curve (Pa·s)	Frequency (kHz)
CB	33.0 ± 4.6^{c}	$1{,}307.1 \pm 113.6^{d}$	$20{,}854 \pm 1{,}564^{d}$	0.63 ± 0.04^{d}	$5{,}308 \pm 744^{c}$
CTW	37.7 ± 9.7^{c}	456.9 ± 95.4^{c}	$9{,}468 \pm 2{,}361^{c}$	0.26 ± 0.06^{c}	$14{,}340 \pm 2{,}799^{d}$
RT	5.8 ± 1.2^{b}	125.9 ± 30.6^{b}	$6{,}891 \pm 995^{b}$	0.18 ± 0.02^{b}	$3{,}987 \pm 271^{b}$
SB	1.1 ± 1.9^{a}	0 ± 0^{a}	$1{,}906 \pm 52^{a}$	0.05 ± 0.01^{a}	$1{,}527 \pm 176^{a}$

Values in each column represent mean ($n = 10$) ± standard deviation.

[a–d] Means in the same column with unlike letters are different ($P < 0.05$).

CB, Crackerbread; CTW, Table Water; RT, Rich Tea; SB, Shortbread.

crispiness negatively, perhaps through plasticization, and exhibited a correlation coefficient with a R^2 of –0.76, –0.96, –0.89 or –0.83 with number of force peaks, number of spatial raptures, sound pressure and number of sound peaks, respectively. The carbohydrate content influenced crispiness positively and exhibited correlation coefficient with a R^2 of 0.74, 0.94, 0.83 or 0.80 with number of force peaks, number of spatial raptures, sound pressure and number of sound peaks.

The number of sound peaks recorded for CB was ~1,300 which was significantly greater (40 times) than the number of sound peaks recorded by Chen *et al.* (2005) for a similar type of biscuit. The high number of sound peaks recorded in the present study is due to the higher sampling frequency used (i.e., 50 kHz compared to 0.5 kHz used by Chen *et al.* [2005]). As stated in the Introduction, high sampling rates, preferably >50 kHz, are recommended for acoustic tests to allow determination of sound frequency over the entire audible range (Castro-Prada *et al.* 2007). Thus, in this study, it was possible to evaluate the frequency of the sound emitted by the four biscuits which was not possible in the study published by Chen *et al.* (2005). In addition, the high sampling rate allowed the capture of all the sound generated during fracture of the sample, in turn providing more information. The number of sound peaks recorded in the present study for three biscuits; CB, RT and SB correlated well (R^2 of 0.99) with the results published by Chen *et al.* (2005) following study of the same biscuits using TA. This shows that the present developed system offers the required high sound and force data sampling rates while at the same time generated results that are in agreement with other comparable published data.

Sensory Evaluation

One of the advantages of the acoustic system developed in the present study is that it can be used independently of the texture-analyzing instrument, and because it is relatively portable, it can be used for testing acoustic crispiness during sensory evaluation. This allowed recording of the sound generated when the samples were being evaluated by sensory panelists. Figure 6 shows the typical amplitude–time curves generated during biting of CB, RT and SB. The CB exhibited the highest number of sound peaks and recorded the highest sound amplitude, while SB recorded the least number of peaks of low sound amplitude.

CB was perceived as the crispiest by 70% of the panelists, while 90% of the panelists perceived SB as being the least crispy (Fig. 7, Table 4). Sensory crispiness is considered as the true measure of crispiness so CB is the crispiest and SB is the least crispy among the biscuits studied.

High sound frequency is one characteristic of highly crispy products. Mechanical testing recorded very high sound frequency (14 kHz) of CTW,

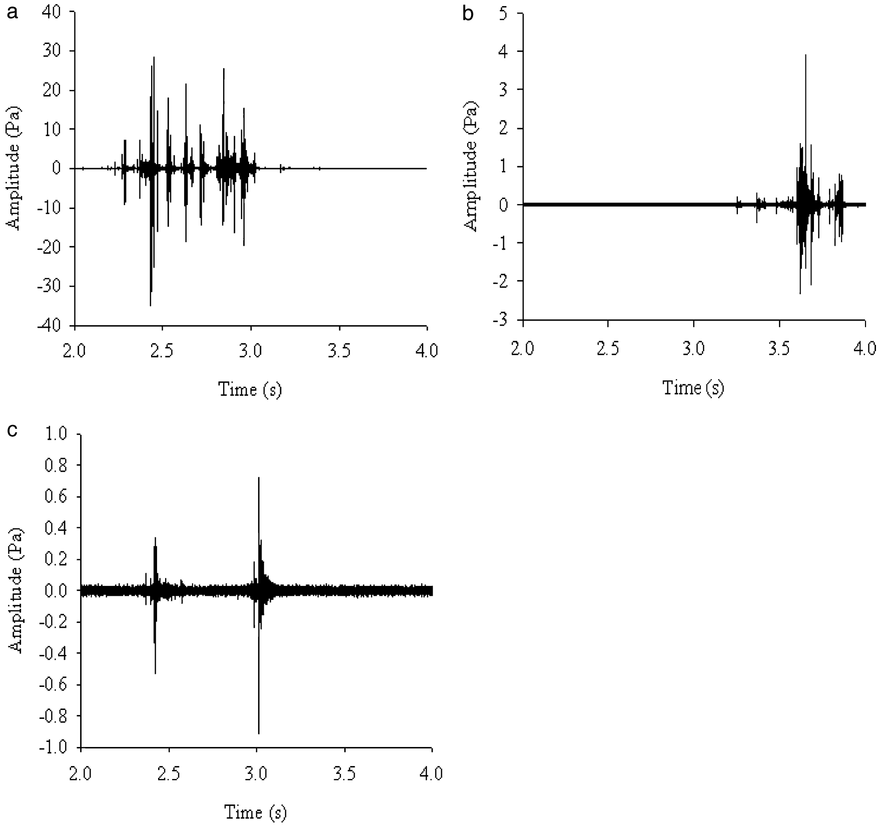

FIG. 6. TYPICAL REPRESENTATIVE AMPLITUDE–TIME CURVES RECORDED DURING ACTUAL BITING OF (a) CRACKERBREAD, (b) RICH TEA OR (c) SHORTBREAD

almost three times that of CB (Table 3). However, sensory panelists did not perceive CTW to be significantly crispier than CB (Table 4). In sensory analysis, the sensation of sound is perceived by the panelist as a result of the combination of the sound conducted through the bones and the air to the ears; while in mechanical testing, sound is conducted only through the air. This may partly explain the observed differences in results.

Both the sound pressure and number of sound peaks recorded during biting exhibited the same, CB > CTW > RT > SB (Table 4) and similar values to those recorded during instrumental puncturing (Table 3). CB had the longest measured curve length and the largest area under the sound amplitude–time curve, while SB had the shortest curve length and smallest area. Most of the parameters that were derived from force–displacement and sound

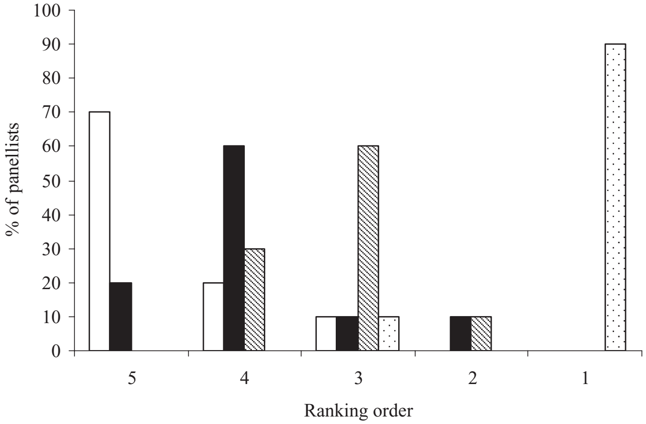

FIG. 7. DISTRIBUTION (%) OF RANKING SCORES AMONG PANELLISTS FOR THE VARIOUS BISCUITS: CRACKERBREAD (□) TABLE WATER (■), RICH TEA (▧) AND SHORTBREAD (⊡) IN DIFFERENT LEVELS OF CRISPINESS (5-MOST CRISPY, 1-LEAST CRISPY)

amplitude–time data correlated well ($R^2 > 0.77$) with sensory ranking (Table 5). The N_{sr} and W_c recorded a very high correlation coefficient of 0.96 and –0.99 with sensory data indicating that N_{sr} and W_c may be a good parameter for objectively determining crispiness. The maximum force and average force had a negative correlation of –0.85 and –0.40, respectively, with sensory crispiness score results (Table 5). This is in agreement with findings by Vincent (1998) who reported that crispy products are characterized by many peaks of low force, while crunchy-to-hard products are characterized by high hardness values and few peaks of high forces. The maximum sound pressure, number of sound peaks and sound curve length recorded during instrumental puncturing all exhibited very good correlation ($R^2 > 0.9$) with those properties determined during the actual biting. This shows that the instrumental results are comparable to actual biting results obtained during sensory evaluation.

CONCLUSION

The proposed acoustic system provides an improved sound capturing setup that can be used with an Instron UTM. The improved system offers high sampling rates (>50 kHz) and can be modified by the user to suit the test requirements. The acoustic system can be used as an attachment with any texture-analyzing instrument and can also be used independently of the instrument. Therefore, it can be used to capture acoustic signals during sensory evaluation of crispiness.

TABLE 4.
MEAN SENSORY SCORES AND ACOUSTIC PARAMETERS DERIVED FROM SOUND GENERATED DURING SENSORY EVALUATION OF BISCUITS STUDIED

Biscuit type	Sensory score	Sound pressure (Pa)	Number of sound peaks	Curve length (Pa)	Area under amplitude–time curve (Pa·s)
CB	4.6 ± 0.7^{c}	28.5 ± 7.4^{d}	$1,362 \pm 300^{d}$	$13,611 \pm 2,569^{d}$	0.36 ± 0.1^{d}
CTW	3.9 ± 0.6^{bc}	22.1 ± 7.8^{c}	389 ± 93^{c}	$6,531 \pm 1,126^{c}$	0.19 ± 0.0^{c}
RT	3.2 ± 0.9^{b}	4.0 ± 1.6^{b}	137 ± 23^{b}	$4,234 \pm 597^{b}$	0.13 ± 0.0^{b}
SB	1.2 ± 0.6^{a}	0.7 ± 0.3^{a}	0 ± 0^{a}	$2,668 \pm 68^{a}$	0.09 ± 0.0^{a}

Values in each column represent mean ($n = 10$) ± standard deviation.

[a–d] Means in the same column with unlike letters are different ($P < 0.05$).

CB, Crackerbread; CTW, Table Water; RT, Rich Tea; SB, Shortbread.

TABLE 5.
CORRELATION COEFFICIENTS (R^2) OF SENSORY SCORES VERSUS DIFFERENT PARAMETERS DERIVED FROM MECHANICAL AND ACOUSTIC ANALYSIS OF THE FOUR BISCUITS STUDIED

Texture test	Texture parameter	R^2
Parameters derived from force–displacement data during mechanical analysis	Maximum force (N)	–0.85
	No. of force peaks	0.77
	Average force (N)	–0.40
	Force curve length (N)	0.64
	Number of spatial raptures (N_{sr}) (mm^{-1})	0.96
	Crispiness index	0.85
	Crispiness work (W_c) (N mm)	–0.99
Parameters derived from sound amplitude–time data during mechanical testing	Maximum sound (Pa)	0.79
	No. of sound peaks	0.81
	Sound curve length (Pa)	0.88
	Area under amplitude–time curve (Pa·s)	0.86
	Sound frequency (kHz)	0.56
Parameters derived from sound amplitude–time data during sensory evaluation	Maximum sound pressure (Pa)	0.88
	No. of sound peaks	0.77
	Sound curve length (Pa)	0.83
	Area under amplitude–time curve (Pa·s)	0.83

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