Acoustic settings combination as a sensory crispness indicator of dry crispy food

Running title: Acoustic analysis as crispness indicator

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Abstract

Crispness is a critical attribute of quality for crispy products, which can be evaluated through both instrumental and sensory analyses. The aim of the study was to identify the best combination of settings of a device coupled to a texture analyzer for acoustic analysis in order to find strong correlations with the sensory texture. For that, nine commercial food products were submitted to force and acoustic (Acoustic Envelope Detector) analyses, using two settings for acoustic data acquisition (gain 1 and gain 4), and two settings for acoustic data management (threshold 0.5 and 2.5). The products were also evaluated using texture descriptive sensory analysis. The gain changing from 1 to 4 (enhancing the test sensitivity) increased the number of acoustic peaks and reduced the sound pressure level. Changing the threshold from 0.5 to 2.5 (reducing the interference of background noise on the acquired data) reduced the number of acoustic peaks. The correlation between the instrumental and the sensory analysis showed gain 1 as the most adequate acoustic setting to obtain the acoustic parameters of products with different crispness intensities. Moreover, threshold 2.5 is the most appropriate for acoustic data collection. Therefore, sensory attributes and instrumental properties strong correlations indicate that texture analyzer in combination with the acoustic envelope detector is a good instrument to mimic human mastication and texture perception, through both force and sound stimuli. This study about dry crisp food may contribute to the literature, food industry and also to future studies about wet crispy and crunchy foods.

Practical applications

Texture, especially crispness, has great importance to crispy products. Although several studies in the literature about acoustic properties analysis in food products exist, differences in the analysis protocols used hamper the discussion of results. Therefore, establishing test conditions for evaluation of acoustic texture analysis of a wide variety of food products with

39 different physical structures, that are correlated with sensory perception of crispness, will
40 allow the convergence of data in future studies, providing relevant information to the
41 scientific area and food industry, and making possible to other authors to study the most
42 appropriate acoustic test conditions applied to other “noisy” food, as wet crispy food and
43 crunchy food.

44 **Keywords:** texture analyzer, Acoustic Envelope Detector – AED, instrumental force, sound
45 emission, correlation.

46

1 Introduction

The consumption of food involves different stages of texture perception, beginning with visual contact and manipulation with the hands, followed by chewing forces and, at the same time, by the emission of sound waves from the rupture of its structure, which are perceived through the ears by air conduction or bone conduction through the mandible (Duizer, 2001; Saeleaw & Schleining, 2011; Szczesniak, 2002). This sound perception may be called crispness or crunchiness, according to sample water activity, mechanical and acoustic properties. Sorting by the water activity, crispy food may be wet or dry crispy food, the first type, as fruits and vegetables, generates sound by the rupture of the cells structure and water content release; in the second case, which are products as potato chips, crackers and popcorn, the water is substitute by air whose release generates the sound energy emission. Mechanically, crispy foods have a more fragile structure than the crunchy ones; and acoustically, crispy foods release high-frequency sounds while the crunchy ones produce sounds of low frequency (Tunick et al., 2013). Moreover, crispness is a critical attribute of the quality of crispy foods, therefore it must be a target for evaluation using instrumental and sensory analyses.

During the instrumental analysis of crispy products with a texture analyzer, the probe compresses the product for rupturing the food structure, and a graph of force (Newton) *versus* time (seconds) is plotted. At the same time, an acoustic envelope detector may be combined with the texture analyzer, to detect the sound waves, convert into electric signals, which are transmitted to a computer and a texture analyzer software plot it in one graph of sound pressure level (decibels) *versus* time (seconds) (Beranek & Mellow, 2012; Taniwaki & Kohyama, 2012).

The acoustic envelope detector consists of a microphone pre-amplifier, a variable gain amplifier, a high pass filter of 1kHz (value for calibration) and whose has a default setting

corner frequency of 3kHz, changeable on the texture analyzer software, this filter neutralizes the background and the texture analyzer noises (Stable Micro Systems, 2012). Different settings may be used for data acquisition and data management for the acoustic curves, which enables variation in the sensitivity of the analysis.

The setting ‘gain’ of the amplifier, which is a ratio between the input voltage (voltage received from the microphone by the amplifier) and the output voltage (voltage that goes from the amplifier to the computer), is read by the texture analyzer software. It has steps of 6 dB each and may be changed in a range from zero to four, where the first is the calibration value, and the last corresponds to a ratio of 24 dB and is the most sensitive detection (Grosse & Ohtsu, 2008).

The setting ‘threshold’ is equivalent to a voltage level on an electronic comparator. The signals which exceed the voltage threshold are detected as acoustic event signals (Grosse & Ohtsu, 2008). This setting discards, during data management, detected sounds under the chosen threshold value (in decibels), eliminating low peaks from the background noise (Chick, 1998).

Moreover, studies developed to identify the best position (distance and angle) of the microphone in relation to the sample, for generating the best acoustic energy measurement, determined that both must be as low as possible (Chen, Karlsson, & Povey, 2005; Castro-Prada, Luyten, Lichtendonk, Hamer, & Van Vliet, 2007). Although the texture analyzer is important, the instrumental analyses cannot faithfully substitute the sensory analysis because texture is a complex sensory attribute (Mosca & Chen, 2017), involving different variables such as the amount of saliva, the temperature of the mouth, the force applied during chewing and the number of chewing cycles (Bourne & Szczesniak, 2003). However, both analyses may be used together. Indeed, as stated by Szczesniak (1987), correlations between sensory and instrumental texture measurements result in: (1) finding instruments to measure quality

control of food in industries; (2) predicting consumer response, such as the degree of liking and the overall acceptance of a new product; (3) understanding what is being sensed and perceived in the mouth during the sensory assessment of texture; (4) improving or optimizing instrumental methods to complement the sensory evaluation. Moreover, if a correct instrumental settings combination is applied and correlation between sensory and instrumental analyses is carried out, it is possible to ensure more accurate texture measurements (Chen & Opara, 2013).

There are several studies in the literature about acoustic properties analysis in food products (Jakubczyk, Gondek, & Tryzno, 2017; Çarşamba, Duerrschmid, & Schleining, 2018). However, differences in the analysis protocols used were found, which hampers discussion of results reported in the literature. Divergences in acoustic analysis protocols are dependent on the food product evaluated, because the choice of the probe used during the analysis must be appropriate to that specific food. However, studies that propose to establish a scale of crispy products, as performed by Paula & Conti-Silva (2014) and Conti-Silva, Ichiba, Silveira, Albano, & Nicoletti (2018) for determining which settings of instrumental acoustic analysis is more adequate to correlate with sensory perception of texture, were not found. Thus, the purpose of this study is to establish test conditions for the acoustic texture analysis that will allow for convergence of data in future studies, using a wide variety of food products with different physical structures. The specific objective is to identify the best combination of settings for acoustic analysis in order to show any strong correlations with the sensory texture.

2 Material and methods

2.1 Material

Based on an initial scanning, nine different products (Fig. 1), purchased from local market (Valencia, Spain) were included in the study, which presented differences in crispness:

corn biscuit, crispy corn, cornflakes, cream cracker biscuit, *mariñera* biscuit, potato chips, extruded snack ball, *tapas* biscuit and toast.

2.2 Instrumental analysis of force and acoustic properties

The compression force of the dry crispy foods was analyzed in a TA.XTplus/30 texture analyzer (Stable Micro Systems, Godalming, UK) with a 25 kg load cell. After some initial tests with different probes and bases, the Volodkevich Bite Jaws probe – HDP/VB (Fig. 2A) and two holed bases, a circular support insert with a support ring (Fig. 2B) and a holed plate with a 9 mm fixing hole (Fig. 2C), were chosen. Being that all of samples were placed on the first base (Fig. 2B), except for the crispy corn and the extruded snack ball, that were placed on the second one (Fig. 2C), for better analysis performance. The test settings were: pre-test speed - 2 mm/s, test speed - 1 mm/s, post-test speed - 10 mm/s, auto trigger force - 5 g, travel distance of the probe - 7 mm. The data acquisition rate was 500 points per second (pps) and the threshold was 0.05 N.

The acoustic signals generated by the breakdown of the foods were analyzed using an Acoustic Envelope Detector - AED (Stable Micro Systems, Godalming, Surrey, UK) coupled to the texture analyzer. A free-field 8-mm diameter microphone (Brüel & Kjær, Nærum, Denmark) (Fig. 2D), calibrated using the Type 4231 acoustic calibrator (94 and 114 dB sound pressure level, 1000 Hz), was positioned 4 cm distant from the sample and at an angle of 0° in relation to the base (Fig. 2D). The acoustic setting ‘gain’ was set at two levels: 1 (6 dB) and 4 (24 dB). Ambient and mechanical noises were filtered by a high pass filter (signal button) of 1.0 kHz, and the sound emitted by the texture analyzer was neutralized by a corner envelope frequency of 3.125 kHz.

Data was obtained through the Exponent 32 software, at a data acquisition rate of 500 points per second (pps). All tests were performed in a laboratory with no special

soundproofing, with a relative humidity of $25 \pm 1\%$ and a temperature of $22 \pm 2^\circ\text{C}$. Force (N) *versus* time (s) and acoustic - sound pressure level (dB) *versus* time (s) curves were simultaneously plotted; the information extracted from each type of curve is described in Table 1. Fifteen replicates of each food were tested at each acoustic setting: “gain 1” and “gain 4”. At the data analysis, two different thresholds, 0.5 dB and 2.5 dB, were applied.

2.3 Sensory texture profile

The sensory texture profile was performed according to Stone, Bleibaum, & Thomas (2012) with adaptations. Ten panelists were recruited from students and employees of the Institute of Agrochemical and Food Technology (IATA), Valencia, Spain, who frequently participate in sensory analyses. The crispness attributes were defined in a collective meeting with the panelists by using a previous list of four possible texture attributes and their respective definitions. Three samples (crispy corn, potato chips, and extruded snack ball) were presented to the panelists in order to determine the attributes (Table 1). The ‘crispness’ was excluded from the previous list because the attributes ‘sound intensity’ and ‘sound duration’ were understood as similar by the panelists, and enough for evaluating the acoustic properties of the foods.

The training stage was performed in three collective meetings and five individual sessions, when crispy corn, cream cracker biscuit, potato chips, extruded snack ball and *tapas* biscuit samples, in combinations of three samples per session, were presented to the panelists. During this stage, the sensory panel considered the cream cracker biscuit and crispy corn samples as having, respectively, the lowest and the highest intensities for all the attributes in an unstructured linear intensity scale of 100 mm in length.

In the selection stage, the panelists evaluated the same samples as evaluated in the training stage, in two repetitions, and were selected according to their discriminative capacity

($p_{\text{sample}} \leq 0.30$), reproducibility capacity ($p_{\text{repetition}} > 0.05$) and capacity for consensus with the sensory panel for each attribute (*Pearson* correlation coefficient ≥ 0.80 , $p \leq 0.05$). All panelists were selected for the crispy products texture evaluation.

The nine crispy products were evaluated by sensory panel in two repetitions, in two sessions of four samples, and two sessions of five samples each, using the unstructured linear intensity scale of 100 mm in length. The analysis was carried out in individual booths, at 22 ± 2 °C, under white light. The samples were coded with three-digit random numbers, with a monadic and randomized presentation. The CompuSense Cloud software (CompuSense Inc., Guelph, Canada) was used for data analysis.

2.4 Statistical analysis

The results of the force characteristics ($n = 30$) were evaluated through analysis of variance, followed by the Tukey test. Results of the acoustic properties ($n = 15$) were also evaluated through analysis of variance, followed by the Tukey test: one test comparing all the nine food products and another test comparing the combination of conditions between different gains and thresholds (see Section 3.1). Results of the sensory attributes ($n = 20$), were evaluated through two-way analysis of variance, considering ‘sample’ and ‘panelist’ as factors, as well as the interaction between the factors, followed by the Tukey test on the samples. The means of instrumental and sensory data were correlated through Pearson correlation, and the correlations were considered strong when coefficient was ≤ -0.70 or ≥ 0.70 , as also considered by Paula & Conti-Silva (2014) and Conti-Silva, Ichiba, Silveira, Albano, & Nicoletti (2018). The IBM SPSS Statistics for Windows, (version 20.0) software (IBM Corp., Armonk, USA) was used and all statistical tests were performed at a 0.05 significance level.

The Principal Component Analysis (PCA) was also applied for correlating means of

instrumental and sensory data. The PCA is a multivariate method which reduces the dimensionality of a large number of interrelated variables (original variables, i.e. instrumental and sensory data), transforming it into a new set of variables (principal components) that are not correlated. Thus, the maximum as possible of the original variation is retained (Ballabio, Consonni, & Costa, 2012; Jolliffe, 2002). PCA was applied to centered data using the STATISTICA version 12 software (StatSoft Inc., Tulsa, USA), and variables with factor coordinates based on correlations ≤ -0.7 or ≥ 0.7 were considered relevant for the result discussion.

3 Results and discussion

3.1 Force and acoustic properties

Typical graphs obtained during texture analysis, in this case for the *marañera* biscuit, are shown in Fig. 3. Force and sound pressure level (SPL) *versus* time curves at gain 1 (Fig. 3A) and at gain 4 (Fig. 3B) are presented in order to make a comparison and identify the differences between the measurement at gain 1 and at gain 4. Both graphs show the moment when the ‘major food structure breakdown’ occurs, detected through the black line related to the force (scale on the left) and the moment when the relevant acoustic emission happens (gray line and scale on the right). Therefore, the data acquisition of force and acoustic peaks came from the region located between the beginning of the analysis (time 0 s) and the time at the end of the ‘major food structure breakdown’, i.e., at the ‘main force decay’ (Fig. 3) (Salvador, Varela, Sanz, & Fiszman, 2009). For the extruded snack ball, the total analysis time was considered for data acquisition because the probe did not totally rupture the sample.

A visual comparison of the acoustic curves shows that the change from gain 1 (detection at 6 dB, Fig. 3A) to gain 4 (detection at 24 dB, Fig. 3B) produces a greater number of sound peaks per second, that may be seen as the higher agglomeration of gray peaks in Fig.

3B. The lower acoustic baseline at around 42 dB at gain 4 indicates a higher sensitivity of the test in relation to gain 1 with a baseline around 53 dB. However, the acoustic baseline at gain 4 is less regular than at gain 1, which means that background noise is being detected during the sample analysis. This detection can be suppressed by the use of higher threshold values, such as 2.5 dB, which discard sound peaks related to the background noise. Two different thresholds, 0.5 dB and 2.5 dB, were applied in order to compare the effect of background noise on the linearity of the baseline and, consequently, on the reduction of the background noise interference on the data (see Section 2.2).

Instrumental tests discriminated the foods both for force and for acoustic properties, indicating that samples are different regarding these variables. It is of great importance to take into account that the nine evaluated products are very different in shape and size, and this factor may interfere in the results. Aiming to neutralize these differences, the travel distance of the probe was standardized in 7 mm for all samples, and the probe chosen was the Volodkevick Bite Jaws (HDP/VB), a cutting probe which does not depend on the sample shape. The extruded snack ball showed statistically the highest number of force peaks (Table 2), which is related to the fracturability of the sample, i.e., to the breaking of the sample macrostructure (Bourne, Kenny, & Barnard, 1978). Crispy products are fracturable, as may be seen by the number of force peaks for all the samples in Table 2, but the extruded snack ball is an expanded product obtained through thermoplastic extrusion, having air vacuoles, being very fracturable (Paula & Conti-Silva, 2014) and so explaining the higher number of force peaks. However, this sample had an intermediate average maximum force, while crispy corn statistically showed the highest force ($p \leq 0.05$). Crispy corn is fried corn grain, having a compact macrostructure, leading to a hard product (high average maximum force) but low fracturability (low number of peaks).

In relation to the acoustic properties (Table 3), the extruded snack ball statistically

showed the highest number of acoustic peaks ($p \leq 0.05$), although it had a sound pressure level as high as those for the other samples ($p > 0.05$), while the crispy corn had one of the lowest number of acoustic peaks but one of the highest sound pressure levels ($p \leq 0.05$) along with the extruded snack ball. This happened because the number of acoustic peaks was statistically discriminated ($p \leq 0.05$) among almost all the samples, while the sound pressure level was less discriminated. Cornflakes statistically ($p \leq 0.05$) showed the lowest number of force peaks and one of the lowest averages of maximum force (Table 2), although they had one of the highest sound pressure levels at gain 1 (Table 3), indicating there is no relationship between force properties and sound pressure level for this product. Moreover, the composition of the food plays an important role in the texture, since cornflakes are products with low water activity, a characteristic that results in large acoustic energy emission (Gondek & Lewicki, 2006).

The change from gain 1 to gain 4, at threshold 0.5 dB (Table 3), did not alter the number of acoustic peaks for most samples, while it enhanced the number of acoustic peaks for most samples at threshold 2.5 dB, as expected, due to the higher sensitivity of the test. These observations permit to infer that the lower threshold negatively influenced the sensitivity of gain 4, annulling its effect. However, the sound pressure level (the ‘average of the ten maximum acoustic peak values’) (Table 1), significantly decreased ($p \leq 0.05$) for all foods from gain 1 to gain 4 at the same threshold (Table 3). This seems contradictory because, by increasing the test sensitivity (from gain 1 to gain 4), more intense peaks would be expected.

Changing the threshold from 0.5 to 2.5 dB, at the same gain, resulted, in a significantly lower number of peaks ($p \leq 0.05$) for all foods, reducing the interference of background noise on the acquired data (Table 3), which is desirable during the analysis. Therefore, although changes in the number of peaks occur, their intensity does not change because the increase in

the threshold only discards sound peaks related to background noise.

3.2 Sensory texture

The sensory panel correctly used the extension of the unstructured scale, since values for all the attributes were found from 0 to 10 (Table 4). This indicates that the cream cracker biscuit and crispy corn samples, respectively considered as having the lowest and the highest intensities for all the attributes, were well defined and used by the sensory panel. Indeed, the sensory panel was capable of statistically discriminating the samples ($p \leq 0.05$) for the three texture attributes (Table 4).

The crispy corn presented the highest hardness, sound intensity and sound duration, while cream cracker biscuit presented one of the lowest intensities for these characteristics. This was expected, since the panelists were told to consider the cream cracker biscuit and the crispy corn as the extremes of minimum and maximum respectively for all the attributes in an unstructured linear intensity scale of 100 mm in length (see Section 2.3). *Mariñera* biscuit and toast also showed high intensity of the texture characteristics. The cornflakes and potato chips, although having presented one of the lowest intensities of hardness, along with the cream cracker biscuit, had intensities of sound and sound duration that were higher than the cream cracker biscuit, which corroborates the instrumental results, in which samples do not have to be very hard to be crispy and to emit sound.

Similar results were found by Jakubczyk et al. (2017), since a co-extruded snack with milk cream filling presented higher values of sound loudness (which corresponds to sound intensity in this study) and duration of sound but low hardness, also indicating that the sample was crispy but not hard. Moreover, pea-protein-fortified extruded rice snacks with higher amounts of pea protein were described by trained panelists as harder samples but less crispy, while snacks with lower quantities of pea protein were described as crispier and less hard

(Philipp, Buckow, Silcock, & Oey, 2017). Both studies corroborate the present study results, showing that there is not a direct relationship between hardness and crispiness for the same product, i.e. a food product can be crispy without being hard.

3.3 Correlation between instrumental and sensory analyses

A Pearson correlation analysis (Table 5) and a principal component analysis (Fig. 4) were used to determine the combination setting analysis that resulted in the most similarity to the sensory texture characteristics perceived by the panelists, aiming complementing and corroborating the results.

Coefficients (Table 5) showed strong and significant correlations ($r \geq 0.70$, $p \leq 0.05$) between the sensory hardness and the average of maximum force; between the number of force peaks and the number of acoustic peaks in the four tested combinations of settings; between all the combinations of number of acoustic peaks tested, except for the number of acoustic peaks measured at gain 4 and applying the threshold 2.5; and between the four combinations of sound pressure level tested. The sensory hardness may be mimic by the instrumental force analysis, as showed by Paula & Conti-Silva (2014) studying expanded snacks, as well as that the number of force peaks and the number of acoustic peaks are directly proportional.

The number of acoustic peaks was not correlated with any other variable, reason why the PCA was applied. Principal component 1 (Fig. 4) explained 41.8% of the data variation, while component 2 explained 35.7%, totaling 77.5% of the total data variation.

Principal component 1 was explained by variables that are positively correlated ($r \geq 0.70$, $p \leq 0.05$), namely the acoustic properties ‘number of acoustic peaks’ under all adopted conditions (different gains and thresholds) and the sound pressure level at gain 4 and threshold 2.5, as well as the ‘number of force peaks’ force variable (Fig. 4). The strong

positive correlations between the number of force peaks and the number of acoustic peaks, as evidenced also through the Pearson correlation analysis, indicate that the rupture of the product generated directly proportional numbers of force peaks and acoustic peaks, validating that the data from AED for sound wave detection was acquired at the same instant as the product rupture. Indeed, the energy release at the product breakdown moment is dissipated as sound energy and occurs in the vicinity of the major rupture point of the product (Chen et al., 2005; Taniwaki & Kohyama, 2012). Therefore, the numbers of acoustic and force peaks correlate positively ($r \geq 0.70$, $p \leq 0.05$) due to their energy release/dissipation relationship at the moment of product fracture. Çarşamba et al. (2018), evaluating wafer products from nine different commercial brands through two probes (three-point bending and craft knife adapter) with simultaneous measurement of acoustic properties through AED, also found strong positive correlations between the number of force and acoustic peaks for both probes.

Principal component 2 (Fig. 4) was explained by the following positively correlated ($r \geq 0.70$, $p \leq 0.05$) variables: all the sensory attributes (hardness, sound intensity and sound duration), along with the acoustic variable sound pressure level obtained at gain 1 with both thresholds (0.5 and 2.5), different from the evidenced through the Pearson correlation analysis, in which just hardness correlated strongly with the average of maximum force. Therefore, acoustic analysis at gain 1, independently of the threshold, must be used to obtain acoustic results that represent the sensory attributes of acoustic texture. The high correlation between the sensory characteristics of sound and the sound pressure level at gain 1 may have been caused by the compatibility between human ability to perceive the sound intensity and duration and the test sensitivity at this acoustic setting. Thus, not only the sensory characteristics related to sound (sound intensity and sound duration) are correlated with the sound pressure level, but also hardness, which indicates that food hardness may be a sensory crispness indicator. These strong and positive correlations between sensory attributes and

instrumental properties indicates that, independently of the setting combination tested, the instrumental analysis adequately mimics the human texture perception of the dry crispy food adopted in this study. Strong positive correlations between sensory attributes and number of force peaks or number of acoustic peaks were found by other authors (Saeleaw, Dürschmid, & Schleining, 2012; Varela, Chen, Fiszman, & Povey, 2006). However, these are studies focused on only one type of product (rye expanded snack and roasted almonds, respectively), while the present study considers a wide variety of food products, with different physical structures.

Curiously, the average of maximum force and the sound pressure level were neither correlated nor significant ($r < 0.70$, $p > 0.05$), as well as in the study of Varela, Chen, Fiszman, & Povey (2006) about roasted almonds. However, although there is no significant correlation between the average of maximum force and the sound pressure level, the number of force peaks and the number of acoustic peaks were positively and significantly correlated, demonstrating that there is correlation between force and acoustic instrumental parameters.

4. Conclusions

Instrumental analyses of force and acoustic detection, as well as the sensory texture analysis, effectively discriminated the samples used in this study. Instrumental and sensory results showed that samples with both high and low hardness produce sound and are crispy. The gain changing from 1 to 4 (enhancing the test sensitivity) increased the number of acoustic peaks at threshold 2.5, and reduced the sound pressure level in general. The threshold changing from 0.5 to 2.5 (reducing the interference of background noise on the data acquisition) reduced the number of acoustic peaks. The correlation between instrumental and sensory analysis allowed us to define gain 1 as the most adequate acoustic condition for obtaining the acoustic parameters of products with different crispness intensity. Moreover,

threshold 2.5 is the most appropriate to eliminate small sound peaks from the background noise and guarantee an analysis more accurate. Therefore, the correlations between the sensory attributes and instrumental properties, force and acoustic, indicate that the combination of the texture analyzer and the acoustic envelope detector appropriate mimics the human mastication process and texture perception, for both force and sound stimuli. The present study investigated the adequate acoustic settings combination settings to analyze dry crispy food, similar future studies may study it to wet crispy food analysis, this is, fruit and vegetables, and also to crunchy food as nut and almonds, in order to establish specific conditions of instrumental acoustic analysis for each type of 'noisy' food.

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Conflict of interest statement

The authors declare that they do not have any conflict of interest.

Ethical statement

For performing sensory analysis, all panelists were informed of the procedure and gave their consent by signing an internal declaration from the sensory laboratory.

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461

462 **Table 1:** Force characteristics and acoustic properties obtained from the texture analyzer for
 463 the dry crispy foods and sensory attributes related to the sensory analysis.

<i>Force characteristics</i>	<i>Definition</i>
Number of force peaks	Number of positive force peaks, considering threshold 0.05 N
Average of maximum force	Average of the three maximum force peak values
<i>Acoustic properties</i>	<i>Definition</i>
Number of acoustic peaks	Number of positive acoustic peaks, considering thresholds 0.5 dB and 2.5 dB
Sound pressure level	Average of the ten maximum acoustic peak values
<i>Sensory attributes</i>	<i>Definition</i>
Hardness	Force needed to bite the product with the incisor teeth
Sound intensity	Intensity of the sound made by the product at the first bite
Sound duration	Necessary chewing time for the product to stop making noise

464

465 **Table 2:** Force characteristics of the dry crispy foods (means $\pm$ SD; n = 30).

Food	Number of force peaks	Average of maximum force (N)
Corn biscuit	17.2 ^d $\pm$ 6.3	15.4 ^c $\pm$ 4.5
Crispy corn	10.9 ^e $\pm$ 4.8	51.2 ^a $\pm$ 16.8
Cornflakes	2.2 ^f $\pm$ 0.9	2.1 ^e $\pm$ 1.1
Cream cracker biscuit	28.4 ^c $\pm$ 4.6	9.3 ^d $\pm$ 1.4
<i>Mariñera</i> biscuit	9.6 ^e $\pm$ 5.1	43.9 ^b $\pm$ 7.6
Potato chips	10.1 ^e $\pm$ 5.6	3.3 ^e $\pm$ 1.2
Extruded snack ball	138.9 ^a $\pm$ 7.1	16.5 ^c $\pm$ 3.6
<i>Tapas</i> biscuit	14.2 ^{de} $\pm$ 6.5	45.2 ^b $\pm$ 6.8
Toast	46.3 ^b $\pm$ 13.3	9.4 ^d $\pm$ 1.7

466 Different letters in the same column indicate statistically different means by Tukey test ($p \leq 0.05$).

467 **Table 3:** Acoustic properties of the dry crispy foods (means $\pm$ SD; n = 15).

Food	Number of acoustic peaks				Sound pressure level (dB)			
	Gain 1		Gain 4		Gain 1		Gain 4	
	Threshold	Threshold	Threshold	Threshold	Threshold	Threshold	Threshold	Threshold
	at 0.5 dB	at 2.5 dB	at 0.5 dB	at 2.5 dB	at 0.5 dB	at 2.5 dB	at 0.5 dB	at 2.5 dB
Corn biscuit	293 ^{cA} $\pm$ 57	136 ^{cC} $\pm$ 27	328 ^{bcA} $\pm$ 43	239 ^{bcB} $\pm$ 36	91 ^{aA} $\pm$ 3	91 ^{aA} $\pm$ 3	86 ^{aB} $\pm$ 2	86 ^{aB} $\pm$ 2
Crispy corn	133 ^{fA} $\pm$ 29	41 ^{efC} $\pm$ 13	155 ^{eA} $\pm$ 40	85 ^{eB} $\pm$ 29	89 ^{abcA} $\pm$ 4	88 ^{abA} $\pm$ 4	83 ^{bcB} $\pm$ 3	81 ^{cB} $\pm$ 3
Cornflakes	54 ^{gA} $\pm$ 19	15 ^{fC} $\pm$ 7	39 ^{fB} $\pm$ 11	21 ^{fC} $\pm$ 7	87 ^{abcA} $\pm$ 5	87 ^{abA} $\pm$ 5	83 ^{bcB} $\pm$ 3	82 ^{bcB} $\pm$ 3
Cream cracker biscuit	216 ^{deB} $\pm$ 37	86 ^{dC} $\pm$ 13	276 ^{cdA} $\pm$ 36	212 ^{cdB} $\pm$ 31	81 ^{dA} $\pm$ 3	81 ^{cA} $\pm$ 3	78 ^{dB} $\pm$ 2	78 ^{dB} $\pm$ 2
<i>Mariñera</i> biscuit	179 ^{efA} $\pm$ 48	65 ^{deB} $\pm$ 25	148 ^{eA} $\pm$ 28	91 ^{eB} $\pm$ 22	90 ^{abA} $\pm$ 3	90 ^{aA} $\pm$ 3	84 ^{abcB} $\pm$ 2	84 ^{abcB} $\pm$ 2
Potato chips	183 ^{efA} $\pm$ 41	59 ^{deB} $\pm$ 23	162 ^{eA} $\pm$ 57	96 ^{eB} $\pm$ 43	86 ^{cA} $\pm$ 4	86 ^{bA} $\pm$ 4	82 ^{cB} $\pm$ 3	82 ^{bcB} $\pm$ 3
Extruded snack ball	661 ^{aC} $\pm$ 28	342 ^{aD} $\pm$ 23	973 ^{aA} $\pm$ 14	707 ^{aB} $\pm$ 36	87 ^{bcA} $\pm$ 2	87 ^{abA} $\pm$ 2	84 ^{abB} $\pm$ 1	84 ^{abB} $\pm$ 1
<i>Tapas</i> biscuit	258 ^{cdA} $\pm$ 56	60 ^{deC} $\pm$ 17	270 ^{dA} $\pm$ 37	175 ^{dB} $\pm$ 37	77 ^{eA} $\pm$ 3	77 ^{dA} $\pm$ 3	76 ^{eA} $\pm$ 2	76 ^{dA} $\pm$ 2
Toast	369 ^{bA} $\pm$ 81	226 ^{bB} $\pm$ 52	358 ^{bA} $\pm$ 94	261 ^{bB} $\pm$ 73	88 ^{abcA} $\pm$ 2	88 ^{abA} $\pm$ 2	85 ^{abB} $\pm$ 1	85 ^{aB} $\pm$ 1

468 Different lowercase letters in the same column indicate statistically different means by Tukey test ($p \leq 0.05$).

469 Different uppercase letters in the same row, for the same acoustic property, indicate statistically different means by Tukey test ($p \leq 0.05$).

470 **Table 4:** Sensory attributes of the dry crispy foods (means $\pm$ SD; n = 20).

Food	Hardness	Sound intensity	Sound duration
Corn biscuit	2.4 ^e $\pm$ 2.0	2.7 ^e $\pm$ 2.1	4.6 ^c $\pm$ 2.2
Crispy corn	9.9 ^a $\pm$ 0.2	9.8 ^a $\pm$ 0.2	9.7 ^a $\pm$ 0.5
Cornflakes	0.8 ^f $\pm$ 0.7	2.2 ^e $\pm$ 1.3	1.9 ^{ef} $\pm$ 1.1
Cream cracker biscuit	0.4 ^f $\pm$ 0.4	0.5 ^f $\pm$ 0.4	0.8 ^f $\pm$ 0.5
<i>Mariñera</i> biscuit	6.9 ^b $\pm$ 1.8	5.6 ^{bc} $\pm$ 2.1	6.7 ^b $\pm$ 1.7
Potato chips	1.1 ^f $\pm$ 1.0	4.2 ^d $\pm$ 1.7	3.5 ^{cd} $\pm$ 1.0
Extruded snack ball	2.5 ^e $\pm$ 1.0	4.5 ^{cd} $\pm$ 1.0	2.5 ^{de} $\pm$ 1.0
<i>Tapas</i> biscuit	3.8 ^d $\pm$ 1.4	2.5 ^e $\pm$ 1.1	3.4 ^{cd} $\pm$ 1.3
Toast	5.2 ^c $\pm$ 2.1	6.3 ^b $\pm$ 2.1	6.5 ^b $\pm$ 1.4

471 Different letters in the same column indicate statistically different means by Tukey test ($p \leq 0.05$).

472 **Table 5:** Pearson correlation coefficients between sensory and instrumental texture of the dry crispy foods.

		Sensory attributes			Force characteristics		Acoustic properties								
		Hardness	Sound intensity	Sound duration	Number of force peaks	Average of maximum force	Number of acoustic peaks				Sound pressure level (dB)				
							Gain 1		Gain 4		Gain 1		Gain 4		
							Threshold at 0.5 dB	Threshold at 2.5 dB	Threshold at 0.5 dB	Threshold at 2.5 dB	Threshold at 0.5 dB	Threshold at 2.5 dB	Threshold at 0.5 dB	Threshold at 2.5 dB	
Sensory attributes	Hardness	1													
	Sound intensity	0.885*	1												
	Sound duration	0.944*	0.914*	1											
Force characteristics	Number of force peaks	-0.129 ^{ns}	0.041 ^{ns}	-0.230 ^{ns}	1										
	Average of maximum force	0.812*	0.526 ^{ns}	0.642 ^{ns}	-0.174 ^{ns}	1									
Acoustic properties	Number of acoustic peaks	Gain 1	Threshold at 0.5 dB	-0.105 ^{ns}	0.012 ^{ns}	-0.168 ^{ns}	0.944*	-0.119 ^{ns}	1						
		Gain 1	Threshold at 2.5 dB	-0.085 ^{ns}	0.079 ^{ns}	-0.105 ^{ns}	0.931*	-0.239 ^{ns}	0.967*	1					
			Threshold at 0.5 dB	-0.139 ^{ns}	-0.013 ^{ns}	-0.231 ^{ns}	0.976*	-0.114 ^{ns}	0.978*	0.933*	1				
		Gain 4	Threshold at 2.5 dB	-0.172 ^{ns}	-0.049 ^{ns}	-0.261 ^{ns}	0.976*	-0.152 ^{ns}	0.978*	0.940*	0.998*	1			
	Gain 1		Threshold at 0.5 dB	0.333 ^{ns}	0.499 ^{ns}	0.510 ^{ns}	0.032 ^{ns}	-0.077 ^{ns}	-0.004 ^{ns}	0.157 ^{ns}	-0.010 ^{ns}	-0.010 ^{ns}	1		
		Gain 1	Threshold at 2.5 dB	0.292 ^{ns}	0.460 ^{ns}	0.473 ^{ns}	0.047 ^{ns}	-0.113 ^{ns}	0.017 ^{ns}	0.180 ^{ns}	0.007 ^{ns}	0.008 ^{ns}	0.998*	1	
	Gain 4		Threshold at 0.5 dB	0.227 ^{ns}	0.426 ^{ns}	0.408 ^{ns}	0.249 ^{ns}	-0.215 ^{ns}	0.249 ^{ns}	0.423 ^{ns}	0.213 ^{ns}	0.219 ^{ns}	0.948*	0.958*	1
		Gain 4	Threshold at 2.5 dB	0.121 ^{ns}	0.326 ^{ns}	0.311 ^{ns}	0.311 ^{ns}	-0.300 ^{ns}	0.340 ^{ns}	0.507 ^{ns}	0.287 ^{ns}	0.297 ^{ns}	0.895*	0.913*	0.986*

*p ≤ 0.01; ns: not significant.

474 **Figure captions**

475 **Fig. 1:** Dry crispy foods used in this study.

476 **Fig. 2:** Combination of texture analyzer and acoustic envelope detector used for instrumental
477 measurements: A. Volodkevich Bite Jaws probe (HDP/VB), B. heavy duty platform
478 (HDP/90), C. circular support insert with a support ring (HDP/CFS), D. Brüel & Kjær
479 microphone position.

480 **Fig. 3:** Typical graph obtained during texture analysis: force in N (black line and scale on the
481 left) and sound pressure level (SPL) in dB (gray line and scale on the right) *versus* time. Gain
482 1 (A) and gain 4 (B).

483 **Fig. 4:** Principal component analysis on sensory and instrumental texture of the dry crispy
484 foods. Legend: Force characteristics: NFP - number of force peaks, AMF - average maximum force, NAP -
485 number of acoustic peaks. Acoustic properties: SPL - sound pressure level, G1 - gain 1, G4 - gain 4, T0.5 -
486 threshold 0.5, T2.5 - threshold 2.5. Sensory attributes: HD - hardness, SI - sound intensity, SD - sound duration.

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