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Review

Methodology of Chewing's sound acquisition by different detectors for dry food in terms of crispness and crunchiness

Piero Sabella [a,*], Angelo Farina [a], Andrea Leporati [b]

[a] *Dipartimento di Ingegneria ed Architettura, University of Parma, Via delle Scienze, 181/A I, 43124 Parma, Italy*
[b] *Barilla G.e R. Fratelli S.p.A, Parma, Italy*

A R T I C L E I N F O

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A B S T R A C T

This paper presents an acoustic detection methodology, providing an overview of Sound Profile Analysis (SPA) and objective data for food sensory analysis. The main goal of present work is improving the sensorial evaluation of crispness and crunchiness on dry food by mastication's sound. This is aimed to the definition of a quality index for "crispy" and "crunchy" perceptual parameters, which are the main texture attributes affecting acceptability of food regarding auditory sensations. The innovative approach consists of using acoustical transducers to measure the objective acoustic parameters on chewing's food sound.

Three different types of transducers were tested (cardioid condenser microphones at a distance, binaural microphones inserted at the entrance of the ear ducts of subject & piezo-electric transducers placed on cheeks of subject) to cover the main principles of vibro-acoustic propagation: air transmission and bone conduction. The binaural microphones resulted in better signals.

The recorded waveforms were processed with existing software for performing spectrum analysis and computing standard acoustical parameters such as levels in dB, reverberation time in seconds and other "objective" acoustical parameters. The ones chosen for SPA are those who revealed better statistical properties and good correlation with laboratory measurements of texture and hardness data.

1. Introduction

It is well known that human sound perception is very subjective, but the design of food products, crispbread for example, shouldn't be based on a subjective basis. This work does not focus on evaluating the relationships between sound produced by dry-food and subjective human sound perception, but on determining the objective acoustical data to guide the design of food structures.

The emission & listening of sound is an important aspect for the perception of crispness and crunchiness on food evaluation during the consumption. While crispness/crunchiness are an indicator of freshness and wholesomeness [1], the moisture level in dry food like bread crust is an indicator of staleness. As crispness is one of the most desirable textural characteristics, we generally prefer crispy snacks and cereals rather than softer [2]. Recent studies have also suggested that acoustic parameters related to food sensory properties, such as crispness and crunchiness, are positively correlated with satisfaction and pleasantness [3]. Those attributes are a highly valued textural characteristic in the food market; sounds made during eating can modulate people's perceptions of moistness, texture, and other aspects of food, and may influence textural and taste perception. The sound emission by crispy/crackly/crunchy foods during fracturing and eating originates from the fracture process [4–9].

Dacremont [10] analyzed the spectral composition of chewing sounds of eight different foods, and classified items into three classes:

- crispy foods, such as extruded flat breads, that generate high-pitched sounds with a high level of frequencies above 5 kHz;
- crunchy foods, such as raw carrot, that generate lower pitch sounds with characteristic peaks in the frequency range 1.25–2 kHz;
- crackly foods, such as dry biscuits, that generate low-pitch sounds with a high level of bone conduction.

Texture properties are the combination of visual inspection, tactile and auditory sensations. Auditory sensations depend on cell arrangement of food structure, chemical bonds and turgidity of the cells that affects sound produced during rupture of cells in crisp/crackly/crunchy products. The most important food textural properties, such as crispness,

* Corresponding author.
E-mail address: piero.sabella@unipr.it (P. Sabella).

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are highly auditory sensations and often judged by the expected sound level. The force required to bite, and corresponding sound emitted are responsible for crispness. Wet cellular products such as apples, that contain fluid within their cells, are composed of turgid cells due to the liquid within cells with elastic cell walls. When the cells are broken, a sound pressure wave is produced [7]. Dry texture products such as potato chips contains air within its cell surrounded by brittle walls. When the force is applied, they bend and then break.

Again, and in sequence, this movement generates vibration and sound pressure waves. They travel by means of acoustical propagation in air and bone transmission, arriving at the hearing organ, the cochlea. The brain elaborates these stimuli, translating them into perceptual sensations, and later in emotions. In conclusion, the above mechanisms explain why wet and dry texture products differ in their composition, and consequently they differ also in their emitted sound [11].

In recent years, instrumental acoustic methods have attracted growing interest for the investigation of the structural properties of foods [12]. In fact, crispness and crunchiness are sensory attributes that can be instrumentally assessed by the recording of the acoustic emission produced during the fracturing process of food samples. Until now, most the research has been focused on the instrumental measurement of objective results (ex. using instruments like Texture Analyzer by Stable Micro Systems) for defining the textural characterization (or profiling) crunchiness/crispness regarding dry foods, such as bakery products, cereal flakes, roasted almonds, potato chips and biscuits [13]. Nevertheless, the human mastication process is different compared with instrumental process (TPA Texture Profiling Analysis on texture analyzer) or other method like the mechano-vibroacoustic detection which are based on the placement of a microphone close to the sample or an accelerometer attached to the mechanical device that contacts the sample. Actually, only a few studies have been published on the application of instrumental acoustic methods to characterize the textural quality of food [14,15]. In contrast, for avoiding the noise from instrumental process (ex. texture analyzer), combining human live mastication process and acoustic recording strategies provide a better and more realistic evaluation of the sensory perceived of crispness/crunchiness than either methodology alone and can bring better understanding of its perception (ref. binaural from automotive researches without manikin).

In fact, digestion involves very complex processes along the oro-gastrointestinal tract, but all food structure changes start in the mouth where food is subjected to physical and biochemical changes (tribology science). Specifically, food oral processing (FOP) involves mastication, salivation, bolus formation, enzyme digestion, and swallowing [16]. Considering the importance of bread on the human diet, the study of its oral processing has been the focus of several research studies.

In recent years, the scientific community has shown an increased interest to combine the sound quality analysis and sensorial food analysis design, as descripts in the review of Luyten et al [7].

Sound quality studies have been often developed during the acoustic characterization of bakery products.

Research suggests that sound quality studies associated with sound-design represent an engineering procedure taken into great account by companies during product development and categorization on market. Most researchers working with acoustic recordings of chewing sounds have compared a large range of different products or concentrated on specific dry-crisp products, for instance, at several water activity levels. The relationship between instrumental texture parameters and sensory descriptors was studied in order to characterize fruit cultivars (apple) according to firmness and crunchiness by means of a more desirable objective and standardized protocol. A study of Harker et al. [17] suggested that chewing sounds could also differentiate between different textures in apples. The energy of the first bite appeared to be the best predictor of the sensory attributes' crispness (defined as the amount and pitch of sound generated when the sample is first bitten with the front teeth) and crunchiness (the amount of sound generated when chewing with the back teeth).

In this work, the focus is on the vibro-acoustic propagation produced by chewing crispbread. Others, like Duizer [6] gave an overview of the sound parameters used to relate audible sound to the perception of crispness/crunchiness related characteristics. Different authors found good correlations of the latter with the measured amplitude of the acoustic signal, sound energy, number of peaks and the duration of the sound emission on fracturing or biting a whole piece of material and with combinations of these parameters. In this article, we will show that it is possible to use the information derived from the sound and from the force signal to understand the physical behavior of the dry food products and to construct constraints regarding product morphology. Emphasis will be on the analysis of the sound signal for dry cellular foods and crusts, like crispbread or rusk.

These data are called objective acoustical parameters characteristic of a particular food. Briefly, the following ones were taken into account:

- Spectral analysis in octave bands
- Average sound pressure level (SPL) in dB(A).
- Reverberation time (a proxy for mastication time) in *s*.
- Derived parameters related to spectral balance, such as spectral slope, bass ratio, high ratio, prominence ratio
- Peak to average ratios: peakiness, impulsiveness, millisecondness.

The goal is to obtain objective data extracted from the chewing sound emitted by a taster, avoiding the subjective evaluation, which is known to be less accurate. After many tests, a sound measurement chain was selected, employing the best transducers for capturing the sound emitted during the whole chewing phase, and selecting the best acoustical parameters for characterizing the 4 main perceptual parameters of a crispbread food: loudness, tonal balance, duration of chewing, sound peak during product fracturing.

2. Materials and methods

In this section, we present the methodology for Sound Profile Analysis. We first discussed the acquisition of sound, recording setup, the sensor selection, participant selection, data collection and processing as well as the experimental protocols, feature extraction and classifications.

Also, the development and implementation of the real-time chewing detection model, data processing as well as the experimental protocols for the second study are discussed in subsection 3.2.

The acquisition of vibro-acoustics signals was carried out within an acoustically "dry" environment as seen in Fig. 1.

The background noise level inside the recording room was below 30 dB(A). Details about acoustics of this lab room are reported in this paper [18].

A representative recording conditions was created with typical eating environments: using a desk, chair, plate, and glass.

Each chewing measurement was repeated five times by each subject with a new piece of crispbread, providing data for repeatability. The test was repeated with 7 subjects, providing data for reproducibility.

The sound emission was recorded for whole mastication using three different types of vibro-acoustic sensors (at the same time) Fig. 2:

Two piezo-electric transducers, basic model produced by Bnineteenteam (Model Nouveau).

Two Antelope Verge cardioid microphones, in 2 positions, frontal and front-lateral, at 0.5 m distance from the mouth.

Binaural ear microphones (DPA 4560 Core).

The piezoelectric transducers capture the sound arriving to the subject's hearing system through bone transmission.

The cardioid microphones capture the sound emitted from the subject performing the chewing test and represent what other people can hear when he is eating.

The binaural microphones capture the sound received in both the listener's left and right ears, and generally are played back through headphones.

All the 6 sensors were connected with an audio interface Antelope Discrete 8 – piezo sensors are in channels 1–2, the only ones equipped with high-Z preamplifiers suitable for such high impedance transducers. The other 4 "normal" microphones were connected con input channels 3–6, which feature preamplifiers equipped with balanced inputs and P48V phantom power supply. The acquisition was performed at a sampling rate of 48 kHz, with 32 bits float resolution. This allows for a bandwidth which contains the whole spectrum of signals, and with a huge dynamic range capable of covering the whole dynamics of transducers without clipping.

The computer was an MSI gaming laptop with USB-3 interface.

The following Table 1 summarizes the sampling conditions.

2.1. Recording phase

The digital audio tracks acquisition of chewing's sound was made by Adobe Audacity software (Version 2.4.1.) (This choice was made for recording into a multichannel WAV file).

During the mastication and recording a procedure was set up:

Installing the binaural microphones in the subject's ears, opening the package of the product, preparing a number of samples of the product (braking large parts in smaller portions, if needed), and then perform a continuous recording while a sequence of 5 portions of each product, which are chewed and swallowed. The First Bite is kept separated by the following chewing action by a pause of 1 s, which later makes it easier to process separately the first bite and the following chewing performed with the lips closed. At the beginning of the recording, the subject is asked to declare the name of the product being tested, so the recording contains a unique identification of it. After the recording is complete, the multichannel WAV file is saved with proper name.

Table 1
Audio setup ADC.

Audio Setup	
Stereo rating (Hz)	48,000
Encoding (bit)	32-bit float
Format file	WAV (uncompressed)
Microphone's Gain on Preamp Interface - Discrete 8	
Piezo-electric (dB)	40
Binaural Gain (dB)	30
Verge Gain (dB)	50

The binaural microphone wore like an earphone, having care of inserting the small capsules at the entrance of the ear duct, whilst the piezoelectric transducers are attached on the area of zygomatic bone and maxilla by dermatological skin compatible sticker (3 M®), as shown in Fig. 3.

The subjects involved in this study reported that these sensors attached to the face did not interfere with normal chewing behavior. The cardioid electret microphones are placed on stands at approximately 0.5 m from the mouth.

The distance between the test desk and the recordist's location, in an adjacent room, required to setup a video monitoring system (no recording).

Fig. 1. Tasting Desk in the Recording Room.

Fig. 2. Setup for sound acquisition, vibro-acoustic sensors and analogic/digital converter. Binaural ear microphones (DPA 4560 Core), Antelope Verge cardioid microphones, Bnineteenteam Nouveau piezo-electric transducers, audio interface Antelope Discrete 8.

Fig. 3. Setup of the three microphones: Binaural microphone, Frontal condenser, Piezo-electric.

The monitoring step to check eventual noise and anomalous signals was performed by playback and signal analysis using Adobe Audition 1.5 software.

2.2. Acoustical tests with one type of crispbread and a panel of subjects

The samples (crispbread) were stored in its original package, in a dark place, at temperature of 16.2 °C and 45 % of relative humidity (RH). The recording room was kept at 18.8 °C/42 % RH. For each experiment, to avoid humidity absorption, a new package was opened. All samples were measured within a maximum of 10 min after opening the package.

An acoustical test was carried out for a qualitative assessment of the crispness on one type of crispbread.

For each subject a new package was open, each slice was handly broken from each subject and 5–6 samples were selected (following hygienic protocol for Covid-19 prevention).

The whole action of mastication mainly contains two phases, the "first bite" and the "remaining". The "first bite" begins with initial contact between teeth and a small piece of food kept with fingers, then a chunk of food is separated breaking the product with teeth, and the mouth is closed. The subject has now to perform a pause of approximately 1 s, after which the "remaining" mastication phase occurs, containing all the subsequent chewing actions until swallowing. The portion of food remained in the fingers of the subject must be placed back on the table without causing any noise.

Apart from the above-described prescriptions, the test person is left free to chew the samples in his own way, using the part of teeth of his choice, to choose his own biting size, chewing's frequency and mastication time until swallowing (like daily routine consume).

Seven untrained participants were involved in the panel test. The subjects were volunteer (4 women; 3 men) between 18 and 66 years of age, of Italian nationality, and without previous mastication pathology.

Fig. 4 shows the "desk" in front of the subject, with 6 samples of the crispbread product.

Fig. 4. Samples of crispbread.

2.3. Data analysis

Digital data analysis was performed on the audio recordings.

The recorded signals have been processed and analyzed by using Aurora "Acoustical Parameters" [19,20] a plugin specially developed for Adobe Audition (1.5 version), which was initially developed for room acoustics according to the ISO 3382 standard [21], and late extended to food sound analysis by adding some additional parameters. From this type of data processing, the main acoustic parameters have been obtained essentially by temporal/spectral analysis of the waveform.

The recordings typically provide 3 stereo tracks coming from the three types of sensors: binaural microphones, piezo transducers and cardioid condenser microphones, as shown in Fig. 5.

The following chapter describes in detail these acoustical parameters.

2.4. Acoustical parameters

Before describing the Acoustical Parameters method analysis, a quick review of the subject matter may be required. The ISO3382 standard describes the calculation of a number of acoustical parameters, based on a recording of the so-called Room Impulse Response. The impulse response is the recording of the sound pressure observed at a point in a room as a result of the emission of a Dirac impulse at another point

Fig. 5. Example of stereo multitrack chewing sound signals acquired by three types of sensors.

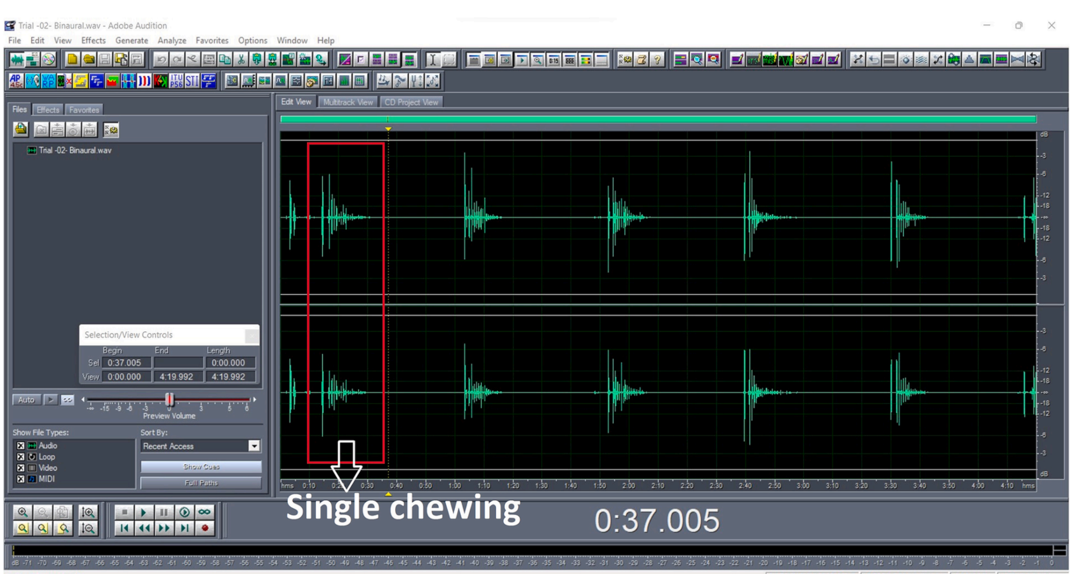


Fig. 6. Example of stereo track with five chewings.

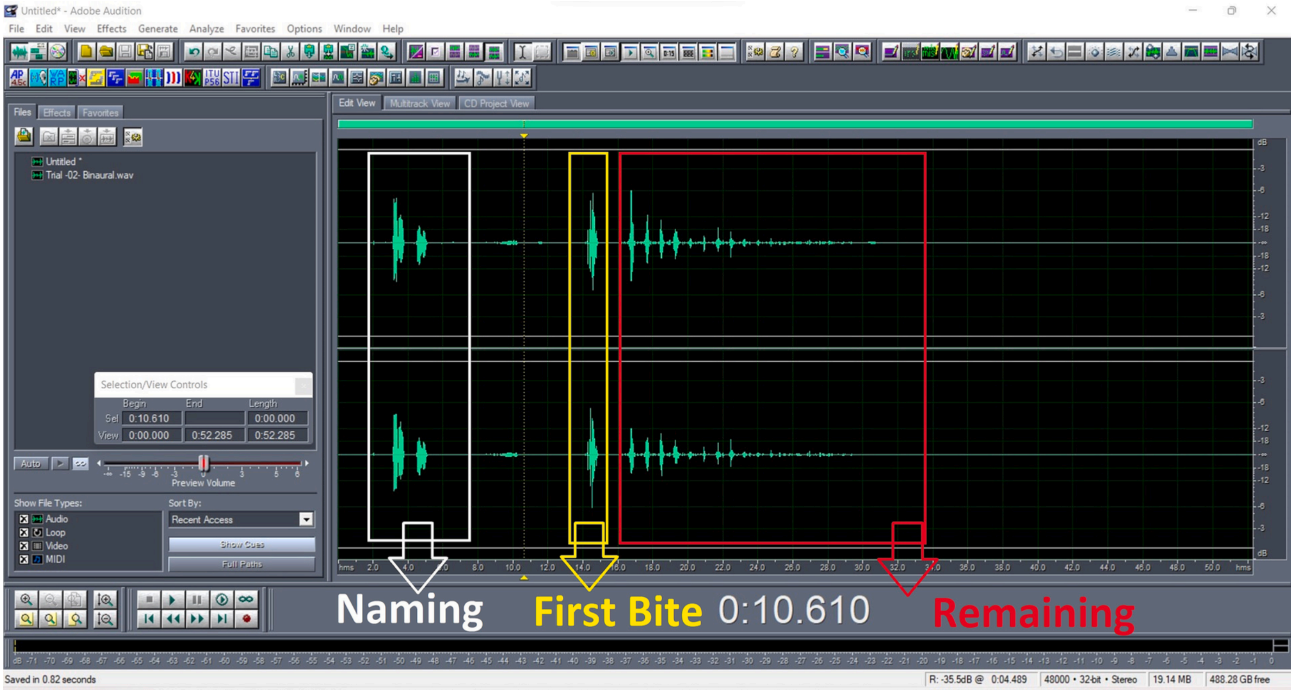


Fig. 7. Segmentation of “first bite” and “remaining” segments.

Fig. 8. Typical Texture Analyzer employed for 3-points bending test of a baked product.

in the room.

Form such a recording it is possible to calculate the Acoustical Parameters defined in the ISO standard 3382, in 10 octave bands (from 31.5 Hz to 16 kHz). These include various kinds of Reverberation Time (EDT, T10, T20, T30), Clarity C_{50} and C_{80}, Definition D_{50}, Center Time t_s. When a set of binaural microphones are used, “spatial” parameters such as IACC can also be computed.

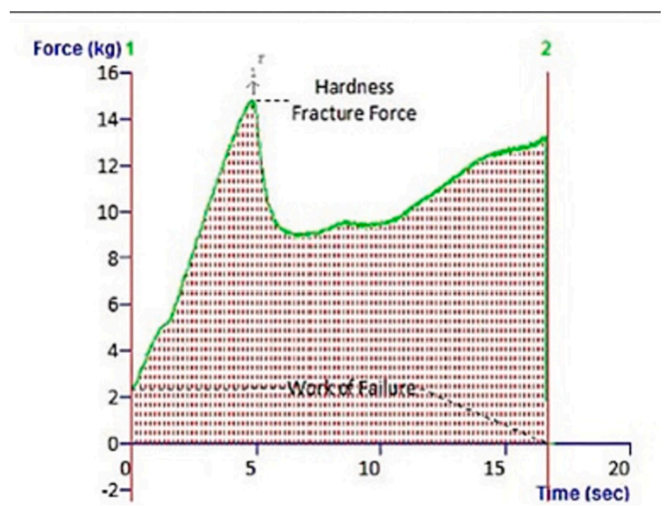


Fig. 9. Typical Texture Analyser graphs with annotated properties of rupture tests.

The following subchapters described the parameters employed in this study, according with the definitions provided by the ISO 3382-1 standard.

2.4.1. Sound pressure level

The sound pressure level is the time-average RMS value of sound pressure, expressed on the decibel scale through the formula:

$$SPL = 10 \bullet log_{10}\left[\frac{1}{T} \bullet \int_0^T \left(\frac{p(t)}{p_0}\right)^2 \bullet dt\right] \text{ with } p_0 = 20\ \mu\text{Pa}$$

SPL is computed in octave bands plus the overall values with Linear and A frequency weighting. The parameter is labeled *Lsg* (Signal Level) in the Aurora software.

2.4.2. A-weighted SPL

The A-weighted value of time-averaged Sound Pressure Level is

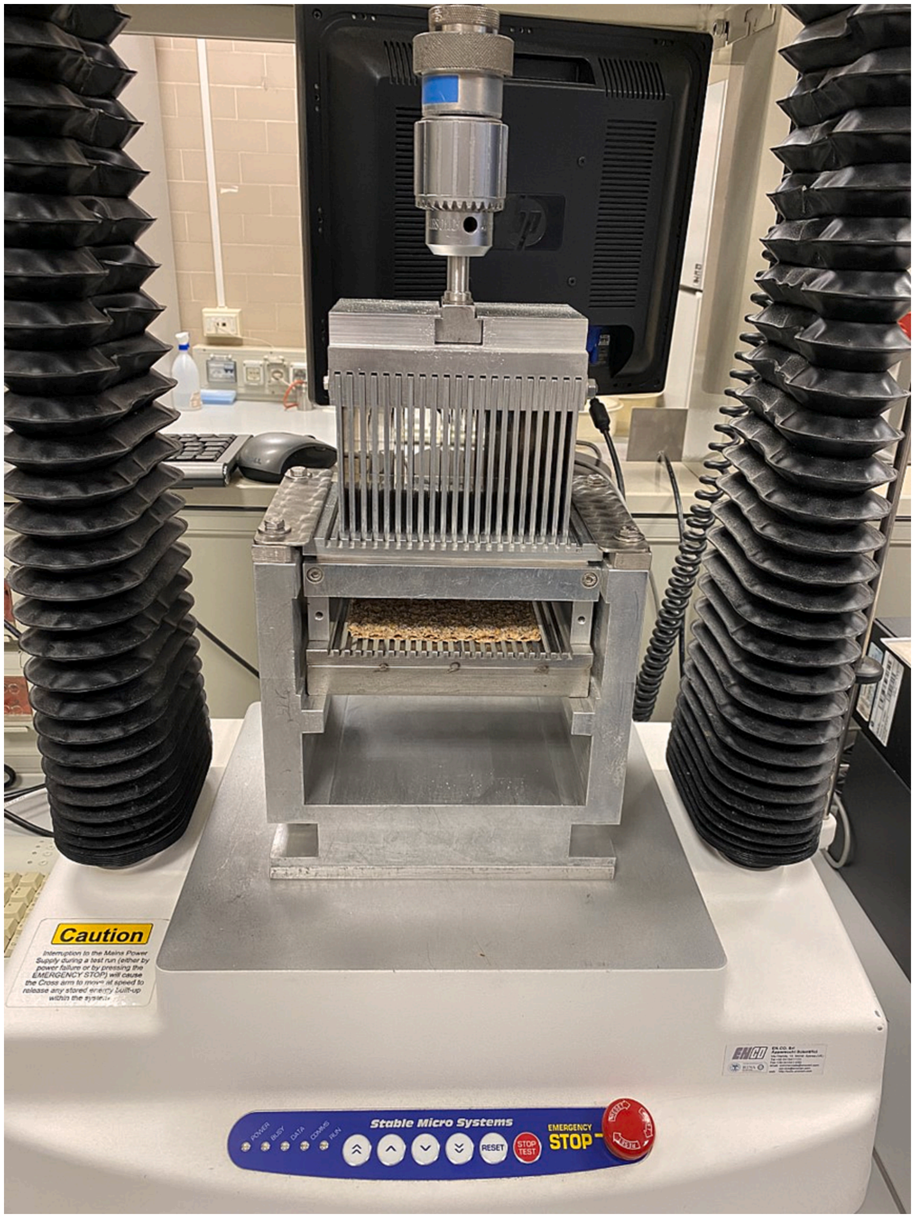


Fig. 10. Kramer shear press cell on TA.HDi texture analyzer.

considered the parameter better representing the perceived loudness and is designated in our text by the symbol Lsg_A. It was measured separately for the First Bite and the Remaining of each sample of product being chewed.

2.4.3. *Tonal balance parameters*

We defined 4 new parameters, based on some previous suggestion by literature (such as Beranek, [23]), named Bass Ratio, High Ratio, Spectral Slope, Spectral Slope2. These parameters were defined as follows:

Bass ratio: difference in dB between the average signal level at low frequencies (125 Hz; 250 Hz) and the average signal level at medium frequencies (500 Hz; 1000 Hz);
High ratio: difference in dB between the average signal level at high frequencies (2000 Hz; 4000 Hz) and the average signal level at medium frequencies (500 Hz; 1000 Hz);
Spectral Slope: it is the slope in dB/octave computed by the 7 values of signal level in the octave bands of: 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, 8 kHz.
Spectral Slope 2: difference in dB between the signal level at 4 kHz and the signal level at 250 Hz.

2.4.4. *Reverberation time*

The reverberation time is an acoustical parameter initially developed for reverberation in concert halls can be useful for evaluating the temporal decay of a phenomenon.

For evaluating reverberation times, the recorded impulse response p(t) must first be converted into a stationary-noise decay curve s(t). This is obtained by a mathematical procedure known as "Schroeder's backward integration" [22], which basically means to perform a reverse integration of the signal, from "running time t" to infinite.

$$s^2(t) = \int_t^{\infty} p^2(t) \bullet dt$$

Reverberation time T60 is defined as the time, in seconds, needed by

Fig. 11. Vibratory sieve shaker Retsch, model AS200 Control.

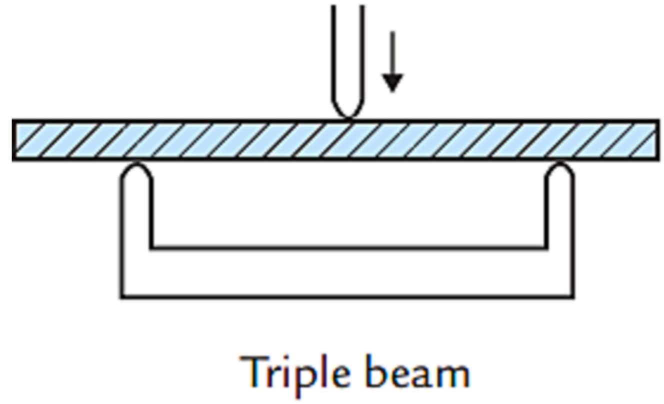


Fig. 12. Ex. triple beam setup.

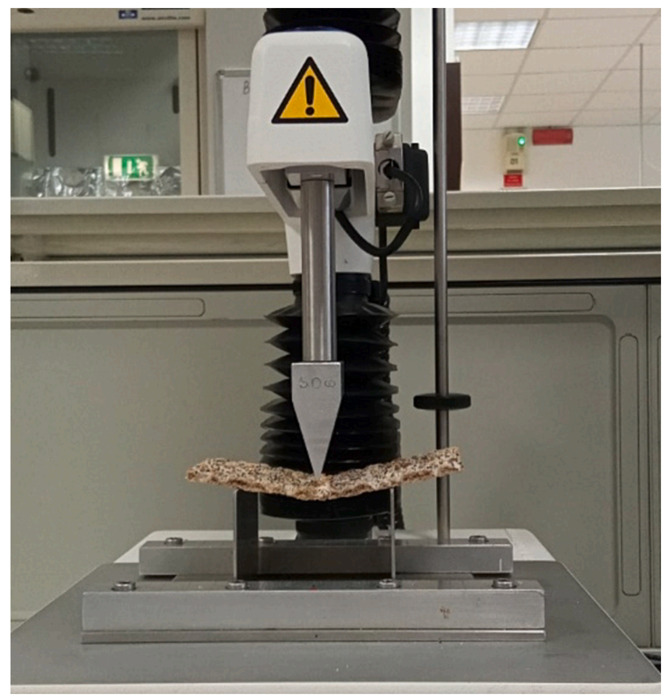


Fig. 13. Three-Point Bending Test on TA.HDi texture analyzer.

the sound pressure level to decrease by 60 dB; but in practice the rate of decay is usually measured by the linear least-squares regression of the measured decay curve s(t) from a level 5 dB below the initial level to 35 dB below. This is called T30.

When the final value is changed to 25 dB we obtain T20. It is important to note that, even if the decay rate is measured over a range of just 30 or 20 dB, the reverberation time is always expressed as the time required for a 60 dB decay. If the decay is linear, hence, T60 = T30 = T20.

2.4.5. *Peakiness and similar parameters*

These parameters are not expressly formalized in ISO 3382, but are common parameters employed when analyzing an acoustical waveform and are useful for evaluating the “crest factor” of a signal. The idea is to evaluate the ratio between some “maximum” value of the waveform and its average value.

When the ratio is expressed in dB, the peakiness is defined simply as:

$$p_{ks} = L_{peak,max} - L_{RMS}$$

Table 2
Fracturability table by Granulometric Analysis. Rejected (g/100 g) particles for each sieve mesh (g/100 g). The values are expressed as Mean ± SD.

Rejected particles (g/100 g) from each mesh by sieving				
Rejected (g/100 g) from mesh 3350 µm	Rejected g/100 g) from mesh 2500 µm	Rejected (g/100 g) from mesh 1000 µm	Rejected (g/100 g) from mesh 500 µm	Rejected (g/100 g) from mesh below 500 µm
7.48 ± 0.54	21.01 ± 0.74	43.7 ± 0.63	14.98 ± 0.45	12.82 ± 0.81

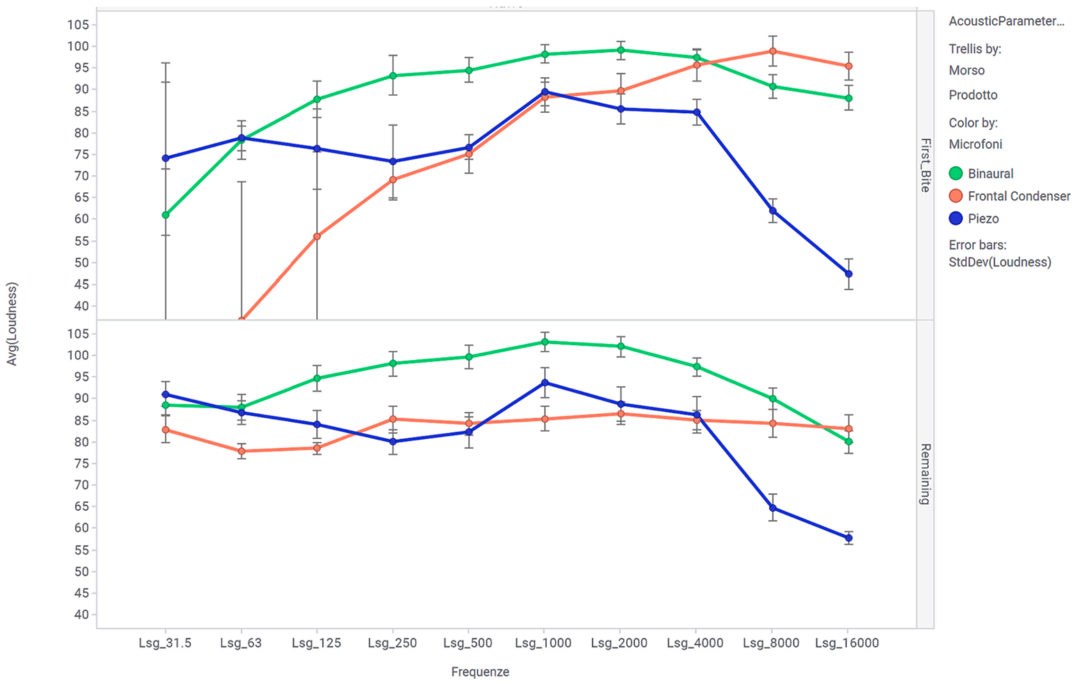


Fig. 14. Sound Pressure Level in octave bands by the 3 microphone types averaged over all 7 subjects and one product (crispbread).

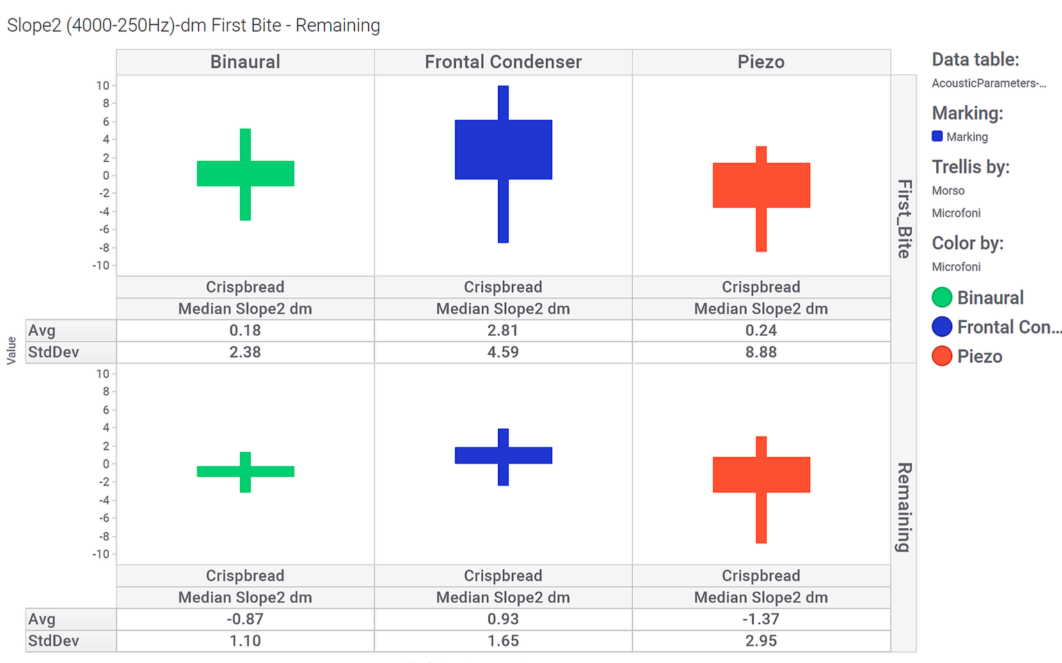


Fig. 15. Shows the comparison of the three types of transducers for another acoustical parameter, slope2.

where $L_{peak,max}$ is the level of the maximum sample value of sound pressure, and L_{RMS} is the standard SPL value averaged over the whole duration of the signal being analysed.

Two other very similar parameters are Impulsiveness and Millisecondness. They differ from Peakiness as the first term of the level difference is given respectively by the Max running value of SPL measured with the "Impulse" time constant (Impulsiveness) and the Max short-RMS value averaged over a sliding window of 1 ms (Millisecondness). These three parameters are a unique feature provided by the Aurora software employed for analysis [20].

2.5. *Analysis procedure*

Each stereo recording contains a sequence of chewing actions on 5 samples of the product, plus some additional noise events occurring in between as shown in Fig. 6.

The evaluation of acoustical parameters was applied separately to the two segments of each recording, named "first bite" and "remaining". This required to perform a preliminary SEGMENTATION step, for ensuring to create segments always having the same durations: 1.5 s for the "first bite" and 30 s for the "remaining". Fig. 7 shows an example of such segmentation procedure.

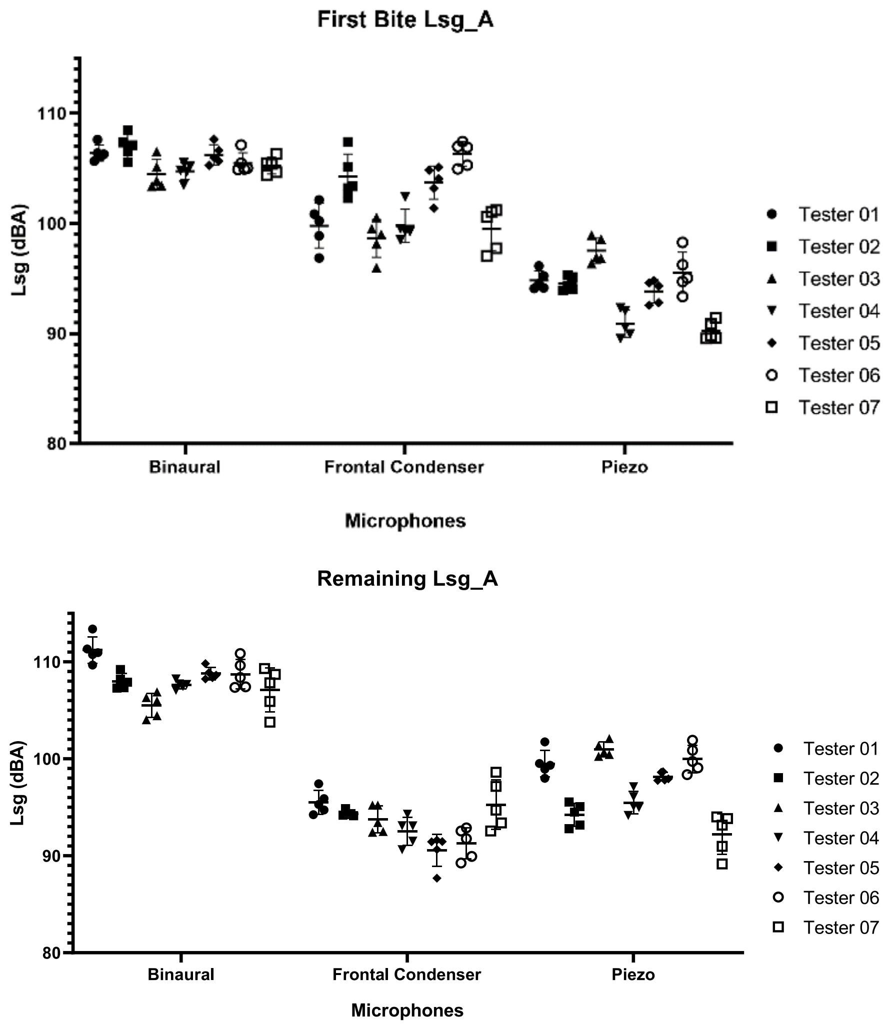


Fig. 16. Values of Loudness (dBA) (First-Bite above, Remaining below).

Table 3
Table of Loudness (First Bite + Remaining): Lsg_A (dBA) are expressed as Mean ± SD.

Microphone type	First Bite Lsg_A (dBA)	Remaining Lsg_A (dBA)
Binaural	106.61 ± 1.20*	108.14 ± 1.99*
Frontal condenser	102.04 ± 3.26	93.27 ± 2.31
Piezo	93.31 ± 2.58	97.22 ± 3.25

2.6. *Post-Processing and data aggregation*

The raw data processed by Audition + Aurora was saved into an Excel spreadsheet, where calculation of additional spectral balance parameters was done.

In the preliminary elaboration phase the variability of dataset was large, due to the differences among subjects (ex. difference in age, gender, mastication's sound culture, dental and auditory physiology efficiency).

Demeaning the data has been proposed for normalizing the dataset, as a simple way to remove the effect of the variability given by different subjects. In practice, for each parameter and for each subject an average value was computed among all products tested, and this value was subtracted from each individual value of the same parameter. This removed almost entirely the bias caused by the subject differences.

The temporal parameter resulting more relevant was T20. Which is defined in ISO 3382 standard as the "reverberation time" and obtained by a mathematical procedure known as "Schroeder's backward integration" [22]. Of course, there was no reverb in these very dry recordings. T20 here assumes the meaning of a decay time and was meaningful only when computed on the "remaining" segment. In practice it resulted a good proxy for the duration of mastication, providing a clear indication of which products need to be chewed more time before being swallowed.

We evaluated other temporal parameters processed by the Aurora software, such as center time **ts**, reverberation times **EDT** and **T30**, but **T20** resulted in more robust data with better repeatability and reproducibility.

Demeaning and statistical analysis of results were performed by using the Analytics Software & Data Visualization TIBCO Spotfire® Analyst (Version 12.0.1) and GraphPad Prism 8 software. Data were first tested for conformity to a normal distribution using the Shapiro-Wilk test, and then analyzed by Two-way ANOVA multiple comparison, followed by Tukey Post Test.

Each chewing measurement was repeated five times by each subject with a new piece of crispbread, providing data for repeatability. The test was repeated with 7 subjects, providing data for reproducibility.

This way the following main acoustical parameters were processed: Signal Level SPL (dB), Bass Ratio (dB), High Ratio (dB), Slope2 (dB), Chewing duration T20 (s). All of them except T20 were computed separately for the "first bite" and "remaining" segments.

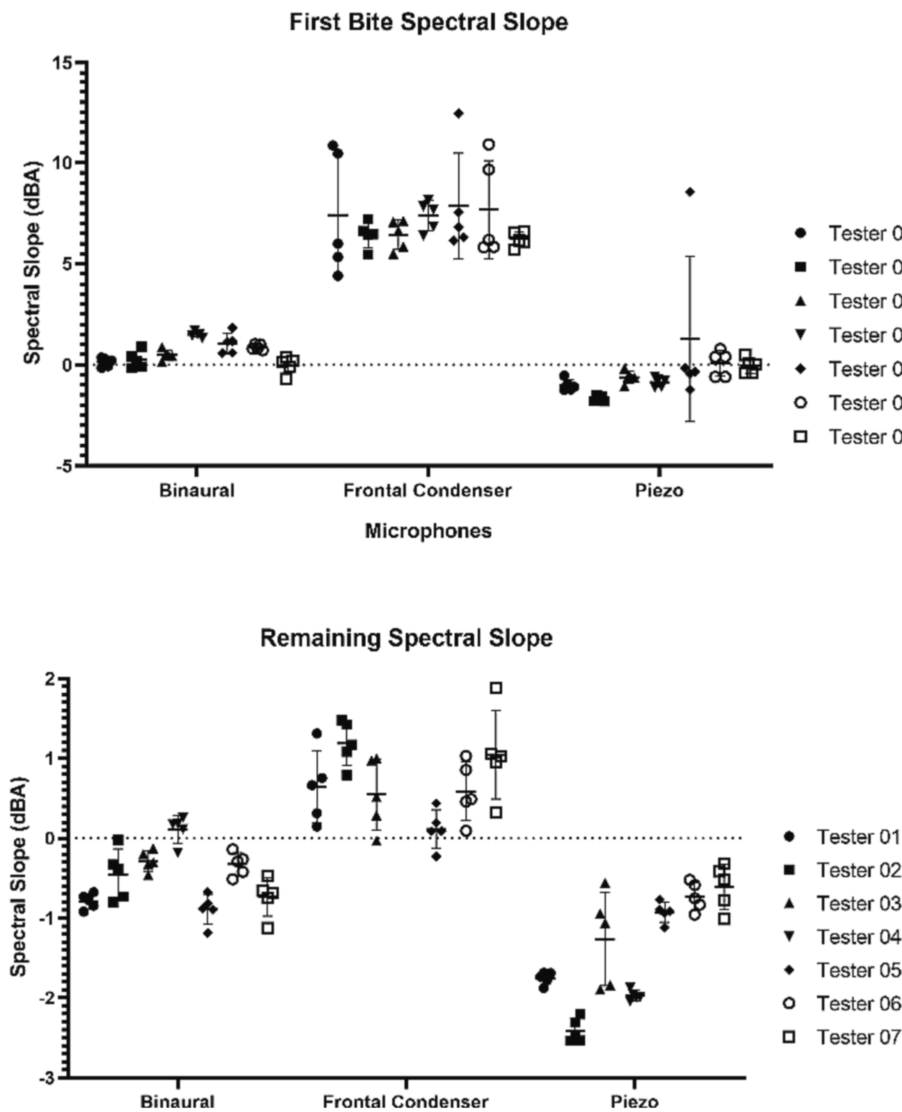


Fig. 17. Values of Spectral Slope (dB/octave) (First Bite above, Remaining below).

3. Mechanical tests

Some instrumental tests can be performed for assessing mechanical properties of food, such as the force required for fracturing the food, the energy required and the texture.

Physically, texture is the way in which the various constituents and structural elements of a food are arranged and combined in a micro and macrostructure and the external manifestations of this structure in terms of flow and deformation [24].

Texture is one of the three primary sensory properties of foods that relates entirely to the sense of touch or feel and is potentially capable of precise objective measurement by mechanical means in fundamental units of force [25]. Texture measurement can be assessed by different instrumental methods. Puncture, compression, extrusion, bending test, shear and tension are the main and generally used procedures for evaluating food texture, giving values of force, deformation, slope and area.

3.1. Textural parameters

Texture is a complex term. The International Organization for Standardization defined texture as “the mechanical, geometrical and surface attributes of a product perceptible by means of mechanical, tactile and where appropriate, visual and auditory receptors” (ISO, 1992) [26]. The texture of a food, then, is perceived by humans via the sense of touch from surface responses within the mouth, deep responses by muscles and tendons, and potentially also auditory cues.

The used methods permit to obtain mechanical parameters using two fracturing devices: a Kramer Cell and a Three-point Bending device. The secondary characteristic of fracturability or brittleness was also estimated by analyzing the sizes of particles resulting from the fracture under the Kramer cell. These parameters can give quite good information about the influence of different ingredients, processes and conservation on final texture [27]. These properties are usually measured using a special lab equipment called a “texture analyzer”. This is basically a machine for measuring force–displacement curves, loading the product progressively under an instrumented press. Fig. 8 shows a typical texture analyzer (courtesy by Stable Micro Systems, inc.).

The texture analyzer can be fitted with different devices for interacting with the food product, such as a Kramer cell, a 3-points bending system, etc.

Two different tests, **Kramer shear press** and **Three-point bending** have been performed in this study. Chapter 4.2 and 4.3 describe in detail the devices used in this study.

The result of a fracture test is a force–displacement chart, or a force–time chart, from which some mechanical parameters can be

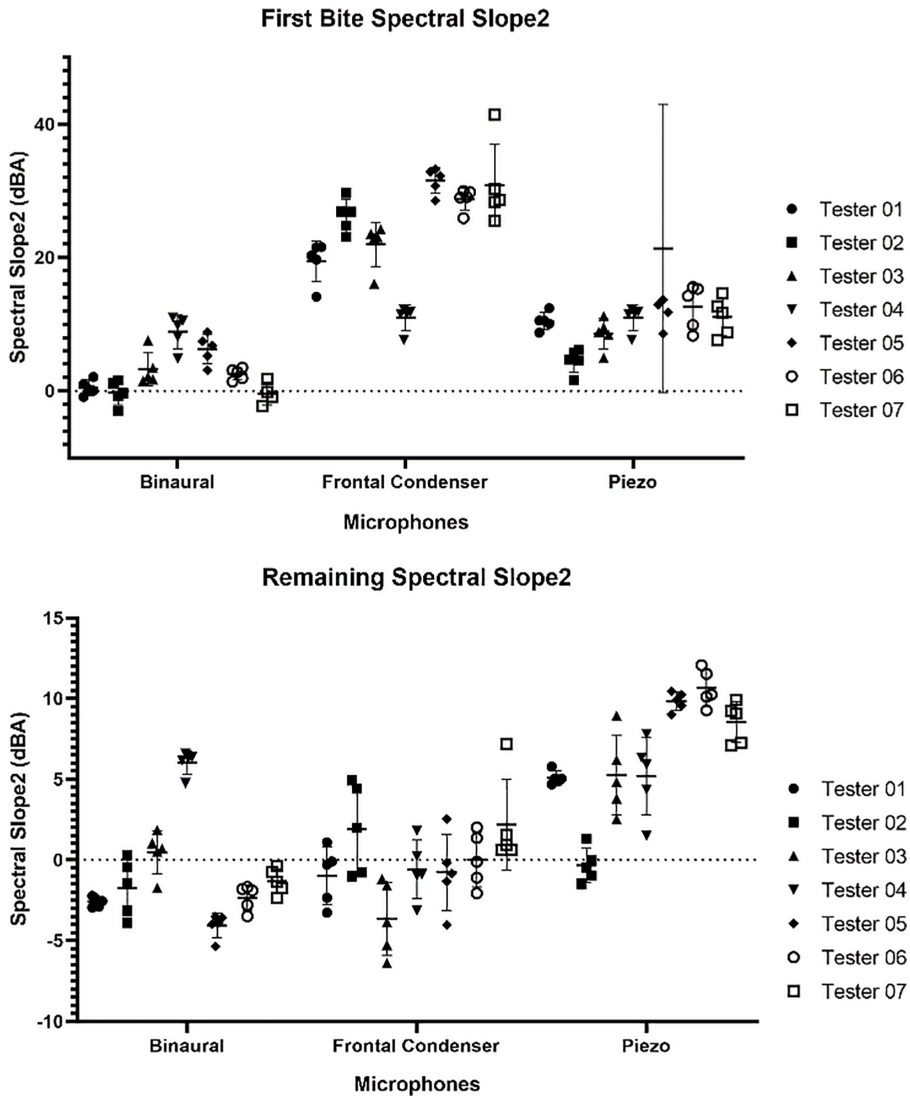


Fig. 18. Values of Spectral Slope2 (dB) (First Bite above, Remaining below.

extracted, as shown in Fig. 9.

The following subchapters describe the mechanical parameters employed in this study.

3.1.1. Hardness

The resistance (in Newtons) at maximum compression during the compression test, as shown in Fig. 9. It is the force necessary to attain the fracture of the product. It represents the hardness of the sample at first bite.

3.1.2. Fracturability and brittleness

Fracturability is the tendency of a material to fracture, crumble, crack, shatter or fail upon the application of a relatively small amount of force or impact. It is usually displayed by a product of high degree of hardness and low degree of cohesiveness and is the textural property commonly possessed by baked goods, snacks and generally dry products. A material is brittle if it is liable to fracture when subjected to stress. That is, it has little tendency to deform (or strain) before fracture and usually makes a snapping sound.

Fracturability is evaluated by the presence of particles of small size resulting from the fracture test. A granulometric analysis on the material resulting from a fracture-crushing test is performed.

3.2. Texture analysis methods: Kramer shear press

The **Kramer shear press** applies a combination of compression, shearing and extrusion.

The **Kramer shear press test** allows to obtain Kramer Mechanical Properties of the foods. In this study we measured with a TA.HDi texture analyzer (Stable Micro Systems Ltd., Godalming, UK) provided with Texture Expert Exceed software (version 2.64), and equipped with a 500 kg load cell, as shown in Fig. 10. A Kramer shear press test was conducted on each food sample using a customized Kramer shear test cell (80 × 140 mm, LxW) with the upper mobile part made of 21 parallel 3-mm thick vertical metal blades, each one is 3 mm distant from the other. 21-bladed head was set at a deformation rate of 1.30 mm/s. At least five samples were performed for each type. This test measures the compression force (Newtons) and work (Joules)(Nm) developed by the texturometer when compressing a piece of bakery food, crispbread in this evaluation.

This test applies a combination of compression, shearing and extrusion. It consists of applying force to a food until it flows through the outlets, that may be in the form of one or more slots or holes that are in the test cell. The food is compressed until the structure of the food is disrupted and it extrudes through these outlets. Usually, the maximum force required to accomplish extrusion is measured and used as an index

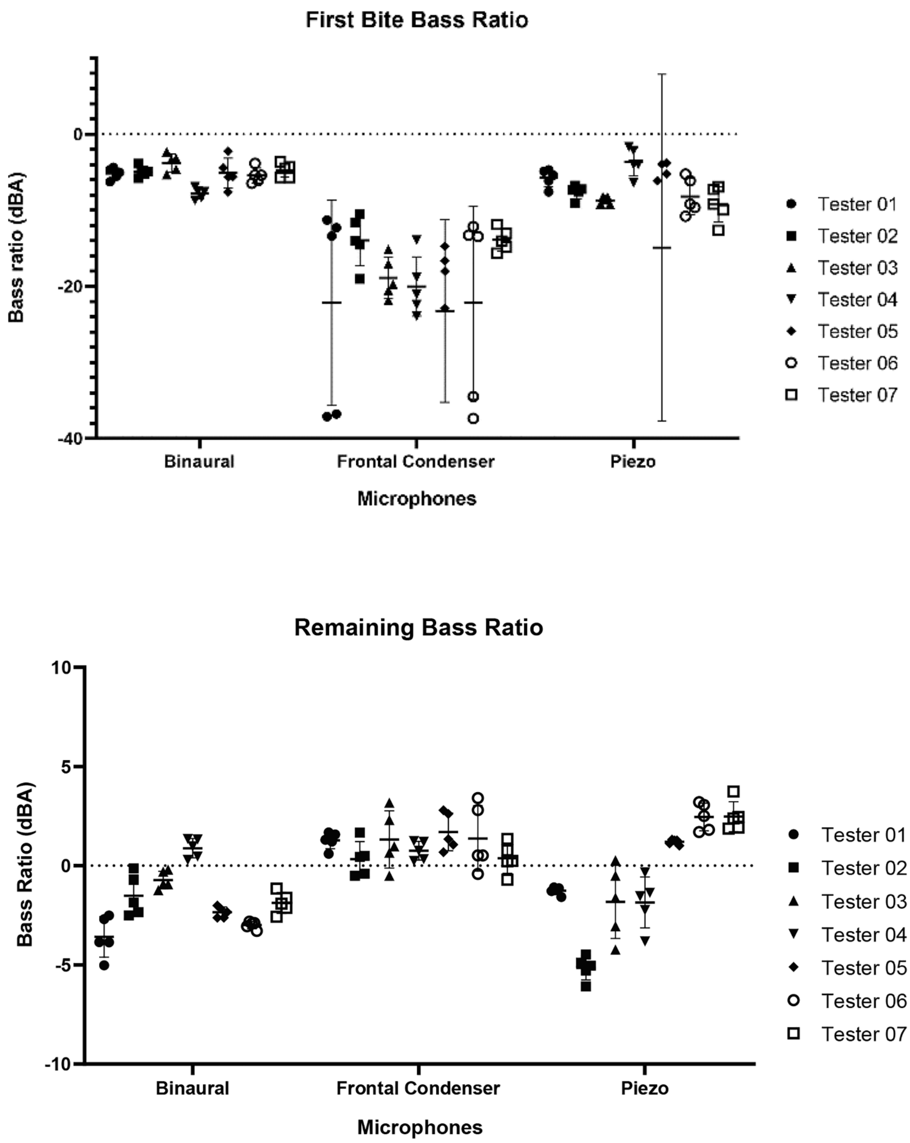


Fig. 19. Values of Bass Ratio (dB) (First Bite above, Remaining below).

of textural quality. Since extrusion requires that the food flows under pressure, it seems reasonable to use it on food that will flow under an applied force and not to use it on those foods that do not flow easily and the samples are irregular or too small, such as bread, cake, cookies, breakfast cereals.

A simple type of compression, shearing, extrusion test is shown in Fig. 10, in which the food is placed in a strong metal box with an open top. A loose-fitting plunger is then forced down into the box until the food flows up through the space between the plunger and the walls of the box. This space is called the annulus. A number of textural parameters were extracted from the resulting force–distance curves, which are closely correlated to sensory evaluations [28]. The samples of crispbread, rectangular piece with dimensions 12 × 6.5 × 1 cm (L × W × D) was used for compression tests in this study.

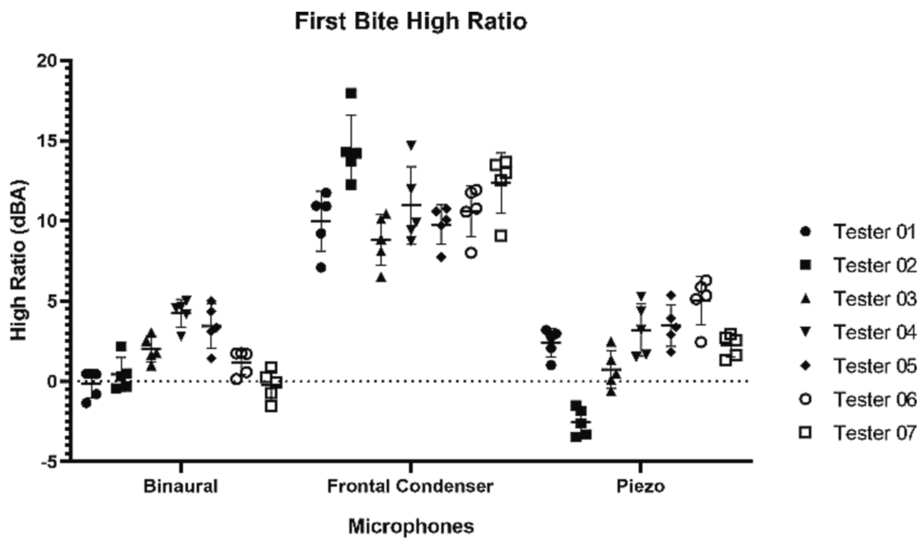
The sample was placed under the probe that moved downward at a constant speed of 10.00 mm s1 (pre-test), 1.30 mm/s (test), and 10.00 mm s1 (post-test).

The test was performed with a constant food sample volume fixed at ≈5.20 cm^3, which corresponds to about half the volume that the bottom compartment of the cell can contain, and which is quite similar to the amount of food sample commonly introduced into the mouth for oral processing.

When the probe first comes in contact with the sample, the thickness of the sample is automatically recorded by the software. The probe continues downwards a pre-fixed distance of the sample equal to 40 mm, then returns to the initial point of contact with the sample. During the test run, the resistance of the sample is recorded at an acquisition rate of 200 Hz and plotted in a force–time (grams-seconds) plot as illustrated schematically by Veland and Torrissen [29]. The area under the force–distance curve was therefore directly proportional to the work performed by the probe during the downstroke and by the sample during the upstroke. From the force–distance plot the Kramer mechanical parameters are calculated.

3.3. *Fracturability test with granulometric analysis*

Fracturability is correlated with particle size determination and in this study is performed with Granulometric Analysis by mechanical sieve. The study of the particle size distribution was performed in sequence after the Kramer shear test where the fragments obtained were carried out using four sieves with different size. The granulometric analysis was performed by mechanical dry sieving using a Vibratory sieve shaker (Model AS200 Control, Retsch, Haan, Germany) as showed in Fig. 11.



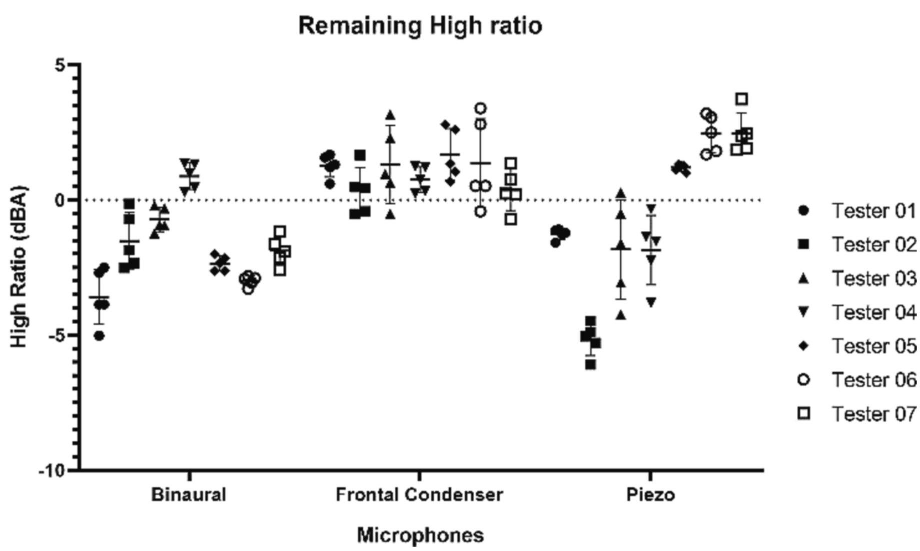


Fig. 20. Values of High Ratio (dB) (First Bite above, Remaining below).

Table 4
Spectral parameters (dB): tonal ratios Slope, Slope2, Bass ratio, High ratio of First Bite.) The values are expressed as Mean ± SD.

First bite - spectral parameters tonal ratios				
	Slope	**Slope2**	**Bass Ratio**	**High Ratio**
Binaural	0.62 ± 0.59	3.08 ± 3.67	−5.29 ± 1.53	1.60 ± 1.86
Frontal Condenser	7.01 ± 1.87	26.48 ± 5.42	−19.04 ± 9.08	11.01 ± 2.44
Piezo	−0.41 ± 1.67	11.40 ± 8.91	−8.28 ± 8.87	2.09 ± 2.49

Table 5
Spectral parameters (dB): tonal ratios Slope, Slope2, Bass ratio, High ratio of Remaining.

Remaining - spectral parameters tonal ratios				
	Slope	**Slope2**	**Bass Ratio**	**High Ratio**
Binaural	−0.48 ± 0.36	−0.78 ± 3.19	−5.03 ± 1.55	−1.73 ± 1.49
Frontal Condenser	0.69 ± 0.49	−0.19 ± 2.79	−2.94 ± 2.18	1.02 ± 1.08
Piezo	−1.37 ± 0.67	6.31 ± 3.72	−6.04 ± 1.59	−0.56 ± 2.71

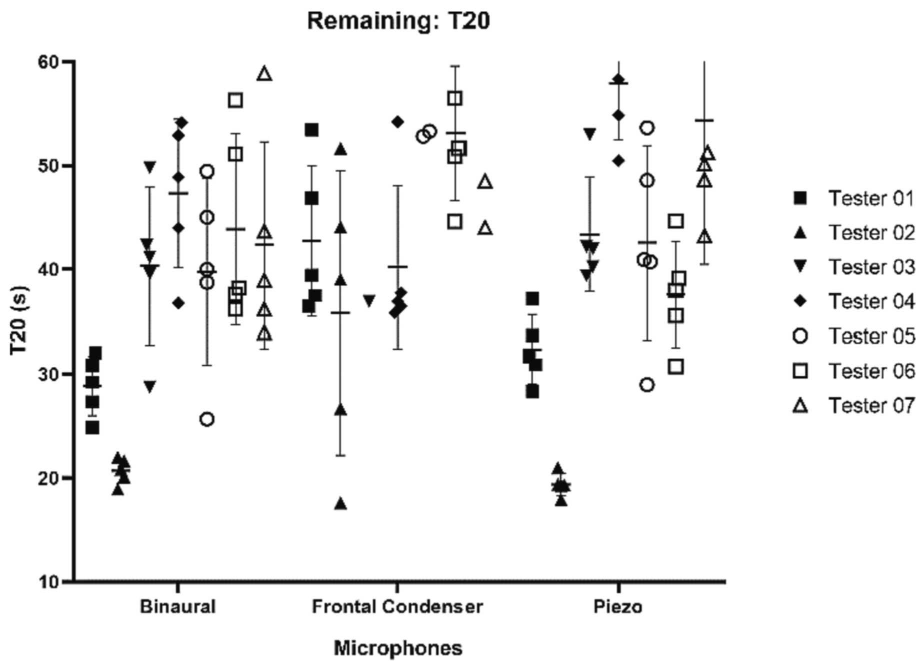


Fig. 21. Values of T20 in seconds (evaluated only on Remaining chewing's sound).

Table 6
Temporal parameters T20 (s) The values are expressed as Mean ± SD.

Microphone type	Remaining T20
Binaural	37.60 ± 10.92
Frontal condenser	55.93 ± 18.22
Piezo	41.08 ± 13.78

Then the sample was poured onto a stack of four sieves with decreasing mesh grids: Order 3350, 2500, 1000, 500 μm. The sample was positioned on the first 3350μ sieve arranged sequentially on the other sieves and the analysis was performed with following parameters: permanent vibration with amplitude 2 mm/g, for a time of 5 min of sieving, the particles retained on each sieve were weighed. The results were expressed as cumulative curves, using the weight of the particles that dropped through each sieve. From each curve, the median particle size (d50), defined as the aperture of a theoretical sieve through which 50 % of the weight of the fragmented food could pass.

The evaluation of the "Friability" is related with fracturability, so the particle size distribution was studied by collecting the data, as shown in the following Table 2, which contains the actual results for the crispbread employed as a test product in this study:

3.4. Three-point bending test

Bending and snapping tests are usually applied to food that is in the shape of a bar or sheet. The common type is the triple beam apparatus in which the piece of food rests on two supports and a third compressing wedge moves down between the two supports bending the food until it snaps (Fig. 12).

Bruns and Bourne [30] studied snapping in foods and found that the force required to snap a test specimen of uniform cross-section complies with mathematical models derived from engineering theory. For uniform bars with a rectangular cross-section the snapping equation is as follows:

$$F = 2/3\sigma_c bh^2/L$$

where F is the snapping force; σ_c, the failure stress; b, the width of beam; h, the height of beam; and L, the length of beam between supports. This type of test can measure the fracture and break strength of hard and brittle products (or their flexibility) by bending the sample, usually until a break occurs. Bending is a combination of compression, tension and some shear. These breaking/bending characteristics can be very important measurement for dry food, normally testing involves large deformations. Fracture and/or yielding then become the salient features. Foods that exhibit fracturability are products that possess a high degree of hardness and low degree of adhesiveness. Snap, meaning to break suddenly upon the application of a force, is a desirable textural property in most crisp foods, and other high turgor vegetable, and potato chips and other snack items. The sharp cracking sound that usually accompanies snapping is the result of high energy sound waves generated when the stressed material fractures rapidly and the broken parts return to their former configuration.

This test indicates product fracturability/brittleness/crispness and can be the major salient feature of a product.

Crispbread bar samples of 12 × 6.5 × 1 cm were stored at 25 °C before analysis. A force–displacement bending profile (as show in Fig. 13) was obtained for each sample using a three-point bending apparatus mounted on a texture analyzer (model TA-HDi, Stable Micro Systems, Godalming, U.K.).

The sample was held on two stationary bending supports, which distance is 90 % of the length of crispbread bar while being displaced at a central axis by the bending probe attached to the moving crosshead traveling at a speed of 1 mm/s. Each crispbread type was measured seven times and averaged.

4. Results

4.1. Selection of the microphone type and position

The acoustical parameters were examined to choose which of the three types of sensors have the major sensitivity and capability of discriminating different products.

The binaural headset microphones show larger SPL values, with flatter spectrum and lower noise along the considered frequency range (125 Hz – 4000 Hz) in comparison with the cardioid and piezo-electric

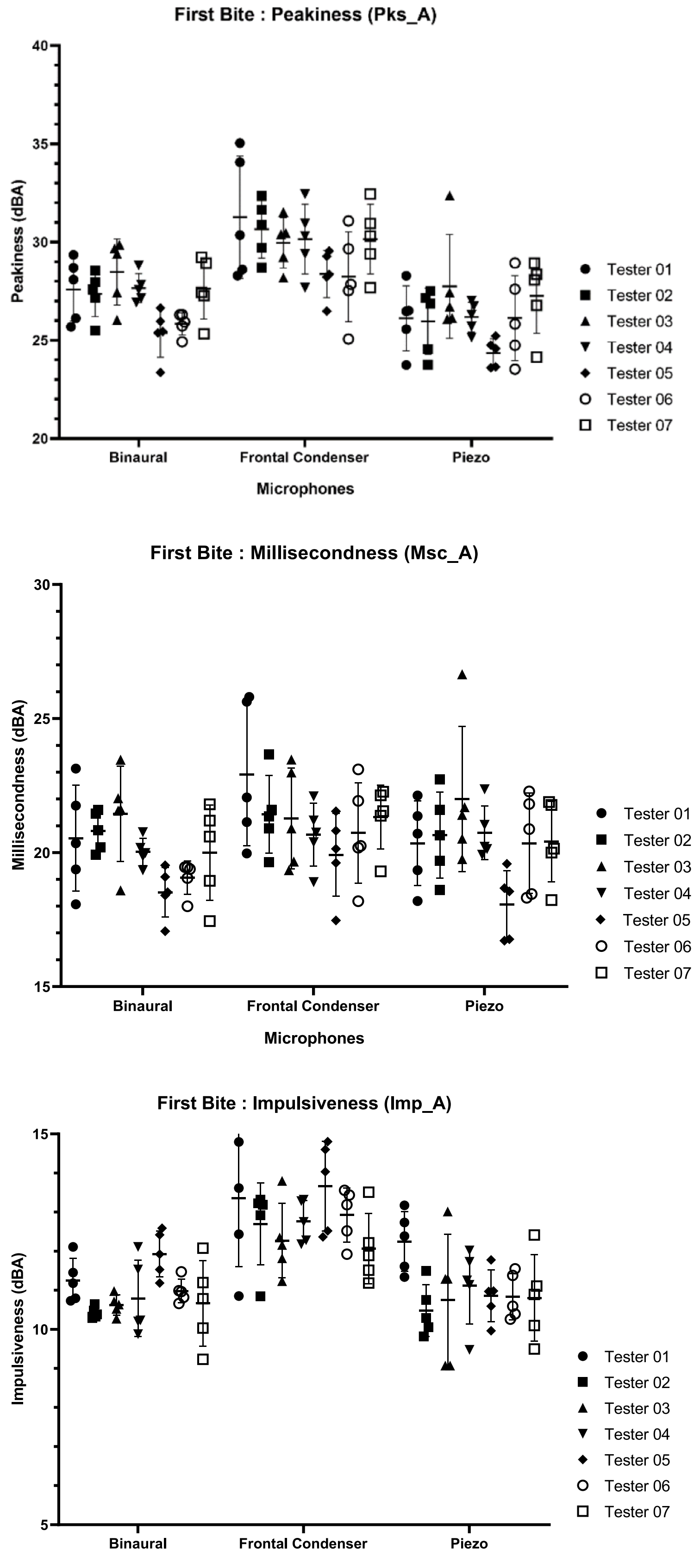


Fig. 22. Values of Peak-to-average ratios (dBA). Evaluated only on First Bite chewing's sound.

Table 7
Values of peak-to-average parameters (dBA) for first bite: Peakiness, Millisecondness, impulsiveness. The values are expressed as Mean ± SD.

Microphone type	Peakiness	Millisecondness	Impulsiveness
Binaural	27.18 ± 1.53	20.03 ± 1.52	10.96 ± 0.75
Frontal condenser	29.77 ± 2.08	21.26 ± 1.86	12.82 ± 1.15
Piezo	26.25 ± 1.87	20.36 ± 1.88	11.01 ± 1.03

transducers, as shown in Fig. 14.

Fig. 14 shows the variability of SPL values recorded with the three transducer types for the first bite and for the remaining. It appears evident how the use of binaural microphones results in smaller variance and more reproducible results than using the other two types of transducers.

In Fig. 15 the results for the spectral slope parameter "Slope2" (dB) (with demeaning) are shown. Slope2 is defined as L_signal at 4 kHz and at 250 Hz. Values in octave bands by the 3 microphones, from chewing's sound of crispbread from seven subject. First bite above, remaining chewing below.

Also, in this case the binaural microphones provided results with less variance, showing that these binaural transducers are the most accurate for evaluating these acoustical parameters.

4.2. Statistical analysis on chewings sounds

Statistical analysis and visualization of results for all the acoustical parameters computed by the Aurora Acoustical Parameters plugin were performed by using the software TIBCO Spotfire® Analyst (Version 12.0.1) and GraphPad Prism 8 software. Data were first tested for conformity to a normal distribution using the Shapiro-Wilk test, and then analyzed by Two-way ANOVA multiple comparison, followed by Tukey Post Test.

In the following subchapters we discuss the results for specific parameters.

4.2.1. Loudness

The first acoustical parameter considered is the sound signal loudness in wideband with A-weighting filter, Lsg_A, which is shown in Fig. 16 for First Bite and Remaining.

The Loudness of chewing's sound is A-weighted total sound pressure level (Lsg_A) in dBA, and are expressed as Mean ± SD from 5 samples for each subject. Significance within and between the groups was analyzed by Two-way ANOVA multiple comparison, followed by Tukey Post Test, using GraphPad Prism 8 software. Normality test was run by Shapiro-Wilk which indicated no evidence of non-normality in the data set. Normality was checked by Shapiro-Wilk and the results suggested no apparent violation of the assumption for the First Bite ($P = 0.3293$), for Remaining ($P = 0.7015$). The test was set at $\alpha = 0.05$.

The results show that the Binaural Microphones present significant difference respect the other two microphones in term of repeatability and reproducibility ($P < 0.0001$) as show in Table 3. Binaural microphones present larger sensitivity and low variance in term of loudness of chewing' sound emission.

4.2.2. Spectral balance parameters

The following Fig. 17 shows the results for **spectral slope**, for first bite and remaining, Fig. 18 shows the results for **spectral slope2**, Fig. 19 shows the results for **bass ratio** and Fig. 20 shows the results for **High ratio**.

This spectral parameter is the slope in dB/octave computed by the 7 values of signal level in the octave bands of: 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, 8 kHz. Results are expressed as Mean ± SD from 5 samples for each subject. Significance within and between the groups was analyzed by Two-way ANOVA multiple comparison, followed by Tukey Post Test, using GraphPad Prism 8 software. The Shapiro-Wilk normality test was run which indicated no evidence of non-normality

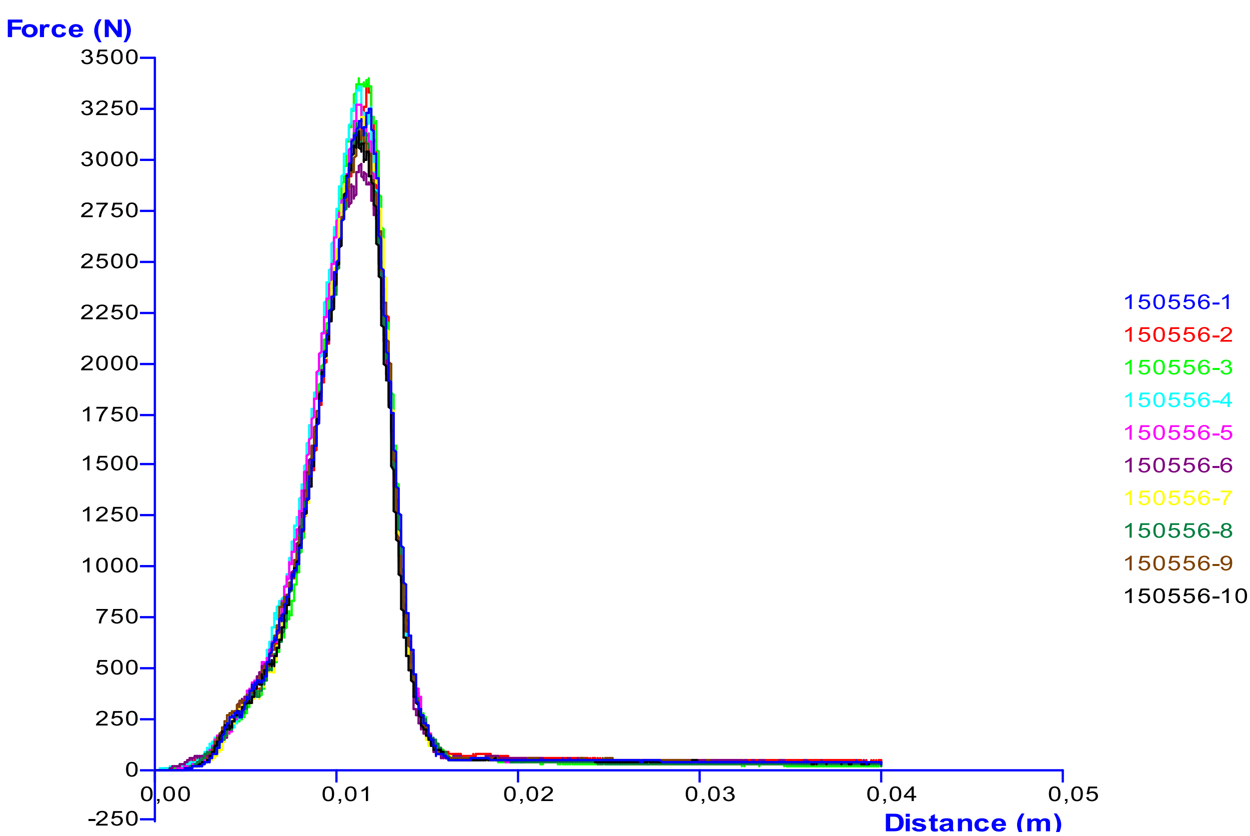


Fig. 23. Graph of Kramer shear press tests of crispbread (10 samples) Fracture Force (N).

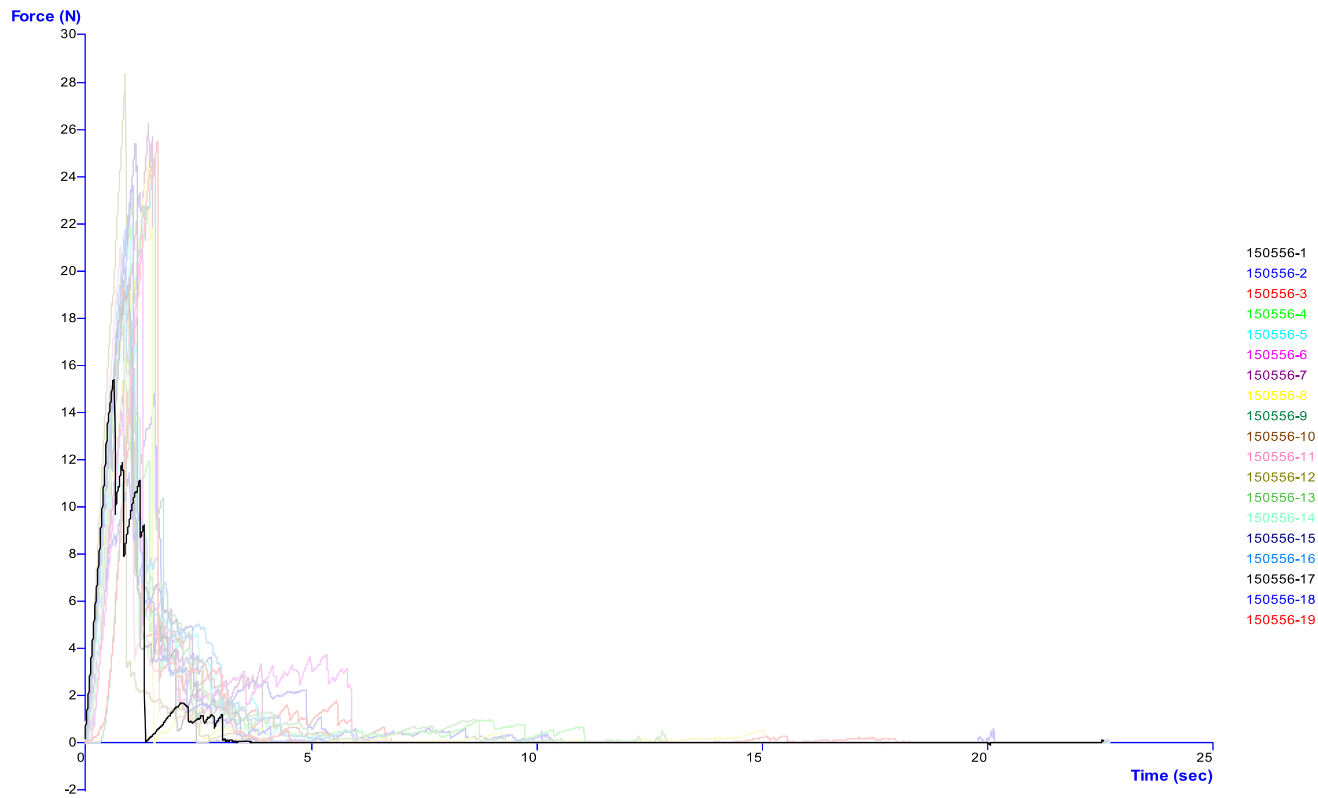


Fig. 24. Graph of Three-point bending tests of crispbread (19 samples). Fracture Force (N).

Table 8
Repeatability error of texture parameters. Fracture Force (N); Fracture Work (Nm). The values are expressed as Mean ± SD.

Texture test type	Fracture Force (N)	Fracture Work (Nm)
Kramer shear press test	3244.1 ± 122.1	16.2 ± 0.5
3-Bending Points	22.1 ± 3.5	22 ± 3.8

in the data set. With the assumption for the First Bite ($P = 0.2691$), for Remaining ($P = 0.2810$). The test were set at $\alpha = 0.05$.

Therefore, a Two-way ANOVA test was carried out.

The results, in the Fig. 17, represent significant difference in repeatability and reproducibility between the microphones factor during the First Bite and Remaining ($P < 0.0001$). In this spectral parameter evaluation, the Binaural microphones are more precise within and between the groups.

The Spectral Slope2 is the difference in dB between the signal level at 4 kHz and the signal level at 250 Hz. Results are expressed as Mean ± SD from 5 samples for each tester.

Significance within and between the groups was analyzed by Two-way ANOVA multiple comparison, followed by Tukey Post Test, using GraphPad Prism 8 software.

Normality test was run by Shapiro-Wilk which passed with the assumption for the First Bite ($P = 0.0562$), for Remaining ($P = 0.4940$). The test was set at $\alpha = 0.05$. Therefore, a Two-way ANOVA test was carried out.

The results represent significant difference in repeatability and reproducibility between the microphones factor during the First Bite and Remaining separately ($P < 0.0001$). Once again, the binaural microphones show better performance. In particular, regard the First Bite and Remaining for repeatability within and between the groups, the binaural show major reproducibility in the First Bite.

The Bass Ratio is the difference in dB between the average signal level at low frequencies (125 Hz; 250 Hz) and the average signal level at medium frequencies (500 Hz; 1000 Hz); it is expressed as Mean ± SD from 5 samples for each tester. Significance within and between the groups was analyzed by Two-way ANOVA multiple comparison, followed by Tukey Post Test, using GraphPad Prism 8 software.

Normality test was run by Shapiro-Wilk which passed with the assumption for the First Bite ($P = 0.5764$), for Remaining ($P = 0.0925$). The test was set at $\alpha = 0.05$. Therefore, a Two-way ANOVA test was carried out.

The results represent significant difference in repeatability and reproducibility between the microphones factor during the First Bite and Remaining ($P < 0.0001$). The Binaural Microphones are more accurate in terms of repeatability and reproducibility respect to the other two microphones.

The High Ratio is the difference in dB between the average signal level at high frequencies (2000 Hz; 4000 Hz) and the average signal level at medium frequencies (500 Hz; 1000 Hz); results are expressed as Mean ± SD from 5 samples for tester. The Normality test was run by Shapiro-Wilk which passed with the assumption for the First Bite ($P = 0.9053$), for Remaining ($P = 0.0530$). The test was set at $\alpha = 0.05$. Therefore, a Two-way ANOVA test was carried out.

Significance within and between the groups was analyzed by Two-way ANOVA multiple comparison, followed by Tukey Post Test, using GraphPad Prism 8 software. The results represent significant difference in repeatability and reproducibility between the microphones factor during the First Bite (especially) and Remaining ($P < 0.0001$).

The results of the 4 spectral balance parameters of First Bite and Remaining are reported in the following Tables 4 and 5.

The values are expressed as Mean ± SD.

The results of Table 4 and Table 5 shows that also for these four spectral balance parameters the Binaural microphones provide lower balance and average values close to an even spectrum with small values of slopes and tonal ratios. This means that the binaural microphones provide well equalized spectral response and low repeatability and

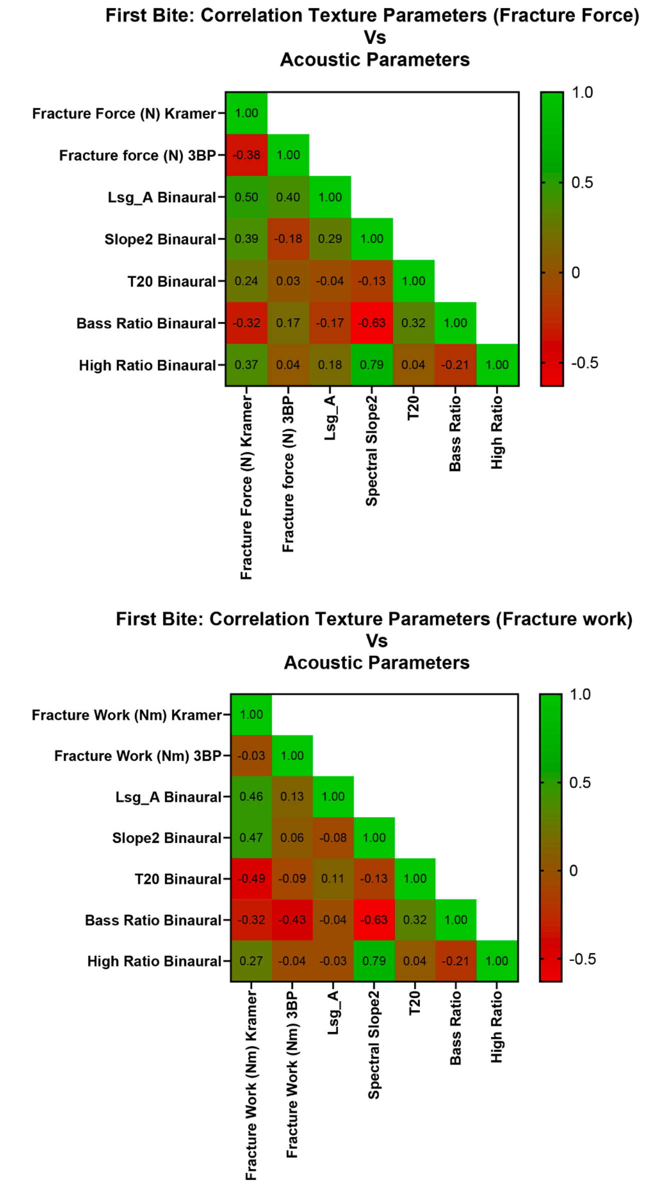


Fig. 25. Correlation matrix of Textural parameters versus Acoustical parameters (First Bite, with Fracture Force above, Fracture Work below). Two different textural tests Kramer shear press (Kramer) and Three-point bending (3 PB). Acoustical parameters Decay Time T20 (T20), Spectral Slope2 (Slope2). The correlation is shown by values ranges from −1 to +1 (where −1 shows inverse relationship between the values of the two variables and +1 shows the positive relationship. A correlation coefficient of zero means that there is no correlation at all between the values of the two variables. The correlation is shown with graded color scale (where red shows inverse correlation and green shows positive correlation).

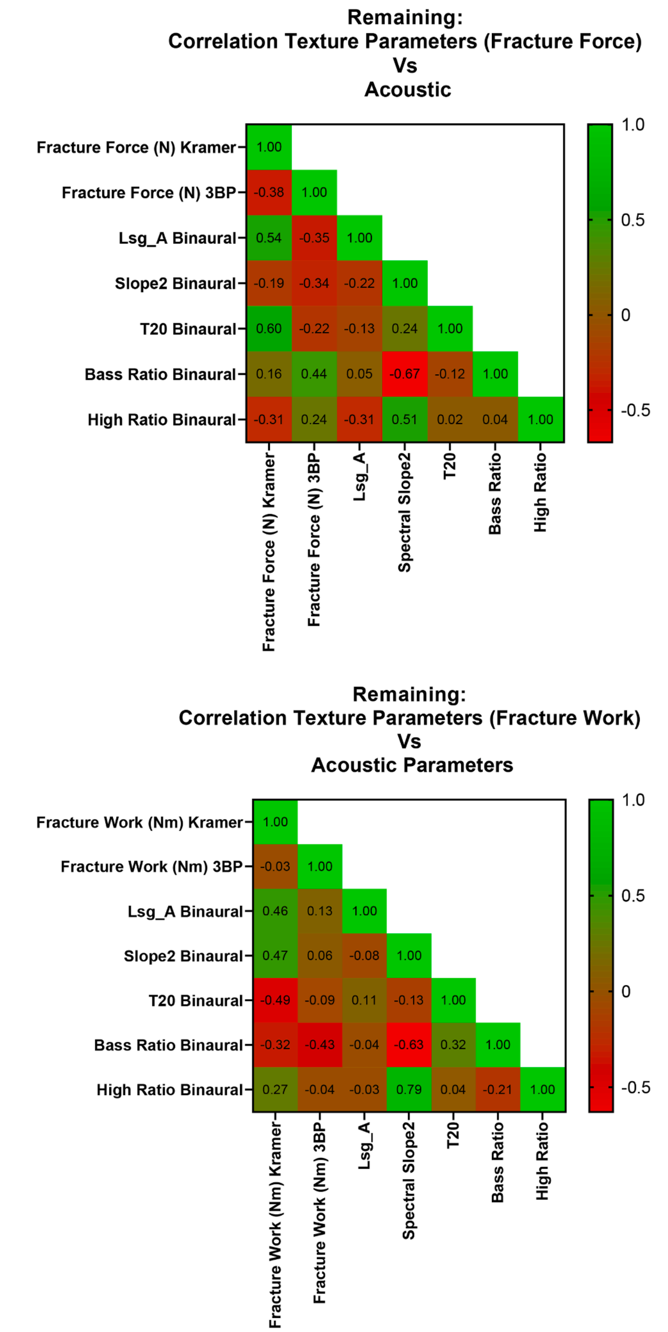


Fig. 26. Correlation matrix of Textural parameters versus Acoustical parameters (Remaining, with **Fracture Force** above, **Fracture Work** below). Two different textural tests Kramer shear press (Kramer) and Three-point bending (3PB). Acoustical parameters Decay Time T20 (T20), Spectral Slope2 (Slope2). The correlation is shown by values ranges from −1 to +1 (where −1 shows inverse relationship between the values of the two variables and +1 shows the positive relationship. A correlation coefficient of zero means that there is no correlation at all between the values of the two variables. The correlation is shown with graded color scale (where red shows inverse correlation and green shows positive correlation).

reproducibility error.

4.2.3. *Chewing duration*

For evaluating the average duration of chewing the T20 Parameter has been used. The results are shown in Fig. 21 and Table 6.

T20 is the time required for a decay of 60 dB, evaluated over a 20 dB range and is expressed as Mean ± SD from 5 samples for tester. Normality test was run by Shapiro-Wilk which passed with, for Remaining ($P = 0.6077$). The test was set at $\alpha = 0.05$. Therefore, a Two-way ANOVA test was carried out. Significance within and between the groups was analyzed by Two-way ANOVA multiple comparison, followed by Tukey Post Test, using GraphPad Prism 8 software. The results represent significant difference in repeatability and reproducibility between the microphones during the Remaining ($P < 0.0001$).

The results of T20 show much larger variability among testers than the previous parameters. But also, for a given tester the repeatability error is large, showing that this parameter is inherently worse than the previous parameters. Still the binaural microphones help in reducing such variability.

4.2.4. Peak – To average parameters

Fig. 22 and Table 7 show the results of Peakiness, Millisecondness and Impulsiveness parameters for the First Bite. These parameters are tailored to analyzing the sound peak produced while fracturing the product during the First Bite.

Peakiness, Millisecondness, impulsiveness, are SPL values (in dBA) of Peak-to-average ratios evaluated on the First Bite and are expressed as Mean ± SD from 5 samples for tester. The normality test was run by Shapiro-Wilk which passed for Millisecondness ($P = 0.7010$), Impulsiveness ($P = 0.5445$), Peakiness ($P = 0.9369$). The test was set at $\alpha = 0.05$. Therefore, a Two-way ANOVA test was carried out.

Significance within and between the groups was analyzed by Two-way ANOVA multiple comparison, followed by Tukey Post Test, using GraphPad Prism 8 software. The result represents significant difference in repeatability and reproducibility between the microphones during the First Bite ($P < 0.0001$) for Peakiness. Instead Millisecondness did not show significant difference in repeatability and reproducibility ($P = 0.0135$).

Impulsiveness shows significant difference in repeatability and reproducibility between the microphones during the First Bite ($P < 0.0001$), but it is not very significant when discriminating among testers ($P = 0.0025$).

The conclusion is again that binaural microphones are preferable for their smaller variance and the Peakiness parameter appears to be the most robust among the three.

4.3. Statistical analysis of texture tests

Texture tests have been performed with two devices (Kramer cell and 3-Bending Points) on a number of samples of the Crispbread product (10 samples for Kramer and 19 samples for 3BP). Of course, the results are not always exactly the same, exhibiting some repeatability error, as shown in the following Figs. 23 and 24 and in the corresponding Table 8.

The 3-bending points test seems to provide lower variability for the Fracture Force parameter and substantially the same significance for the fracture work. A better comparison could be made only by analyzing different products, which is beyond the scope of this paper.

4.4. Fracturability test

Fracturability tests have been performed on a number of samples of the Crispbread product, by analyzing the particle sizes resulting from the tests with the Kramer cell.

Table 1 shows the results on the 10 samples analyzed, in terms of average values and standard deviation of repeatability.

All these parameters show a good repeatability, meaning that the fracturability tests provide consistent results for a given product. Also in this case, a better evaluation of these parameters could only be done by performing tests on multiple products with different degrees of fracturability. For the same reason the fracturability test was not taken in account for following correlation test.

5. Comparison of the results and discussion

After the individual analysis of each technique, the present section aims to compare the results obtained and identify a possible correlation between the mechanical property estimated using Texture Analysis Profile (TPA) and acoustical property using Sound Profile Analysis (SPA), namely the modulus of fracture and the emitted sound during of chewing of the crispbread. The conclusions are important to point out practicability issues on how to perform condition assessment and characterization of mechanical properties and acoustical properties of the materials in dry foods as crispbread.

5.1. Correlation of textural parameters with acoustical parameters

The results of Figs. 25 and 26 shows the correlations between physical phenomenon by textural parameters and chewing's sound by acoustical parameters.

The correlation test was applied using GraphPad Prism 8 software. Only results from binaural microphones and the main parameters are taken in account. Considering the reduced data set was not found a strong correlation, the main reason is because this is a methodological comparison of three different types of acoustic transducers and thus only one food product was tested. Despite the need for more data and further validation, the results show that for the studied cases the acoustical tests provide a similar estimation of the mechanical properties of the crispbreads to the one obtained through sound testing. In any case, the positive correlation is still visible, even though the coefficient of determination is reduced (less than 0.64). The results of the first bite show a correlation of fracture force with Lsg_A (0.49) and Spectral Slope2 (0.39); the correlation fracture work of Kramer with Lsg_A (0.45) and Spectral Slope2 (0.46) considering the use of Binaural microphones. For the Remaining Binaural the most robust correlation are among the fracture force Kramer with Lsg_A (0.53) and Decay time T20 (0.60); the correlation fracture work Kramer with Lsg_A (0.58), Decay time T20 (0.64) and Bass Ratio (0.42).

6. Conclusions

This work provides a complete methodology for determining a Sound Profile Analysis (SPA) for dry foods. It was identified employing a representative sample of crisp foods.

Generally, food textural quality is evaluated by descriptive sensory analysis (subjective). The within-panel variability in sensory attributes and the subjectivity are an important limitation, which should be minimized as much as possible to obtain reliable conclusions [31]. Furthermore, the sensory evaluation of crispness and crunchiness is complex because the great variability in the definition of descriptors may depend on semantics. In fact, they are defined differently among dictionaries, consumers, and researchers.

These difficulties, together with the time required and the high cost of sensory evaluation, have demanded objective and quantitative measurement of the texture characteristics by instrumental analysis methods [32].

The acoustic characterization of the products has been done in a controlled acoustic room using different transducers, including binaural microphones. A recording test suitable for the case study was defined and a chewers group was selected. The statistical application allowed us to discriminate the data obtained from the acquisition step in order to obtain an accurate result. The recorded spectrum differed from subject to subject, which made it extremely difficult to use single or combined frequency bands as a common measure of crispness.

So, we defined some spectral slope parameters, enabling the comparison of different spectra of different subjects based on dimensionless ratios, which are more independent on the subject.

Repeating the test with a number of samples eaten by each subject and a number of different subjects enabled the evaluation of the repeatability and reproducibility error for each acoustical parameter. A similar repeatability analysis was performed on samples of the same product being tested with two texture analyzers and deriving a number of texture parameters.

The following acoustical parameters resulted as reliable descriptors of the sound emitted during chewing of crispbread products:

- Loudness: correlate with A-weighted total sound pressure level
- Spectrum: having measured the sound pressure levels in octave bands, and derived the tonal parameters Bass ratio, High ratio, Slope, Slope2.

We concluded that the best single parameter is Slope2 is one of the preferable acoustic parameters to use for better evaluate and discriminate dry food products by chewing's sound. Mainly when is combined with Binaural microphones in terms of accuracy between the signal level at 4 kHz and the signal level at 250 Hz.

- Temporal analysis: decay time T20 of the "remaining" of each sample, segment after the "First Bite."
- Peak-to-average ratios: of the three measured (peakiness, impulsiveness, millisecondness), measured on the First Bite (initial crack of the product) the most reliable one resulted to be peakiness.

Each of these 4 parameters maps to a different perceptual aspect of chewing crunchy food.

Regarding transducers for capturing the sound during chewing, the best ones resulted to be the binaural microphones, which are more sensible, less affected by ambient noise or reverberation, and providing lower variance of the results.

The binaural microphones show better performance. In particular, regard the First Bite and Remaining for repeatability within and between the groups, the binaural show major reproducibility in the First Bite. In term of comparison of textural properties versus with acoustical properties, again that binaural microphones are preferable for their better correlation with physical phenomenon by two textural parameters, fracture force which are more representative of first bite and fracture work for remaining chewing.

In conclusion, the procedure applied in the study, both mathematical approach and data processing, could be seen as a reference point for the design of a good product during prototyping in term of chewing's sound evaluation. It would be useful to improve the research work extending the analysis to a number of different subjects and crispbreads, for a better evaluating how the variations of the acoustical parameters are correlated with variation of the mechanical parameters measured on texture analyzers.

On the other hand, it would be useful to correlate the acoustical parameters measured with the method described in this paper with sensory results obtained by questionnaires administered to the subjects. Since the crispness and crunchiness are essential for quality assessment of these kind of crispbread products, the availability of an objective measurement method (an instrument able to measure the interaction between people and product during the whole consumption experience) and established acoustical parameters are very useful for performing objective comparative evaluations and optimizing the recipe of the product towards an established target.

The paper illustrates the need for more research in this field to further validate the technique, find appropriate correlations and eventually define other standards for acoustical testing so professionals can gain confidence on the method and allow its widespread use for characterization dry food products.

This work is a first step aimed to find the optimal recording procedure and equipment, the best acoustical parameters and to standardize the processing procedure. In a following work we will extend the study to a number of different food products of the same category (i.e. bread substitutes) and possibly enlarging the panel of subjects. These preliminary data on a single product allow already to speed up the following processing, avoiding to evaluate parameters which revealed to be unreliable or not statistically significant.

7. Ethical compliance

The experimental protocols were approved by the ethics committee of University of Parma.

CRediT authorship contribution statement

Piero Sabella: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Angelo Farina:** Writing – review & editing, Writing – original draft, Conceptualization, Investigation, Methodology, Formal analysis, Data curation, Validation, Visualization, Funding acquisition, Resources, Project administration, Software, Supervision. **Andrea Leporati:** Writing – review & editing, Visualization, Validation, Project administration, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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