MECHANICAL–ACOUSTIC AND SENSORY EVALUATIONS OF CORNSTARCH–WHEY PROTEIN ISOLATE EXTRUDATES

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ABSTRACT

*The mechanism relating sensory perception of brittle food foams to their mechanical and acoustic properties during crushing was investigated. Cornstarch was extruded with four levels of whey protein isolate (0, 6, 12 and 18%) and two levels of in-barrel moisture (23 and 27%). Hardness, fracturability and roughness of mass were three main sensory attributes that varied substantially between products. High correlations (*r = *0.841–0.998) were observed between sensory attributes and instrumentally determined mechanical properties, including crushing force (11.2–57.9 N) and crispness work (4.6–75.8 N·mm). Based on acoustic data obtained during instrumental crushing, time-domain signal processing and a novel voice recognition technique utilizing frequency spectrograms were successfully employed for understanding the differences in the sensory properties of various products. Microstructure features, including average cell diameter (1.00–2.94 mm), average wall thickness (0.04–0.27 mm) and cell number density (7–193 cell/cm^3), were characterized noninvasively using X-ray microtomography, and proved to be critical in relating sensory perception of the cellular extrudates to their mechanical–acoustic signatures.*

PRACTICAL APPLICATIONS

The sensory perception of crispy and crunchy food products is primarily a function of their mechanical response and emission of sounds during

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fracture. The current study was focused on understanding these relationships in the context of brittle extruded foods. The mechanical–acoustic techniques outlined in this study have the potential of reducing the time, costs and subjectivity involved in evaluation of new foods by human panels, and can be a useful tool in the overall product development cycle. These techniques need not be limited only to food systems, as properties of any rigid, fracturable material can be characterized based on its mechanical–acoustic signature.

KEYWORDS

Extrusion, mechanical-acoustic analysis, microstructure, sensory analysis, whey protein, X-ray microtomography

INTRODUCTION

The textural perception of foods during product development has been traditionally evaluated by sensory panels that develop descriptive attributes specific to the food products and then rate them on those attributes (Chambers *et al.* 2004). Decisions related to transfer of any product concept from the lab to the processing plant and retail stores rely heavily on results from such panels. Selection of panelists and their training, and the evaluation of products can be a time-consuming process if highly trained panels are desired (Hootman 1992; Chambers *et al.* 2004). Although sensory panels can never be replaced, the product evaluation cycle can be shortened, and some of the time and costs involved can be reduced by the use of appropriate instrumental measurements. Moreover, product quality data derived from standard instruments can be shared easily between different geographical and cultural regions, in contrast with data based on descriptive sensory terms that might lose meaning in translation.

Crispness and crunchiness are sensory sensations used to describe the textural perception of many foods, including breakfast cereal, various fried and baked snacks and some fruits and vegetables such as apples and celery (Vickers and Bourne 1976a,b; Vickers 1987; Duizer 2001; Luyten *et al.* 2004; Dijksterhuis *et al.* 2007). A big proportion of breakfast cereal and a variety of crispy/crunchy snacks are produced by extrusion, which is an important and widely used processing technology. Extruded products usually have a brittle, foam-like cellular structure, and the sensory perceptions associated with them are largely related to their fracture properties. Typically, mechanical properties under compression or puncture have been used as instrumental measures of texture for these products (Hutchinson *et al.* 1987; Hayter and Smith 1988;

Van Hecke *et al.* 1998; Vincent 1998). In recent years, research has increasingly focused on the contribution of microstructure parameters to the mechanical properties of extrusion-puffed foods (Barrett and Peleg 1992; Warburton *et al.* 1992; Barrett *et al.* 1994; Van Hecke *et al.* 1995; Gao and Tan 1996; Gogoi *et al.* 2000; Agbisit *et al.* 2007). These studies have related average crushing force, breaking stress, plateau stress, modulus of deformability, Young's modulus and failure strain of brittle cellular extrudates to such structural features as mean cell size, cell edge thickness, cell density and amount of drainage from the cell walls to edges.

Apart from mechanical properties, an additional dimension that has a significant role in the sensory perception of crispness and crunchiness is acoustics or the sound emitted during biting and mastication of foods. Human ear physiology and acoustic perception were reviewed by Gold and Morgan (2000). The signal processing involved in speech recognition technology, which automatically converts spoken words captured by a microphone into text, somewhat mimics what we understand of the processing performed in the human ear and brain to comprehend words and separate speech from noise. The fundamental basis of any speech recognition system and most acoustic studies involving crispy foods is the transformation of amplitude–time sound signals into a frequency spectrogram. Both amplitude–time signals and frequency spectra provide a crucial link between mechanical properties and sensory perception of crispy/crunch foods, and are important for the instrumental quantification of the latter (Vickers and Bourne 1976b; Vickers 1987; Duizer 2001). The underlying role of microstructure parameters has also been documented (Luyten and Van Vliet 2006; Marzec *et al.* 2007). However, "transliteration" of sensory properties of such food products to instrumental data or vice versa is still an evolving area.

The objective of this research was to study the relationships between sensory perception of cornstarch and whey protein isolate (WPI)-based expanded extrudates and mechanical–acoustic data obtained instrumentally. A new classification algorithm, based on discriminating features used in voice-recognition systems, is proposed in this study for distinguishing acoustic emissions from different extrudates. Given that voice recognition systems were developed as a generic signal processing method based on the human auditory system, this method has the potential to better match sensory panel perceptions of samples. Moreover, to understand the role of microstructure, non-invasive X-ray microtomography (XMT) was used for characterization of cellular features of the extrudates.

WPI was used as an additive at various concentrations to obtain extrudates with different cell structures and textures. WPI is produced using technologies such as micro- and ultrafiltration, and is increasingly being used in extruded breakfast cereal and snack products (Kim and Maga 1987; Matthey and Hanna 1997; Onwulata *et al.* 2001). Apart from being a rich source of amino acids, such as lysine, in which cereals are deficient, whey proteins have several additional nutritional benefits, including enhancement of immune function and antioxidant activity, appetite suppression, antihypertension effects, greater muscle functionality and improved general health (Burrington 2004; Onwulata and Tomasula 2004). WPI is also used as a functional ingredient for its good foaming/emulsifying properties, and provides texture and physical stability to food systems (Huffman 1996; Alavi *et al.* 1999; Shim and Mulvaney 2002; Davis and Foegeding 2004).

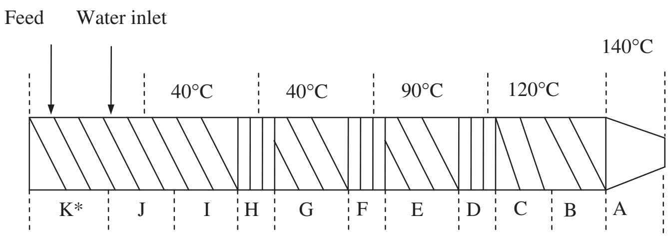
MATERIALS AND METHODS

Materials

Unmodified cornstarch (~25% amylose and 75% amylopectin; Cargill Gel 03457, Minneapolis, MN) was the control formulation and base ingredient for all extrusion runs. WPI (minimum 92% protein; INPRO 90, Vitalus Nutrition, Inc., Bellingham, WA) was preblended with the control formulation at three different levels (6, 12 and 18%) using a ribbon mixer.

Extrusion Processing

A pilot-scale twin screw extruder (model TX-52, Wenger Manufacturing, Inc., Sabetha, KS) with screw diameters of 52 mm, length-to-diameter ratio (L/D) of 16, medium-shear screw profile (Fig. 1) and circular die opening of 3.3 mm, was used to process all materials. Before extrusion runs, the extruder was calibrated to ensure selected feed rate and water injection rates were accurate. With the screw speed fixed at 300 rpm, the cornstarch–WPI blends were each extruded at in-barrel moisture content (MC) of 23 and 27% (wet basis). The feed rate of raw material was set at 60 kg/h and controlled through a gravimetric feeding system. Water flow to the preconditioner was maintained at a constant 7.0 kg/h. Water flow to the extruder barrel was adjusted to obtain the desired in-barrel moisture, taking the moisture of the raw material in consideration. The barrel temperature profile and location of water injection to the extruder are also shown in Fig. 1. The expanded, cellular product was cut immediately after exiting the extruder die with a face-mounted rotary cutter turning at 860 rpm. Extruder conditions were allowed to stabilize for approximately 10 min before samples and process data were collected for 3–5 min for each treatment. Extrudates were subsequently dried at 100C with a double-pass dryer/cooler (series 4800, Wenger) adjusted for 15 min retention time (7.5 min each for the top and bottom belts). Cooling was accomplished at room temperature, with a 5-min retention time on the cooling belt.



Section	Number of elements	Element length, mm	Element description
A	1	78	¾ pitch, double flighted, conical
B	1	78	¾ pitch, double flighted
C	1	52	½ pitch, double flighted
D	1	26	kneading block, forward
E	1	78	¾ pitch, double flighted
F	1	26	kneading block, forward
G	1	78	¾ pitch, double flighted
H	1	26	kneading block, forward
I	1	78	¾ pitch, double flighted
J	2	78	full pitch, double flighted
K	2	78	¾ pitch, double flighted

*The first two elements of the right shaft at the inlet (K) are ¾ pitch, single flighted.

FIG. 1. DIAGRAM OF THE EXTRUDER SCREW CONFIGURATION, WATER INJECTION SITES AND BARREL TEMPERATURES USED FOR ALL TREATMENTS
Lengths of screw elements are not to scale.

A computerized data acquisition system was used to collect extrusion process data, including screw speed and motor load. Averages for each data collection period were calculated and subsequently used in computations of specific mechanical energy (*SME*) as follows

$$SME = \frac{36(L - L_0)(N / N_r)P_r}{\dot{m}} \quad \text{(kJ/kg)} \tag{1}$$

where L = percent motor load while running with product, L_0 = percent motor load while running empty, N = screw speed (rpm), N_r = rated screw speed (336 rpm), P_r = rated power of extruder motor (22.4 kW) and $\dot{m}$ = net mass flow rate in the barrel (kg/h).

Prior to sensory evaluation and mechanical–acoustic testing, dried extrudates were transferred to a controlled environment chamber (model 532, Electro-Tech Systems Inc., Glenside, PA) to equilibrate at 25C and 35% relative humidity. The extrudates were removed from the conditioning chamber after 48 h, and put into double-layered, sealed plastic bags before further testing.

Microstructure Analysis and Physical Properties

Extrudates were non-invasively scanned using a bench-top XMT imaging system (20–100 kV/0–250 μA; model 1072, SkyScan, Aartselaar, Belgium) set at 40 kV/100 μA to obtain optimum contrast between solid and gaseous phases. After reconstruction, a set of 15 two-dimensional (2-D), virtual "slices" were obtained for each sample, perpendicular to the direction of extrusion. Calculations of three-dimensional (3-D) microstructural parameters were based on measurement of 2-D features from each slice using image analysis software (Scion Image for Windows, Frederick, MD), and their subsequent integration over all the slices. These 2-D features included individual cell perimeters and void areas, and overall solid and void areas for each slice. The computed 3-D parameters included volume weighted average cell diameter ($\overline{D}$), cell wall thickness (t_{wall}) and cell number density (N). Details of XMT scanning, image reconstruction, thresholding, measurement of 2-D features and computation of 3-D microstructural parameters have been described previously (Trater *et al.* 2005). As the measurements required a significant amount of time, two representative samples from only one replicate of each treatment were analyzed for cellular structure. Bulk densities (δ) were determined by measuring the mass of 1 L of dried extrudates. Piece densities (ρ) were obtained by the rapeseed displacement method (Penfield and Griswold 1979).

Sensory Analysis

Extrudates from all the treatments were evaluated at the Sensory Analysis Center at Kansas State University (Manhattan, KS). The sensory analysis panel consisted of 10 highly trained descriptive panelists. Each panelist had more than 120 h of descriptive training and an average of more than 2,000 h of testing experience. The whole sensory analysis process consisted of two parts: (1) discussion and determination of sensory attributes that best described the texture of extrudates; and (2) the actual evaluation or scoring on these attributes. Three commercial products, expanded breakfast cereal (Cheerios, General Mills, Minneapolis, MN), raw elbow macaroni (American Beauty Elbo-Roni, New World Pasta Company, Harrisburg, PA) and corn taco shell (Taco Bell Taco Shells, Home Originals, Kraft Foods, Northfield, IL) were chosen as references. The texture of the test and reference products was first discussed by the panel, and then 10 appropriate sensory attributes were identified and their intensities quantified for the reference samples. Reference and test product attribute scores were based on a 15-point scale with 0.5 point increments. During the evaluation sessions, the panelists consumed 5–10 pieces from each treatment, one whole piece at a time, and scored the intensity of the attributes. This was repeated three times, and average scores were computed.

Mechanical–Acoustic Experimentation

Thirty pieces (or replicates) with approximately the same dimensions (diameter and height) were tested for each treatment. Force–deformation and acoustic data for each piece as a whole were obtained simultaneously using a texture analyzer (TA-XT2, Stable Micro Systems, Godalming, U.K.) and a lab-assembled sound recording system. A test probe of 38 mm diameter was used at a speed of 10 mm/s to compress samples to 90% of their original height, parallel to the direction of extrusion. From the force–deformation curve, number of peaks n, integral of the curve S (or area below the curve from 0 to 100% strain) and distance of compression d were computed. From n, S and d values, the following parameters were calculated (Van Hecke *et al.* 1998).

$$N_{sr} = \frac{n}{d} \quad \text{(mm)} \tag{2}$$

$$F_{cr} = \frac{S}{d} \quad \text{(N)} \tag{3}$$

$$W_c = \frac{F_{cr}}{N_{sr}} = \frac{\frac{S}{d}}{\frac{n}{d}} \quad (\text{N}\cdot\text{mm}) \tag{4}$$

where N_{sr} is the number of spatial ruptures, F_{cr} is average crushing force and W_c is crispness work.

Acoustic emissions from the sample being crushed were captured with a microphone (M550, Earthworks Audio, Milford, NH). This was a precision instrument capable of measuring frequencies as high as 100 kHz, because preliminary experiments suggested that samples emit sounds up to this frequency. The microphone signal was amplified (#1021, Earthworks Audio) and digitized at a sampling rate of 196 kHz by a computer using a sound card (Waveterminal 192X, Ego Systems, Cupertino, CA) that was able to capture the higher-frequency sounds. Audio recording software (Cool Edit Pro v2.1, Syntrillium Software, Phoenix, AZ) was used to initiate recording and save the digitized acoustic emission as uncompressed "wav" files for analysis at a later time. Each recording was initiated manually when the texture analyzer started the crushing and terminated manually at the completion of crushing.

Acoustic Signal Processing

Voice Recognition Method. The audio recording for each crushing test had a total length of approximately 5 s. However, the actual duration of crushing was usually around 1 s, about as long as a typical spoken word or a single bite, and contained about 200,000 data points. Because the duration of an individual fracture sound was very short, the entire signal was segmented into short time windows of 256 points (1.3 ms) to compute the frequency spectrogram and classify a sample. Each window overlapped by 1/4 of the window length (64 points) so as not to miss a fracture occurring on the edges of a window. Thus, a 200,000 point clip contained 1,042 windows.

A discrete Fourier transform (DFT) of each window was computed by using the fast Fourier transform algorithm and a hamming window. The magnitude of the DFT was computed by taking the square root of the squared sum of the complex and real portions of the DFT. Afterward, the logarithm of the magnitudes was computed and the frequency spectrograms were created by displaying these magnitudes in gray scale on a chart with one axis as the time domain and the other as the frequency domain.

The spectrogram was divided into $M = 24$ nonuniform frequency sub-bands, and a histogram, h_i, $i = 1, 2, \ldots, M$, of the signal magnitudes in each sub-band was computed. The sub-bands were distributed across the frequency domain according to a "mel scale," which is linear at low frequencies and logarithmic thereafter. This mimicked the frequency resolution of the human ear. Below 10 kHz, the DFT was divided linearly into 12 equally spaced bands. At higher frequency bands, covering 10–98 kHz, the sub-bands were divided in a logarithmic manner into 12 sections equally spaced on a log scale. Therefore, more emphasis was given to low-frequency information than to high-frequency data. In other words, the DFT coefficients were grouped into $M = 24$ sub-bands in a nonuniform manner.

All of the histograms were combined into a single data set, and stepwise discriminant analysis was used to select significant features ($P = 0.05$) for classifying each sample into its WPI category. This was performed separately for the two MCs studied. After feature selection, discriminant analysis was used to classify each sample into a WPI category. Training was performed on a random selection of one quarter of the data and validated on the other three quarters. This cross-validation method was applied a total of four times, and the average was reported.

Time Domain Method. Signal slope and signal amplitude were two parameters used to analyze the acoustic properties in the time domain separately from the voice recognition parameters, as these time domain parameters are easier to relate to mechanical properties. The signal was divided into three regions based on the absolute value of slope: (1) low slope, ranging from 0 to 3,500 analog to digital (A/D) counts; (2) medium slope, ranging from 3,500 to 7,000 A/D counts; and (3) high slope, above 7,000 A/D counts. The slope for a particular data point was computed as the difference between signal amplitudes 5 points before and after the point of interest. This can be correlated with the amplitudes of the peaks when the signal frequencies are similar, or their frequency when the amplitudes are similar. However, different samples emit signals with different frequencies and amplitudes so slope is not always well correlated with either. The signal data points were also classified into three levels of amplitude absolute values: (1) low amplitude, ranging from 0 to 3,500 A/D counts; (2) medium amplitude, ranging from 3,500 to 7,000 A/D counts; and (3) high amplitude, above 7,000 A/D counts. Most data points fell in the medium range for both signal amplitude and slope. The number of data points in each signal having a high slope and high amplitude, as well as the number of data points having a low slope and low amplitude, were counted and used to describe the acoustic response of each sample.

Experimental Design and Data Analysis

A completely random 2×4 factorial experimental design, with two levels of MC (23 and 27%) and four levels of WPI (0, 6, 12 and 18%), was used to produce extrudates with different microstructures and textures. Each extrusion treatment was duplicated on a different day. Mechanical–acoustic tests were conducted on 30 replicate samples from each duplicated extrusion treatment. Microstructural parameters, obtained by XMT, were averages of two representative samples from only one replicate of each treatment. Sensory analysis was also conducted on one replicate of each treatment. Fisher's least significant difference (95% confidence level) tests were performed on mechanical and sensory data using SAS (SAS System for Windows, release 8.2, SAS Institute, Inc., Cary, NC). The "Pearson" function of EXCEL software (2002 edition, Microsoft Corporation, Seattle, WA) was used for finding the Pearson's coefficient of correlation (r) between sensory parameters and mechanical properties. To provide descriptive terms to the degree of correlation, criteria outlined by Franzblau (1958) were used ($|r| < 0.20$, negligible; $|r| = 0.20$–0.40, low; $|r| = 0.40$–0.60, moderate; $|r| = 0.60$–0.80, marked; and $|r| > 0.80$, high).

RESULTS AND DISCUSSION

Physical and Microstructural Properties

It was clear from the bulk density (δ) and piece density (ρ) data (Table 1) that for all levels of WPI, extrudates processed at 23% MC exhibited much

TABLE 1.
MICROSTRUCTURE AND PHYSICAL PROPERTIES OF EXTRUDATES

WPI (%)	In-barrel MC (%)	SME (kJ/kg)	δ (g/L)	ρ (g/L)	$\bar{D}$ (mm)	t_{wall} (mm)	$t_{wall}/\bar{D}$	N (cells/cm^3)
0	23	315 ± 2	98 ± 5	192 ± 11	2.94	0.072	0.024	7
6	23	324 ± 15	82 ± 15	120 ± 8	1.24	0.058	0.047	93
12	23	332 ± 28	75 ± 14	116 ± 13	1.06	0.062	0.058	152
18	23	359 ± 4	67 ± 0	123 ± 17	1.15	0.043	0.037	119
0	27	274 ± 37	154 ± 6	235 ± 21	1.57	0.161	0.102	45
6	27	287 ± 30	183 ± 33	257 ± 13	1.52	0.272	0.179	54
12	27	314 ± 26	119 ± 7	227 ± 16	2.05	0.126	0.062	23
18	27	310 ± 8	107 ± 1	206 ± 20	1.00	0.092	0.092	193

Standard deviations, wherever available, are shown after the symbol "±."
WPI, whey protein isolate; MC, moisture content; *SME*, specific mechanical energy; δ, bulk density; ρ, piece density; $\bar{D}$, cell diameter; t_{wall}, cell wall thickness; *N*, cell number density.

higher expansion than those at 27% MC. For 27% MC, δ ranged between 107 and 183 kg/m^3 depending on the WPI content, and was higher by 57–123% than the corresponding δ for 23% MC (67–98 kg/m^3). For 27% MC, ρ ranged between 206 and 257 kg/m^3 depending on the WPI content, and was higher by 22–114% than the corresponding ρ for lower in-barrel moisture extrudates (116–192 kg/m^3). Greater in-barrel moisture led to a less viscous melt in the extruder barrel and consequently reduced the *SME* input, which is the main driving force for expansion. *SME* was 274–314 kJ/kg for 27% MC as compared to 315–359 kJ/kg for 23% MC (Table 1). Previous studies have reported similar effects of extrusion moisture. Parsons *et al.* (1996) reported a decrease in the expansion ratio of cornmeal when the extrusion MC was increased from 19.5 to 21.5% (w/w). Reduction of extrudate expansion at high MC was also observed by other researchers (Liu *et al.* 2000; Onwulata *et al.* 2001; Ding *et al.* 2006). According to Ilo *et al.* (1996), an increase in MC decreased the *SME*, apparent viscosity and radial expansion ratio during extrusion of maize grits. Reduced resistance to extrudate shrinkage and collapse, in a less viscous melt, has also been discussed as a reason for decrease in expansion with increased moisture (Kokini *et al.* 1992; Della Valle *et al.* 1997).

In general, an increase in WPI content from 0 to 18% led to a progressive increase in *SME* and extrudate expansion at both 23 and 27% MC (Table 1). Upon the addition of WPI, δ decreased by as much as 30 and 32% (at 18% WPI for both MC), and ρ by 12 and 40% (at 18 and 12% WPI for 27 and 23% MC, respectively) as compared to corresponding treatments with no WPI. Increased expansion caused by the addition of WPI can be attributed to higher *SME*, and also the gelation of whey proteins leading to a matrix more resistant to collapse as reported by Alavi *et al.* (1999) for extrudates puffed by supercritical CO_2.

However, these results were contrary to previous studies on steam-puffed extruded products, which showed that addition of whey proteins to extruded products significantly reduced expansion (Kim and Maga 1987; Matthey and Hanna 1997; Onwulata *et al.* 2001).

Representative 2-D XMT slices of samples from each treatment are shown in Fig. 2, and microstructure data are also presented in Table 1. Extrudates exhibited different cell structures depending on the in-barrel moisture and WPI content, but were mostly closed cell in nature as has been observed by our research group previously (Trater *et al.* 2005). Cell density (N) ranged from 7 to 152 and from 23 to 193 cells/cm^3 for 23 and 27% MC, respectively. An increasing trend was observed for N with the addition of 6–18% WPI, which might be a result of enhancement in foaming caused by whey proteins (Davis and Foegeding 2004). Average cell diameter ($\bar{D}$) ranged from 1.06 to 2.94 mm and from 1.00 to 2.05 mm for 23 and 27% MC, respectively. For the corresponding levels of MC, average cell wall thickness (t_{wall}) ranged from 0.04 to 0.07 mm and from 0.09 to 0.27 mm, respectively. Both $\bar{D}$ and t_{wall} decreased as the WPI content increased, with some exceptions. Overall, the microstructure data indicated that irrespective of MC, the addition of 6–18% WPI led to greater number of cells with smaller sizes and thinner cell walls. However, the effect of MC on different microstructure parameters was not

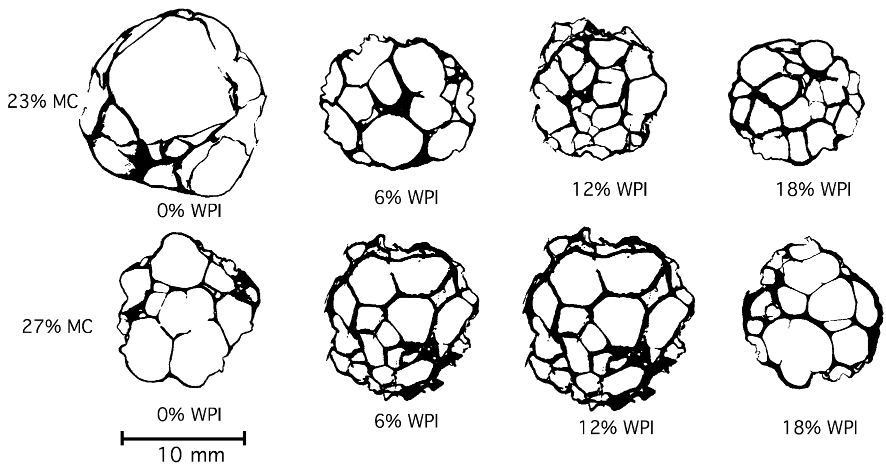


FIG. 2. X-RAY MICROTOMOGRAPHY IMAGES OF REPRESENTATIVE TWO-DIMENSIONAL SLICES (PERPENDICULAR TO THE DIRECTION OF EXTRUSION) OF FOAMS FROM EACH TREATMENT

All images correspond to the scale indicated on the bottom left.
WPI, whey protein isolate; MC, moisture content.

consistent, with the exception of t_{wall}, which was higher for 27% MC at all WPI levels.

Sensory Analysis of Texture Attributes

Ten texture attributes were detected, evaluated and scored by the panelists (Table 2). Variation in sensory parameters between different WPI treatments was not substantial. However, hardness, fracturability and roughness of mass were three parameters that varied the most between the two in-barrel MCs. Therefore, further discussion was focused on these three parameters only. The effect of in-barrel MC and WPI content on hardness, fracturability and roughness of mass is shown in Fig. 3.

Hardness was defined as the force required to completely compress the sample with the molar teeth on the first bite down. The reference products, General Mills Cheerios and raw American Beauty Elbo-Roni, scored 5.5 and 14, respectively, on the hardness scale. Hardness of all extrudates in this study lay between these two reference values (Fig. 3A). Both MC and WPI had significant effect on hardness. Higher MC (27%) resulted in significantly greater hardness, and the difference was more pronounced at lower WPI content. At 27% MC, there was no significant difference in hardness between samples with 0 and 6% WPI. As WPI content increased beyond 6%, a significant decrease in hardness was observed. For extrudates processed at lower in-barrel moisture (23%), the control (0% WPI) was significantly harder than

TABLE 2.
SENSORY ANALYSIS RESULTS

In-barrel MC (%)	23	23	23	23	27	27	27	27	LSD
WPI (%)	0	6	12	18	0	6	12	18	
Surface roughness	3.7bc	4.6a	4.0b	4.9a	3.4cd	3.2d	3.9b	4.8a	0.43
Hardness	**7.8c**	**6.4d**	**5.6e**	**6.1d**	**13.6a**	**13.4a**	**10.8b**	**7.5c**	**0.47**
Fracturability	**8.7cd**	**8.2d**	**7.0e**	**7.0e**	**12.0a**	**12.4a**	**10.6b**	**8.8c**	**0.49**
Initial crispness	11.4c	10.6d	10.3d	9.8e	13.0a	13.0a	12.2b	11.3c	0.44
Sustained crispness	3.8d	4.0bcd	3.9cd	4.3bc	1.9e	1.4f	4.4b	5.0a	0.43
Denseness	2.6c	3.2b	2.6c	3.4b	1.3d	1.4d	2.3c	4.1a	0.41
Roughness of mass	**8.1c**	**7.8c**	**5.5e**	**5.2e**	**13.3a**	**13.4a**	**10.3b**	**7.2d**	**0.52**
Cohesiveness of mass	6.6b	7.6a	6.1c	6.1c	0.9e	1.0e	4.2d	6.2bc	0.52
Particles (residuals)	4.0b	3.7b	4.2b	3.6b	2.8c	1.3d	5.3a	3.4bc	0.82
Toothpacking	6.1b	8.2a	8.7a	8.3a	0.9c	0.8c	6.4b	8.0a	0.85

Parameters marked in bold were selected for further analyses as they showed the greatest variation between treatments.
Means with the same letter within a row are not significantly different at 95% confidence level.
MC, moisture content; LSD, Fisher's least significant difference error; WPI, whey protein isolate.

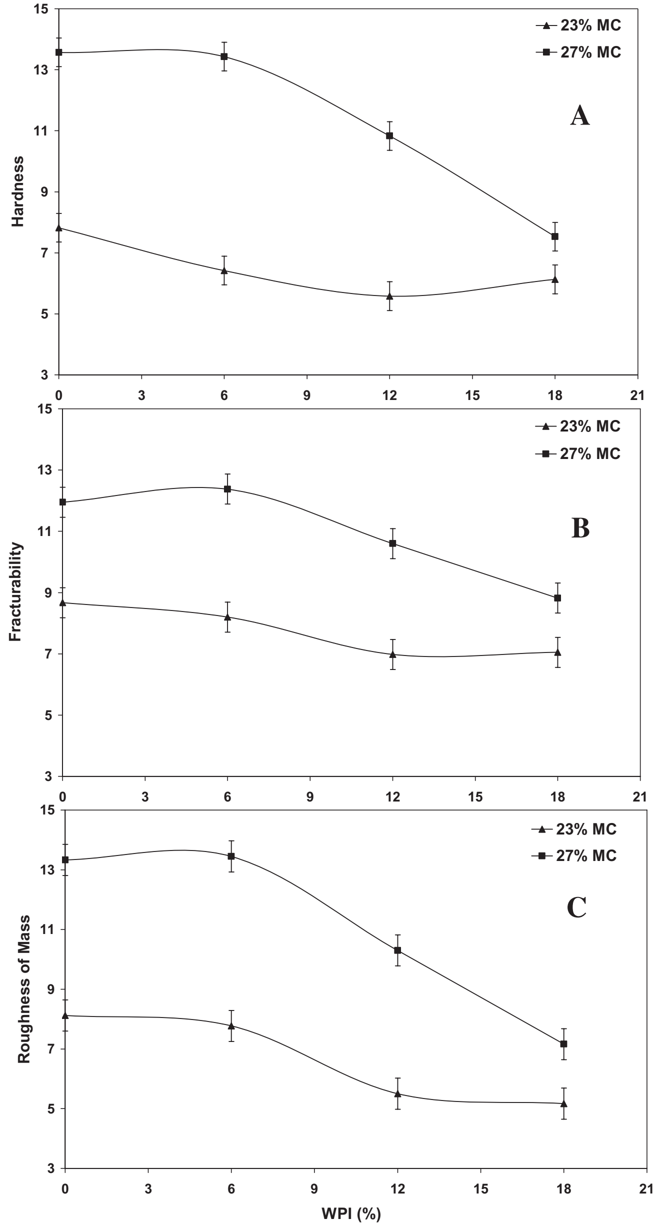


FIG. 3. EFFECT OF WHEY PROTEIN ISOLATE (WPI) CONTENT AND IN-BARREL MOISTURE CONTENT (MC) ON EXTRUDATE SENSORY PARAMETERS (15–POINT SCALE)
(A) Hardness, (B) fracturability and (C) roughness of mass. The error bars represent the least significant difference at $P = 0.05$. Overlap of bars signifies that means are not significantly different.

all other treatments. Hardness decreased as WPI content increased from 0 to 12%. Further increase in WPI content to 18% resulted in slightly harder extrudates. However, none of the differences between any of the samples with WPI were significant. In general, the addition of WPI made extrudates softer especially at higher MC, although in-barrel MC played the more dominant role in deciding extrudate texture.

Fracturability was defined as the force with which the sample ruptured on the first bite down with the molars. The reference products, General Mills Cheerios and raw American Beauty Elbo-Roni, scored 4.0 and 12.5, respectively, on the fracturability scale. Fracturability of most extrudates in this study lay between these two reference values (Fig. 3B). WPI and MC had almost the same effect on fracturability as on hardness. The only major difference was at 23% MC, where fracturability of the control did not differ significantly from the rest of the treatments. As in the case of hardness, in-barrel moisture played a greater role than WPI in deciding fracturability.

Both hardness and fracturability of the extrudates increased as their bulk and piece densities increased. This explained the decrease of both these sensory parameters with lower in-barrel MC or higher WPI content. The more pronounced effect of MC, as compared to WPI, on hardness and fracturability corresponded with the greater impact of MC on the expansion of the extrudates. Barrett *et al.* (1994) observed a linear correlation of corn meal extrudate hardness and crunchiness with their bulk density. Crunchiness, in their case, was defined similarly as fracturability in the current study. Instrumental parameters that measure hardness or strength of extrudates, like breaking strength, compressive modulus and average puncturing force, have also been shown to correlate well with extrudate density (Hutchinson *et al.* 1987; Hayter and Smith 1988; Barrett and Peleg 1992; Van Hecke *et al.* 1998; Agbisit *et al.* 2007). The power-law function has been demonstrated, both experimentally and theoretically, to relate the mechanical strength of a variety of cellular products to their density (Gibson and Ashby 1997).

Microstructure parameters (like $\bar{D}$ and t_{wall}) and strength of the solid matrix are the fundamental properties of cellular materials that affect their overall mechanical strength (Gibson and Ashby 1997; Agbisit *et al.* 2007). Results from this study indicated that a decrease in t_{wall} (because of lower MC or higher WPI) was accompanied by a decrease in extrudate hardness and fracturability. However, it is the ratio $t_{wall}/\bar{D}$ that has a critical role in determining the mechanical strength of brittle foams, as hypothesized theoretically (Gibson and Ashby 1997) and also validated by our research group (Agbisit *et al.* 2007). In this study, lower $t_{wall}/\bar{D}$ ratio was observed for extrudates processed at 23% MC as compared to those at 27% MC (average values of 0.042 and 0.109, respectively) (Table 1). Also, higher *SME* in the case of the former would lead to macromolecular degradation and consequently a weakened cell matrix (Van Hecke *et al.* 1998). Thus there was a good correspondence between theory and the results obtained for hardness and fracturability. Interestingly, at constant processing MC, hardness and fracturability ratings of extrudates with different WPI levels did not follow the same order as their $t_{wall}/\bar{D}$ ratio. This was attributed to increase in SME and greater discontinuities in the starch matrix with addition of WPI, resulting in a weakened solid phase. Thus, higher WPI reduced the overall mechanical strength of the brittle foams even though the $t_{wall}/\bar{D}$ ratio did not follow the same trend.

Roughness of mass was defined as the degree of abrasiveness of particles perceived when gently manipulating the mass against the palate after two to three chews. The reference products, General Mills Cheerios and Taco Bell Home Originals taco shell, scored 4.0 and 10.0 on the roughness of mass scale, respectively, after five to seven chews. All the extrudates processed at 23% MC had roughness of mass values that lay between the two references, while most of those processed at 27% MC exceeded the roughness of the taco shell reference (Fig. 3C). For both MC, there were no significant differences between roughness values of the control and 6% WPI samples. However, roughness of mass decreased as WPI increased from 6 to 18%. Roughness or degree of abrasiveness of the extrudates would depend to a large extent on the strength of the cell walls. As explained previously, lower MC or higher WPI would lead to softer cell walls, and thus, less abrasive particles during chewing.

Mechanical Properties and Their Correlations with Sensory Attributes

Figure 4 presents a typical compressive force–deformation curve for extrudates obtained using the TA-XT2 texture analyzer. Most curves from the mechanical tests had a similar pattern. Each peak on the force–deformation curve theoretically represents one cell being broken, but sometimes it could be a signal for a group of cells being fractured at the same time and/or breaking of the whole sample into two or more pieces. The mechanical properties that showed the largest differences between various treatments were average crushing force (F_{cr}) and crispness work (W_c). The effects of WPI and MC on F_{cr} and W_c are shown in Fig. 5.

F_{cr} is a measure of the average force that is required to crush the foam structure, and is similar to the sensory parameter of hardness that was defined as the force required for completely crushing the sample with the molars. For the most part, F_{cr} decreased as WPI increased, although the differences were not always significant (Fig. 5A). This trend was similar to that for hardness with WPI. For all extrudates with WPI, MC did not have a definite or significant effect on F_{cr}. For the control extrudates (0% WPI), F_{cr} was 59% lower for 27% MC as compared to 23% MC.

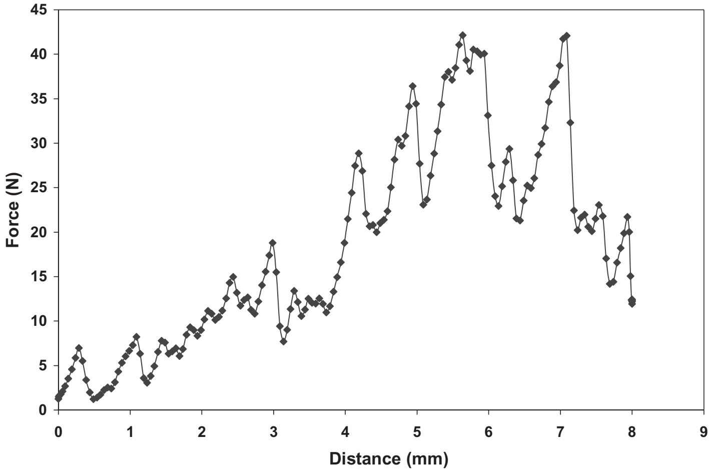


FIG. 4. TYPICAL COMPRESSIVE FORCE–DEFORMATION CURVE OF EXTRUDATE PROCESSED AT 23% IN-BARREL MOISTURE CONTENT AND 18% WHEY PROTEIN ISOLATE

W_c is the average area under the force–deformation curve per fracture peak, and is a measure of the average work required to fracture one cell or a group of cells simultaneously. W_c is similar to the sensory parameter of fracturability that was defined as the force with which the sample fractures on the first bite down with the molars. As shown in Fig. 5B, the effects of MC and WPI on W_c are very similar to what was observed for F_{cr}. As WPI increased, a reduction in W_c was observed in general. For all extrudates with WPI, in-barrel MC did not have a definite or significant effect on W_c. For the control extrudates (0% WPI), W_c was 79% lower for 27% MC as compared to 23% MC.

F_{cr} and W_c were highly correlated with sensory hardness and fracturability, respectively. Pearson's correlation coefficient (r) values for F_{cr} and hardness were 0.998 and 0.926, while those for W_c and fracturability were 0.841 and 0.850, at 23 and 27% MC, respectively. The trends for instrumental mechanical parameters (F_{cr} and W_c) with respect to MC were in contrast with those for sensory properties (hardness and fracturability). In most cases, the mechanical parameters for products processed at 23% MC were either not significantly different or were higher in magnitude than those for 27% MC. The latter was especially true for samples without WPI. This can be explained by the different fracture patterns of samples processed at the two MC levels. Because of their hardness, extrudates processed at 27% MC and 0% WPI fractured into several pieces at a relatively small travel distance for the probe.

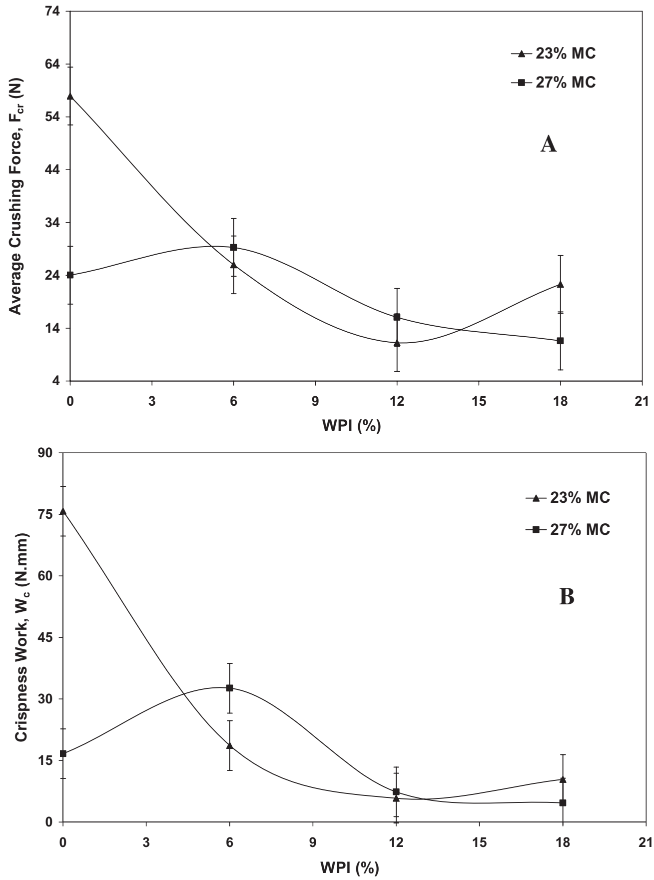


FIG. 5. EFFECT OF WHEY PROTEIN ISOLATE (WPI) CONTENT AND IN-BARREL MOISTURE CONTENT (MC) ON EXTRUDATE MECHANICAL PROPERTIES

(A) Average crushing force (F_{cr}) and (B) crispness work (W_c). The error bars represent the least significant difference at $P = 0.05$. Overlap of bars signifies that means are not significantly different.

This resulted in a few major peaks on the force–deformation curve followed by zero resistance as the probe traveled to the set testing distance, leading to lower F_{cr} and W_c because of a smaller area under the curve. Extrudates with 0% WPI processed at 23% MC fractured into relatively less number of pieces, and the TA-XT2 probe continued crushing the pieces until the set distance was reached. This resulted in more peaks with relatively small magnitudes, but higher F_{cr} and W_c were obtained because of a greater area under the curve. Extrudates with 6, 12 and 18% WPI processed at both 23 and 27% MC showed a more gradual fracture pattern because of their relatively lower hardness.

These samples did not break into separate pieces, although their inner cell structure broke down as the extrudates were compressed.

Acoustic Properties

Voice Recognition Signal Processing. Samples from various treatments clearly had different acoustic signatures during crushing. As an example, the amplitude–time signals and frequency spectrograms of two high MC samples with 0 and 18% WPI are shown in Fig. 6. The spectrogram of 0% WPI sample (Fig. 6A) had a few large amplitude spikes of low to high frequencies, separated by relatively large time intervals of low amplitude and low frequency signals or no sound. In contrast, the sample at 18% WPI (Fig. 6B) had many high-frequency spikes of medium amplitude, with little time between them. The vibrations of fractured elements are affected by their size, shape and also the material properties of the solid material (Luyten and Van Vliet 2006). The greater stiffness of structural elements in the first treatment, because of thicker cell walls (75% higher t_{wall}) and the absence of WPI in the matrix, probably led to acoustic emissions with higher amplitude and frequency. The number of acoustic events is a function of the cell number density and fracture pattern of the treatments (Luyten and Van Vliet 2006). For the sample with 0% WPI, N was 77% lower, and this sample also fractured abruptly into a few pieces because of its hardness, leading to relatively less numbers of spikes in the spectrogram. On the other hand, the 18% WPI sample had higher N, and it fractured gradually, leading to numerous spectrogram peaks.

The stepwise discriminant analysis picked only two signal magnitude histogram features to distinguish samples with different WPI contents. Interestingly, these histogram values were both from the sub-band centered at 84 kHz. One feature was the number of data points with a low signal magnitude (between –8.5 and –9.5 dB), and the other feature was the number of data points with a moderately high magnitude (between –4.5 and –5.5 dB). Two typical 84 kHz sub-band histograms from 0 and 18% WPI samples extruded at high MC are shown in Fig. 7. The two low WPI sets (0 and 6%) were well distinguished by the count of data points having low signal magnitude in 84 kHz sub-band. The sample sets having WPI of 6, 12 and 18% were well distinguished by using the count of high signal magnitude data points in the same sub-band, with greater amount of WPI corresponding with higher signal strength. The overall predictive performance based on these features was very good, as shown in Table 3. Only 4 out of 120 samples (error rate of 3.3%) were incorrectly classified in the case of high MC treatments, while 9 out of 120 (error rate of 7.5%) were incorrectly classified for low MC treatments. In most instances of incorrect classification, the predicted WPI was at the next level from the actual WPI.

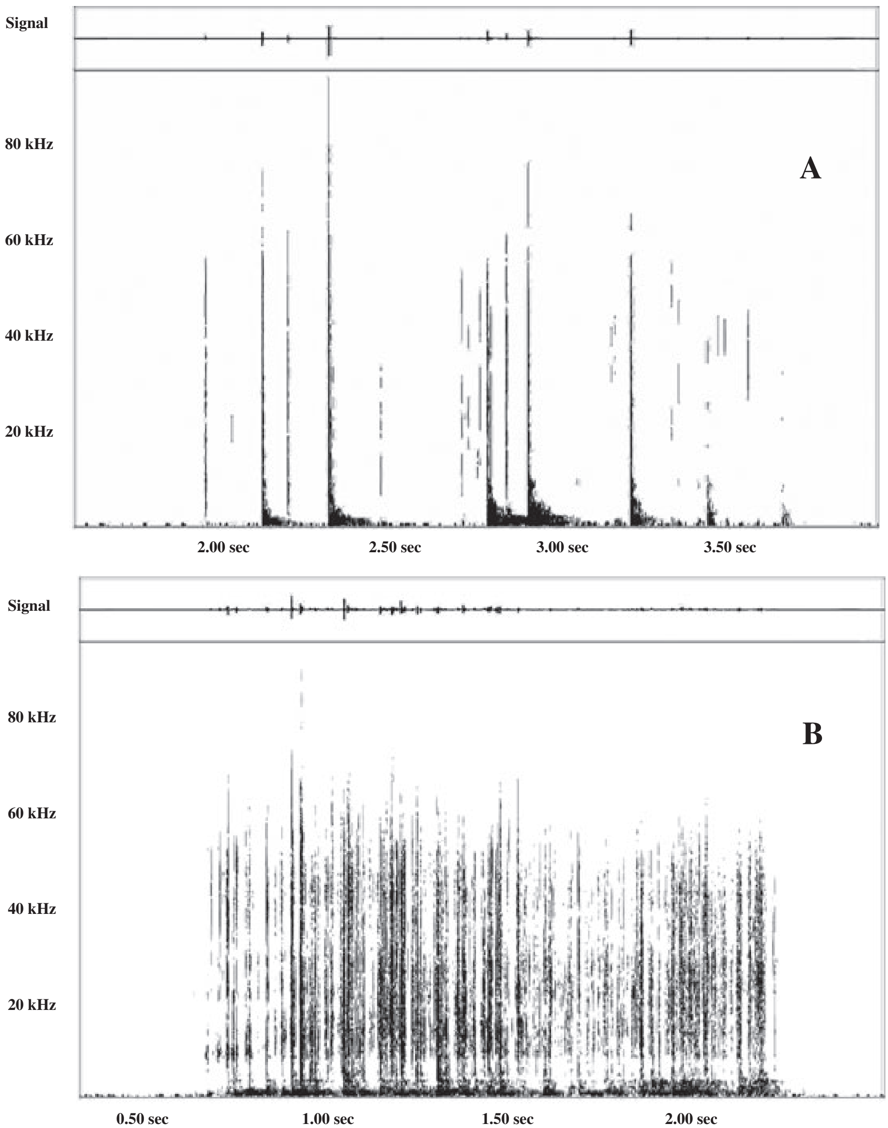


FIG. 6. TYPICAL ACOUSTIC SIGNALS AND CORRESPONDING FREQUENCY SPECTROGRAMS OF EXTRUDATES
(A) 0% Whey protein isolate (WPI) and 27% moisture content (MC), and (B) 18% WPI and 27% MC.

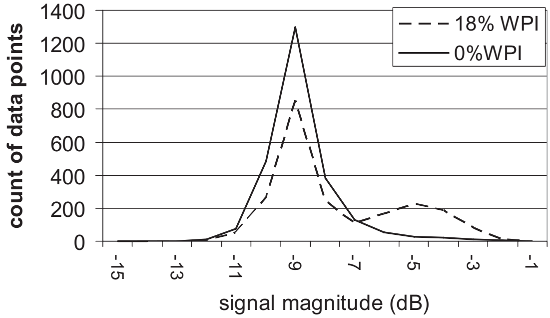


FIG. 7. VOICE RECOGNITION METHOD
Signal magnitude histograms in the 84 kHz band of the frequency spectrogram are shown for 27% moisture content extrudates with 0 and 18% whey protein isolate (WPI). Note that the two distinguishing features used to classify samples based on their acoustic emissions were the histogram bins centered at –9 and –5 dB.

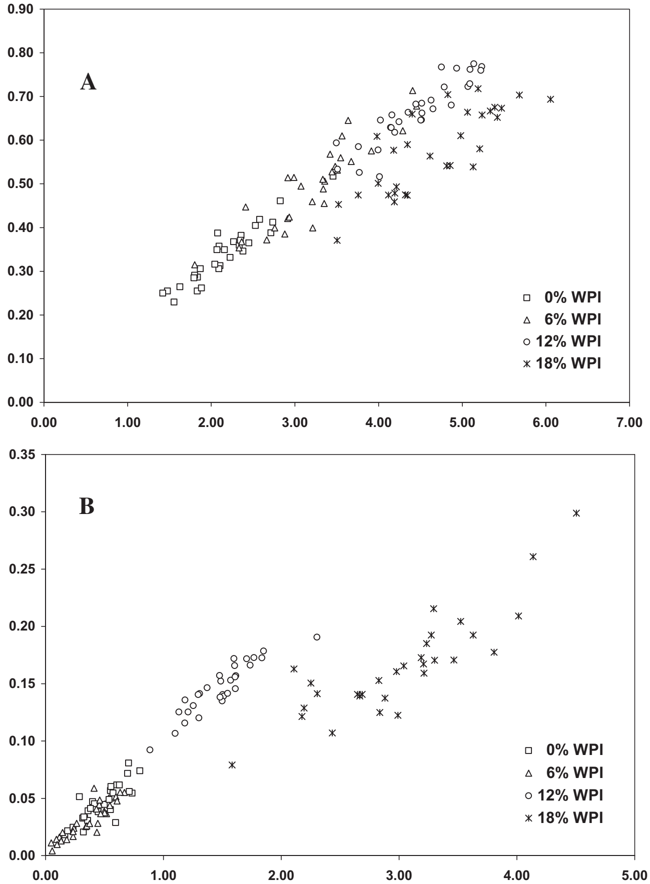
TABLE 3.
ACTUAL WHEY PROTEIN ISOLATE (WPI) VERSUS PREDICTED WPI ACCURACY FOR SAMPLES AT 23 AND 27% IN-BARREL MOISTURE CONTENT (MC) BY USING VOICE RECOGNITION METHOD OF SIGNAL PROCESSING

Actual WPI	Predicted WPI				Total
	0	6	12	18	
	23% In-barrel MC				
0	30	0	0	0	30
6	0	29	0	1	30
12	0	2	24	4	30
18	0	1	1	28	30
Total	30	32	25	33	120
	27% In-barrel MC				
0	29	1	0	0	30
6	0	30	0	0	30
12	0	2	28	0	30
18	0	0	1	29	30
Total	29	33	29	29	120

Interestingly, the two acoustic features used in the discriminant analysis were from the ultrasonic frequency range. Although ultrasonic signals have been used to study fracture behavior of nonfood structural materials, there is a dearth of literature on studies involving acoustic signals from brittle, crispy foods outside the audible region (20 Hz to 20 kHz) (Luyten and Van Vliet

2006). Ultrasound signals travel well through solids, and can actually be transmitted to the cochlea (inner ear) if fed directly into the skull bone, as is the case during chewing of crispy foods.

Time-domain Signal Processing. Figure 8 shows the time-domain acoustic signal distributions, which are plots of percentage of data points with high signal amplitude and high slope (*y*-axis) versus that of data points with low signal amplitude and low slope (*x*-axis). For extrudates processed at 23%



X-axis: % of data points w/ low slope and low amplitude
Y-axis: % of data points w/ high slope and high amplitude

FIG. 8. TIME-DOMAIN ACOUSTIC SIGNAL DISTRIBUTIONS FOR EXTRUDATES PROCESSED AT (A) 23% AND (B) 27% IN-BARREL MOISTURE CONTENT
WPI, whey protein isolate.

MC, the distribution of acoustic signal data for 12 and 18% WPI is somewhat separated by the number of data points having a high slope and signal amplitude (Fig. 8A). The 18% WPI samples, with thinner cell walls and solid material of less stiffness, emitted acoustic signals with reduced high slope and high amplitude content as compared to 12% WPI samples. For the same reason, as WPI content increased from 0 to 12%, the acoustic signals had greater low amplitude and low slope content, shifting distributions to the right. Hardness ratings for 23% MC had a similar trend as the time-domain signals, with WPI content having a significant effect in the 0–12% range.

For extrudates processed at 27% MC, the distributions for all treatments shifted downward with reduced high slope and high amplitude content, as compared to 23% MC (Fig. 8B). This was contrary to expectations, as the former had greater average t_{wall} and stiffer solid matrices, and was likely because of the effect of aging associated with higher process moisture. It has been reported previously in the case of extruded flat breads that aging leads to dampening of acoustic signals and lesser sound energy or amplitude, although the frequency spectrum remains unchanged (Luyten and Van Vliet 2006). In this study, all treatments were dried under the same time and temperature conditions after extrusion, but samples processed at higher MC had higher final moisture. As detailed earlier, prior to mechanical–acoustic and sensory testing, samples were equilibrated to the same moisture level in controlled humidity conditions. However, the intervening time was probably long enough for aging to proceed in the higher MC samples.

For extrudates processed at 27% MC, the distributions for 0 and 6% WPI overlapped and were indistinguishable from each other (Fig. 8B). Although 6% WPI samples had a weaker solid matrix as compared to 0% WPI, the thicker cell walls for the former could have offset that. As expected, the acoustic signals had greater low amplitude and low slope content as WPI level increased from 6 to 18%, shifting distributions to the right. Hardness ratings from 27% MC also had a similar trend as the time-domain signals, with WPI level having a significant effect in the 6–18% range, but no significant difference between 0 and 6% WPI.

CONCLUSION

Extrusion processing of cornstarch at different in-barrel MCs, in combination with varying levels of WPI, resulted in brittle, cellular foams having a wide range of microstructures and textures. Physical and microstructural properties of extrudates were determined, and their mechanical–acoustic signals during instrumental crushing and sensory properties were also characterized. High correlations ($r > 0.80$) were observed between mechanical and sensory properties of the extrudates. It was also clear that the acoustic signatures of the brittle foams were closely related to their microstructural, mechanical and sensory properties. Voice recognition methods, based on discriminant analysis of frequency spectrograms, were able to correctly predict the WPI levels of extrudates with high accuracy (92–97%). Time-domain signal analysis was also very useful in distinguishing samples with different hardness ratings. The mechanical–acoustic techniques outlined in this study can be applied to most crispy foods that fracture and emit sound while being crushed, and can be a useful tool for product evaluation and development. These techniques need not be limited only to food systems, as properties of any rigid, fracturable material can be characterized using a unique set of mechanical–acoustic signals.

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