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Hazelnut kernels (*Corylus avellana* L.) mechanical and acoustic properties determination: Comparison of test speed, compression or shear axis, roasting, and storage condition effect

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A B S T R A C T

The aim of this work was to compare different texture test conditions for the evaluation of instrumental mechanical and acoustic properties of raw and roasted hazelnut (*Corylus avellana* L.) kernels cv. Tonda Gentile Trilobata (TGT). A comparison of compression and shear tests, test speed (0.2, 1.0, 10.0 mm/s), and analyzed axis (x, y, z) combinations was performed. Joint mechanical and acoustic emission acquisitions were used for the first time on hazelnut kernels. The compression test method using 1.0 mm/s speed and analyzed on the x-axis showed the lowest variability of the results. These conditions were then used to evaluate raw kernels during 12 months of storage, conducted in-shell (at ambient temperature) and shelled (refrigerated, vacuum, frozen, with nitrogen modified atmosphere). The main differences among storage conditions were evidenced in rupture force, rupture slope and acoustic maximum peak parameters.

1. Introduction

The use of hazelnut (*Corylus avellana* L.) kernels in food production requires important quality standards, which can be affected by growing condition, cultivar, harvest, storage, and roasting process.

Hazelnut kernel quality standards may include physical (dimension, weight, color), compositional, mechanical-acoustic, and sensory properties. While the first properties are easily detectable, the others resulted to be more complex since they often require sample preparations and analysis, instrumental tests under specific conditions, and sensory tests. The latter, moreover, can be affected by subject-variability requiring an adequate number of trained panelists.

Previous studies regarding hazelnuts mechanical properties were mainly focused on the postharvest selection and shelling (Güner et al., 2003; Valentini et al., 2006; Delprete and Sesana, 2014; Bonisoli et al., 2015), storage conditions and moisture content (Borges and Peleg, 1997; Martinez-Navarrete and Chiralt, 1999; Aydin, 2002), and roasting process (Demir and Cronin, 2004; Alamprese et al., 2009; Delprete et al., 2015). Few studies linked the mechanical results with the sensory perceptions of the kernels (Saklar et al., 1999) or with the final food product preparations (Di Monaco et al., 2008).

An analysis of the current published literature highlight that no standardized test conditions are defined for the mechanical properties acquisition methods: test type and speed, used probe, compression axis and other method parameters often differ across studies. To our best knowledge, no studies have been evaluated if the results obtained using different test speeds or methods could be compared, or at least which difference they show.

Joint mechanical-acoustic determination on hazelnuts kernels is a novelty in current literature. The development of acoustic determinations on hazelnut kernels could permit the evaluation of crispness and crunchiness sensory perceptions, thus improving the quality assessment for food preparations. The unique interest found regarding acoustic techniques in this field was previously focused on very different applications, as the product selection of underdeveloped hazelnuts using acoustic impact methods (Onaran et al., 2006). Moreover, sensory-mechanical and sensory-acoustic correlation studies on hazelnuts are scarcely found in literature (Saklar et al., 1999), while some crispness studies were conducted on

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almonds, seed-type fruits already widely used in the sweet-type food preparations (Varela et al., 2006).

The present work aims to the evaluation and comparison of several test conditions on the mechanical-acoustic properties of both raw and roasted hazelnuts. Compression and shear tests were performed to understand how the differences between the results are induced by the test type, and to verify the tests robustness. The evaluation of the results obtained using several test speeds and considering the three nut compression axes could show a trend influenced by these conditions, which could affect also the variability of the results. Moreover, the different test conditions were evaluated also in the perspective of using fast tests to simulate the sensory approach, which is usually characterized by fast jaw movements and where acoustic perceptions have an important role. After the test comparison, the analysis of the results variability may indicate a optimal condition for the evaluation of mechanical-acoustic properties of hazelnut kernels. The optimized operating conditions were then used for the analysis of raw hazelnut kernels under different storage conditions during 12 months, to evaluate their mechanical and acoustic properties evolution.

The hazelnut cultivar chosen for this study was Tonda Gentile Trilobata (TGT), one of the most important varieties grown in northwest Italy, used both for consumption and in food preparations.

2. Materials and methods

2.1. Test comparison samples

C. avellana L. cultivar Tonda Gentile Trilobata hazelnuts were supplied by La Gentile srl (Cortemilia, CN, Italy). For the test comparison, the hazelnuts were shelled and the kernels treated as-is (raw) and after roasting (roasted at 160 °C, 30 min condition). The moisture content (AOAC, 2000) was of 4.08 ± 0.16% and 2.21 ± 0.13% w.b. for raw and roasted hazelnuts kernels, respectively. These samples were used for the test comparison trial, in order to evaluate the best conditions for the assessment of mechanical-acoustic properties of the analyzed hazelnut kernels.

2.2. Instrumental mechanical properties

For the evaluation of the mechanical and acoustic properties a TA.XTplus Universal Testing Machine (Stable Micro Systems, Godalming, UK) was employed with a 50 kg load cell and acquiring 250 points per second.

The hazelnuts kernels were analyzed at 20 ± 2 °C temperature along the compression axes x, y and z, corresponding to “the nut longitudinal axis through the hilum (length), the transverse axis containing the minor dimension (width), and the transverse axis containing the minimum dimension (thickness)”, respectively, as defined by Güner et al. (2003). The sample deformation was limited to 50% for all the determined parameters. This deformation percentage was found to be sufficient to break the kernel in all the tests conducted.

Two tests (compression and shear) were performed, using three different test speeds. For the compression test, a P/75 flat probe and HDP/90 platform (Stable Micro Systems) were used, while for the shear test a HDP/BS non-sharp single blade probe from the same manufacturer was employed. In order to evaluate the test speed effect, three different test speeds (0.2, 1.0, and 10.0 mm/s) were applied. The first value was determined in accordance to previously published articles which stated 10 mm/min (about 0.17 mm/s) as test speed (Borges and Peleg, 1997; Saklar et al., 1999; Demir and Cronin, 2004) and within the ASABE S368 (ASABE, 1995) standard provided range. The second value was applied from the works of Güner et al. (2003; 0.91 mm/s), Valentini et al. (2006) on unshelled hazelnuts, and Ghirardello et al. (2013) on shelled hazelnuts. The third value was tested as a very fast speed condition with no direct references in hazelnuts literature, but already used in the mechanical and acoustic evaluation of other kinds of fruits with the same blade probe (Giacosa et al., 2015) and generally used to simulate the sensory biting and chewing actions (Meullenet and Finney, 2002).

The force-distance parameters (Fig. 1a) were calculated by the Texture Exponent software (Stable Micro Systems) following the Saklar et al. (1999) method: rupture point (mm), rupture force (F1, N), rupture slope (E1, N/mm), and rupture energy (E1, mJ) at the first fracture point. In addition, the total energy (Wtot) was calculated as the area under the force-distance curve from the starting point to the end (50% deformation). The sample height (mm) was also acquired by the instrument at each run and used jointly with the rupture point to calculate the specific deformation (Braga et al., 1999) in percentage as follows: specific deformation (%) = (compression applied to the kernel until rupture point in mm/sample height in mm) × 100.

For the test comparison 40 hazelnuts kernels were randomly selected and analyzed for each test combination (product, test, axis, speed).

2.3. Instrumental acoustic properties

The instrumental acoustic properties evaluated during the mechanical test were acquired using an acoustic envelope detector (AED) (Stable Micro Systems) equipped with a 12.7-mm diameter Brüel & Kjær 4188-A-021 microphone (Nærum, DK). The microphone was positioned at an angle of 30° and at 40 mm distance

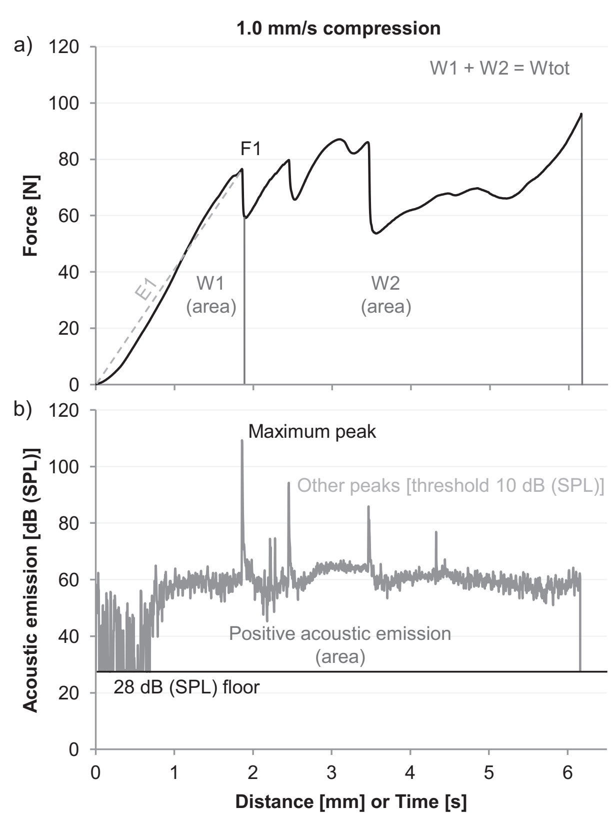

Fig. 1. Force-distance (a) and force (or time)-acoustic emission (b) curves of raw hazelnut kernel compression test (x-axis, 1.0 mm/s test speed).

from the sample (due to the shape of the probes), and connected to the AED unit, which was, in turn, connected to the TA.XTplus texture analyzer, thus allowing a joint measurement of force and acoustic emission. The instrument was calibrated before each session at 94 and 114 dB (sound pressure level as SPL) using a Brüel & Kjær model 4231 acoustic calibrator. In usual test conditions the registered noise was found to be 28 dB (SPL). No instrumental gain or filters were applied during the analysis.

The entire compression/shear test acoustic emission was acquired jointly with the mechanical response, and the following parameters were calculated from the acoustic curve (Fig. 1b) by the same software (Texture Exponent) used for the mechanical evaluations. The acoustic curve was re-plotted placing a floor equivalent to the noise value [28 dB (SPL)], thus removing any point below this value. On this curve the following parameters were calculated according to Torchio et al. (2012) and Giacosa et al. (2015): maximum acoustic emission peak [dB (SPL)], positive acoustic energy [dB (SPL) × s], acoustic peak number, and average peak emission [dB (SPL)] using a peak threshold value of 10 dB (SPL). In particular, the positive acoustic energy parameter was expressed as the area under the acoustic curve [dB (SPL)], with the graph axis units in seconds: from this calculus it was subtracted the energy corresponding to the average instrumental noise [28 dB (SPL)], thus keeping only the acoustic emission due to the sample test.

2.4. Storage trial

The suitable mechanical-acoustic test conditions investigated in the test comparison trial (1 mm/s compression test on 20 kernels) were applied on another set of raw TGT hazelnuts (provided by the same supplier) during a 12-months storage trial. A sample was taken at the beginning of the storage to perform the initial point mechanical-acoustic tests and the moisture content determination, this last parameter accounted for 3.98 ± 0.19% w.b. Then, the storage trial considered both in-shell hazelnuts at ambient temperature (10–25 °C, 60–80% RH, shelled only prior to mechanical-acoustic analysis) and shelled hazelnuts (kernels); the latter were separated in groups, allowing the application of different conditions: refrigerated (5 °C, 55% RH), refrigerated in a modified atmosphere (5 °C, 1% O_2, 99% N_2), refrigerated under vacuum (5 °C), flushed with nitrogen and then refrigerated under vacuum (5 °C), frozen under vacuum (−25 °C).

Woven polypropylene bags were used to store the hazelnuts during the 12-months period except for vacuum-stored trials, which required aluminum vacuum bags. At 4, 8, and 12 months of storage, 2-kg samples were taken from each storage condition for the evaluation of the mechanical-acoustic properties as previously described, using 1 mm/s as compression test speed and analyzing 20 kernels for each sample.

2.5. Statistical analysis

Statistical analysis was performed using the software package IBM SPSS Statistics (IBM Corporation, Armonk, NY, US). The Tukey-b test at $p < 0.05$ was used in order to establish statistical differences by one-way analysis of variance (ANOVA).

The coefficient of variation (CV) was calculated as CV = (standard deviation/average). The minimum number of samples was calculated according to the formula described by van Belle (2008) based on one group calculation:

$$\text{minimum number of samples} = \left[8\ (\text{CV})^2\right] \Big/ \left\{[\ln(0.90)]^2\right\}$$

where CV is the coefficient of variation and 0.90 is the ratio of the means (as 1–10% change in the mean evaluated). The result is then rounded by excess to the integer. The percentage change in the mean value was estimated after the tests by looking at the obtained data, as there were no suitable direct references in literature.

3. Results and discussion

3.1. Mechanical properties

Raw hazelnut kernels used in the test comparison trial and analyzed during the compression tests ($n = 120$) resulted to have the following dimensions: x-axis 12.73 ± 0.85 mm, y-axis 12.10 ± 0.65 mm, z-axis 11.04 ± 0.65 mm. As shown in Table 1, the specific deformation varied considerably in the shear test by test speed, axis, and product analyzed. In comparison, the compression test was less influenced by these conditions. However, the roasted products always showed lower values with respect to the raw samples analyzed using the same conditions, and significant differences were particularly found analyzing along the x-axis. These differences are understandable in regards to compositional and microstructural changes occurring with the roasting, such as those induced by moisture evaporation (Demir and Cronin, 2004).

The mechanical properties values are shown in Table 2. The rupture force compression data is coherent with other measurements done on the same hazelnut cultivar (Ghirardello et al., 2013) or on other varieties (Güner et al., 2003), either for raw or roasted kernels (Alamprese et al., 2009). The mechanical results are described and analyzed as influenced by test type (compression or shear), product (raw or roasted), test axis (x, y, z), and test speed (0.2, 1.0, 10.0 mm/s).

Table 1
Specific deformation (%) for the analyzed raw and roasted hazelnut kernels, by the compression/shear axis and test speed.

Product	Speed mm/s	x	y	z	*Sign.*[b]
Specific deformation (%) – Compression (flat probe)					
Raw	0.2	17.2 ± 3.6[B]	14.6 ± 2.4[A]	15.4 ± 3.6[abA]	**
	1.0	16.1 ± 3.1	14.4 ± 3.4	14.9 ± 3.7[a]	ns
	10.0	16.5 ± 5.7[AB]	14.1 ± 4.3[A]	17.1 ± 4.8[bB]	*
	Sign.[a]	ns	ns	*	
Roasted	0.2	15.1 ± 4.5[b]	13.4 ± 3.0	14.9 ± 3.8	ns
	1.0	13.0 ± 5.2[ab]	13.6 ± 3.6	14.5 ± 2.3	ns
	10.0	11.7 ± 5.1[a]	12.9 ± 5.2	13.8 ± 4.4	ns
	Sign.[a]	**	ns	ns	
Sign.[c]		*,**,***	ns, ns, ns	ns, ns,**	
Specific deformation (%) – Shear (non-sharp single blade probe)					
Raw	0.2	22.0 ± 3.4[cC]	14.0 ± 3.8[bA]	17.7 ± 4.0[cB]	***
	1.0	20.0 ± 4.2[bC]	13.3 ± 3.8[bA]	15.5 ± 3.7[bB]	***
	10.0	14.6 ± 3.3[aC]	8.9 ± 2.9[aA]	11.0 ± 3.6[aB]	***
	Sign.[a]	***	***	***	
Roasted	0.2	13.3 ± 4.3[bC]	8.7 ± 3.5[A]	11.2 ± 3.9[B]	***
	1.0	12.2 ± 3.9[abB]	8.1 ± 2.9[A]	9.2 ± 4.2[A]	***
	10.0	10.5 ± 3.6[a]	8.7 ± 4.3	10.0 ± 5.7	ns
	Sign.[a]	**	ns	ns	
Sign.[c]		***,***,***	***,***, ns	***,***, ns	

Values are expressed as average ± standard deviation ($n = 40$). Different lowercase letters within the same column indicate significantly different values among test speeds results in the same product-test type conditions (Tukey-b test, $p < 0.05$). Different uppercase letters within the same row indicate significantly different values between analysis axis results (Tukey-b test, $p < 0.05$).
x, y, z = compression or shear axis.
[a]: *, **, *** and "ns" means significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between values obtained with different test speeds.
[b]: *, **, *** and "ns" means significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between values obtained with different analysis axes.
[c]: *, **, *** and "ns" means significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between raw and roasted values for each of the three test speeds considered (0.2, 1.0, and 10.0 mm/s, respectively).

Table 2
Mechanical properties values, evaluated with two different tests on raw and roasted hazelnut kernels, by the compression axis and test speed.

Product	Speed mm/s	Compression (flat probe)				Shear (non-sharp single blade probe)			
		x	y	z	*Sign.*[b]	x	y	z	*Sign.*[b]
Rupture force [F1, N]									
Raw	0.2	80.85 ± 20.73^{A}	97.88 ± 19.03^{B}	95.60 ± 20.10^{aB}	***	27.98 ± 5.03^{cA}	27.38 ± 7.24^{cA}	33.75 ± 6.90^{cB}	***
	1.0	79.88 ± 12.77^{A}	97.15 ± 18.03^{B}	106.32 ± 23.54^{bC}	***	22.94 ± 4.52^{bAB}	21.08 ± 5.22^{bA}	25.20 ± 5.38^{bB}	**
	10.0	83.48 ± 20.54^{A}	97.26 ± 23.86^{B}	109.49 ± 23.61^{bC}	***	11.32 ± 2.92^{aA}	16.07 ± 4.82^{aB}	15.81 ± 4.45^{aB}	***
	Sign.[a]	ns	ns	*		***	***	***	
Roasted	0.2	70.50 ± 22.76^{bA}	89.73 ± 24.68^{B}	98.33 ± 30.22^{B}	***	8.29 ± 2.29^{bA}	9.56 ± 3.12^{A}	11.30 ± 2.67^{cB}	***
	1.0	59.56 ± 16.97^{aA}	91.26 ± 22.47^{B}	94.85 ± 21.68^{B}	***	6.58 ± 1.97^{aA}	8.92 ± 2.91^{B}	9.73 ± 3.13^{bB}	***
	10.0	52.54 ± 17.31^{aA}	85.14 ± 21.13^{B}	93.92 ± 22.12^{B}	***	6.30 ± 1.48^{aA}	8.20 ± 2.81^{B}	7.94 ± 2.06^{aB}	***
	Sign.[a]	***	ns	ns		***	ns	***	
Sign.[c]		*,***,***	ns, ns,*	ns,*,**		***,***,***	***,***,***	***,***,***	
Rupture slope [E1, N/mm]									
Raw	0.2	37.45 ± 6.09^{aA}	58.90 ± 14.67^{B}	59.43 ± 11.86^{aB}	***	9.50 ± 1.86^{bA}	15.39 ± 3.51^{bB}	16.93 ± 4.00^{cB}	***
	1.0	40.00 ± 5.83^{abA}	58.01 ± 12.10^{B}	67.20 ± 12.06^{bC}	***	8.75 ± 2.94^{bA}	13.21 ± 3.12^{aB}	14.76 ± 3.74^{bB}	***
	10.0	41.77 ± 6.36^{bA}	58.80 ± 12.47^{B}	62.65 ± 14.13^{abB}	***	5.73 ± 1.93^{aA}	13.67 ± 5.08^{abB}	12.15 ± 4.25^{aB}	***
	Sign.[a]	**	ns	*		***	*	***	
Roasted	0.2	37.90 ± 8.10^{A}	58.44 ± 12.14^{B}	63.97 ± 18.14^{B}	***	5.02 ± 1.08^{bA}	9.33 ± 2.80^{B}	9.89 ± 3.59^{B}	***
	1.0	39.00 ± 9.93^{A}	58.05 ± 16.12^{B}	61.36 ± 12.71^{B}	***	4.28 ± 1.15^{aA}	9.67 ± 4.26^{B}	10.73 ± 5.20^{B}	***
	10.0	39.18 ± 8.03^{A}	61.52 ± 13.26^{B}	63.62 ± 13.28^{B}	***	4.73 ± 1.45^{abA}	8.24 ± 4.01^{B}	8.28 ± 4.92^{B}	***
	Sign.[a]	ns	ns	ns		*	ns	ns	
Sign.[c]		ns, ns, ns	ns, ns, ns	ns,*, ns		***,***,*	***,***,***	***,***,***	
Rupture energy [W1, mJ]									
Raw	0.2	90.17 ± 43.51	87.72 ± 29.48	83.55 ± 35.57	ns	38.00 ± 12.34^{cB}	25.99 ± 11.20^{cA}	36.05 ± 12.73^{cB}	***
	1.0	81.06 ± 30.41	88.51 ± 36.20	92.16 ± 41.68	ns	31.30 ± 10.50^{bC}	19.59 ± 8.41^{bA}	25.06 ± 9.18^{bB}	***
	10.0	80.33 ± 58.10	75.88 ± 38.99	94.67 ± 8.59	ns	11.04 ± 3.91^{a}	9.61 ± 4.27^{a}	10.29 ± 4.58^{a}	ns
	Sign.[a]	ns	ns	ns		***	***	***	
Roasted	0.2	70.72 ± 39.29^{c}	74.57 ± 35.08^{b}	83.67 ± 46.31	ns	7.51 ± 3.96^{c}	6.42 ± 3.99	8.25 ± 3.83^{b}	ns
	1.0	47.40 ± 26.14^{bA}	80.88 ± 35.52^{bB}	74.81 ± 24.07^{B}	***	5.74 ± 3.27^{b}	5.43 ± 2.71	6.79 ± 6.30^{ab}	ns
	10.0	31.75 ± 21.46^{aA}	53.25 ± 26.60^{aB}	64.63 ± 36.43^{B}	***	4.10 ± 2.01^{a}	4.84 ± 3.77	4.64 ± 3.51^{a}	ns
	Sign.[a]	***	**	ns		***	ns	**	
Sign.[c]		*,***,***	ns, ns,**	ns,*,**		***,***,***	***,***,***	***,***,***	
Total energy [Wtot, mJ]									
Raw	0.2	499.9 ± 115.1^{b}	556.7 ± 118.0^{b}	525.3 ± 101.5^{ab}	ns	103.5 ± 27.0^{c}	104.8 ± 32.4^{c}	105.6 ± 30.8^{c}	ns
	1.0	485.7 ± 75.8^{bA}	530.6 ± 89.9^{bB}	563.4 ± 97.2^{bB}	***	87.7 ± 22.0^{b}	77.2 ± 23.5^{b}	78.2 ± 17.8^{b}	ns
	10.0	404.5 ± 108.6^{aA}	403.0 ± 139.2^{aA}	492.7 ± 88.1^{aB}	***	48.7 ± 12.8^{a}	47.0 ± 20.4^{a}	48.3 ± 15.1^{a}	ns
	Sign.[a]	***	***	**		***	***	***	
Roasted	0.2	499.0 ± 127.1^{c}	478.2 ± 118.1^{b}	523.2 ± 130.3^{b}	ns	45.2 ± 17.3^{bB}	45.9 ± 14.4^{bB}	34.2 ± 16.5^{bA}	**
	1.0	409.5 ± 157.0^{b}	450.4 ± 130.5^{b}	460.4 ± 112.2^{a}	ns	36.4 ± 13.0^{a}	36.9 ± 13.9^{a}	35.6 ± 14.1^{b}	ns
	10.0	327.3 ± 127.0^{aA}	351.3 ± 159.6^{aA}	448.4 ± 108.0^{aB}	***	29.5 ± 13.1^{aAB}	33.4 ± 11.4^{aB}	25.1 ± 10.7^{aA}	**
	Sign.[a]	***	***	*		***	***	**	
Sign.[c]		ns,**,**	**,**, ns	ns,***,*		***,***,***	***,***,***	***,***,***	

Values are expressed as average ±standard deviation ($n = 40$). Different lowercase letters within the same column indicate significantly different values among test speeds results in the same product-test type conditions (Tukey-b test, $p < 0.05$). Different uppercase letters within the same row indicate significantly different values between analysis axis results (Tukey-b test, $p < 0.05$).
x, y, z = compression or shear axis.
[a]: *, **, *** and "ns" means significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between values obtained with different test speeds.
[b]: *, **, *** and "ns" means significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between values obtained with different analysis axes.
[c]: *, **, *** and "ns" means significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between raw and roasted values for each of the three test speeds considered (0.2, 1.0, and 10.0 mm/s, respectively).

3.1.1. *Test type influence*

As expected, compression and shear tests gave substantially different results: the shear measurements showed lower values in all the force parameters evaluated due to the absence of sample compression after the first rupture, regardless of the test speed and compression/shear axis. Indeed, the shear test seemed to reduce, by the probe design, the energy contribution of the compressive action limiting only to the fracture event. The reduction between tests was also previously verified on extruded snacks when using 1.0 mm/s as test speed (Paula and Conti-Silva, 2014).

Given the shape of the probe, the shear test (done with a non-sharp blade like the model used in this study) can simulate the action of the incisor teeth on the hazelnut kernel, while the flat compression probe is aiming at the chewing action of the molar teeth (Tunick et al., 2013). This different response influenced by the probe type is clear when looking at the energy from the beginning to the first fracture point (W1) and at the total energy (Wtot) parameters, which marked a steep decrease in shear tests as a function of the deformation and force opposed by the sample.

The aforementioned probe shape difference could be important in studies aiming to correlate the mechanical properties with sensory characteristics: the crispness perception seems to be likely associated to the shear probe and the crunchiness to the compression probe. A single non-sharp blade can extend the applicability of the incisor teeth shear tests, generally carried out using a Volodkevich bite jaw probe (Volodkevich, 1938), also to irregular samples or samples larger than the pre-defined cross-section dimensions (10 mm × 10 mm). In addition, custom-made denture probes were tested and used on different foods for this aim (Meullenet and Finney, 2002; Giacosa et al., 2015). Therefore, the use of these probes can aid to better simulate the jaw action, hopefully improving the correlation between sensory and instrumental tests. Indeed, a better correlation between sensory and instrumental analyses when using the shear test (same blade type probe) instead of the compression flat probe was found when analyzing extruded snacks (Paula and Conti-Silva, 2014): the hardness perception was found to be positively correlated with the shear test results (called cut-guillotine in the cited article) as well as the fracturability and crunchiness perceptions, while for the crispness a positive not significant correlation was found.

3.1.2. Product influence

Roasted hazelnuts kernels showed lower values compared to the raw kernels in almost all observations. As previously discussed, compositional and microstructural changes during roasting, related also to the moisture evaporation (Demir and Cronin, 2004), induced these mechanical modifications. A very particular case was evidenced in the evaluation of the rupture slope (E1) parameter (Table 2), which resulted in lower but not significant differences between the two products in the compression tests. Therefore, the force-distance curve showed a similar force slope with the same angle, but, given the lower rupture force achieved, also a rupture energy (W1) reduction was found.

Differences due to nut roasting on the rupture force behavior were also found by Demir and Cronin (2004). Moreover, they also evidenced a very slight increase in whole kernel Young's modulus of elasticity parameter, from 4.81 ± 2.30 to 4.93 ± 3.03 MPa for the raw and roasted samples, respectively.

3.1.3. Test axis influence

The x-axis values can generally be significantly separated from those referred to the other two axes. X-axis data were generally lower except for the energy parameters (W1 and Wtot). A possible explanation was given in Table 1 data: y and z-axis compressed hazelnuts needed shorter deformation to fracture, and this parameter effectively affected the rupture force and slope measurements. Shorter deformations meant limited energy values, as they are represented by the area under the force curve.

Regarding to the specific influence of the compression axis, x-axis values seemed to show the highest differences between raw and roasted products.

There is very little specific literature regarding the test axis influence in hazelnut kernels analysis. Saklar et al. (1999) tested all the three axes and found the longitudinal axis as the most reproducible, but no figures related to the other axes measurements were shown. Güner et al. (2003) limited the kernel analysis to the x-axis. Delprete and Sesana (2014) analyzed 5 mm-cylinders specimens obtained from the kernel and considering the three kernel axes separately, with no significant differences in the reported Young's modulus values in relation to the analyzed axis: for the subsequent analysis the authors considered only the *A* direction (x-axis).

In other studies, the axis influence on hazelnut shell break energy values was found. Y-axis rupture force and energy figures were the lowest among shell break measurements in most cultivars (Valentini et al., 2006), although this behavior can be influenced by the nut shell moisture content (Güner et al., 2003).

3.1.4. Test speed influence

A decreasing effect on some parameters influenced by the test speed increase was found (Table 2) mainly in the shear test, both in raw and roasted kernels. As previously stated in this section, the shape of the probe influenced the response also in relation to the test speed condition.

Higher test speeds (10.0 mm/s) often presented the most variable results, and 0.2 and 1.0 mm/s tests seemed to give similar values at least for the x- and y-axis raw kernel compression analysis.

The test speed of 10.0 mm/s was chosen as substantially more similar than 0.2 and 1.0 mm/s tests to the jaw speed normally applied during the sensory tests for biting and chewing actions. Indeed, the use of different test speeds in mechanical tests obtained different results, and this aspect could influence the correlation between instrumental measurements and sensory judgments. Meullenet and Finney (2002) also evidenced this difference on other food products. The authors detected the real jaw speed, during biting (ranging from 19.8 to 35.1 mm/s), and they found better correlations between instrumental and sensory hardness assessments when both were conducted at a similar test speed. In addition, they did not find a significant correlation between the hardness of the food bitten and the jaw speed applied by the sensory judges, in contrast to other observations which indicated the jaw speed as induced by the nature of the food (Mioche and Peyron, 1995; Chen, 2009). Specific literature on hazelnut kernels, however, is not present at this time to our knowledge.

Based on these observations, test speeds lower than 10 mm/s seemed to be inadequate to a real correlation between sensory and instrumental mechanical measurements, at least for some types of food products. The test speed of 10.0 mm/s, previously used as predetermined speed (Meullenet and Finney, 2002), could be better suited in this kind of correlation and, given the results obtained in this study, it could be tested in hazelnut kernels standard instrumental-sensory studies. Test speeds equal or higher than 20 mm/s, although not tested in this study, could potentially give more similar results related to the sensory perceptions.

3.2. Acoustic properties

The acoustic properties results are shown in Table 3. With the exception of the acoustic maximum peak, the acoustic measurements were highly influenced by the different test speed. This was caused by several aspects: the time required to reach the 50% of sample deformation was longer for the slower tests, they were generally characterized by higher specific deformation values (Table 1), and most importantly a different test speed influences the acoustic data obtained due to product micro-fractures during the test and possible noise. Therefore, a normalization by the test speed parameter is not feasible: acoustic measurements simply explain different aspects of the compression according to the chosen test speed, making really important the choice of this parameter, particularly for mechanical-sensory studies.

Acoustic tests were usually associated to the maximum acoustic emission during the product fracture, as a possible indication of the crispness perception (Saeleaw and Schleining, 2011). Among compression axes, x-axis analysis gave some of the highest maximum peak values, particularly in raw kernels, with the maximum of 96.2 dB (SPL) reached in the compression tests at 10.0 mm/s. Lower values were detected in the shear test mainly for roasted kernels.

In the shear test, the 1.0 mm/s test condition seemed to be more able to discriminate raw and roasted samples by their acoustic peak number parameter. A decrease of this parameter was caused by the roasting process for all the three different shear axes tested. By comparing with the other values found, the coefficient of variation was rather low for this kind of measurements in the raw product analysis, being less than 30% for the three axes measured; the roasted samples, instead, showed the highest coefficient of variation of the whole group. In the compression test, the 0.2 mm/s test condition seemed to be the more able to discriminate raw and roasted samples for the same parameter.

The test speed induced a interesting behavior in the acoustic peak number and average emission results: as previously discussed, slower test speeds increased the test time and hence the possibility of acoustic events. This is verified as the peak number was found about ten times higher in the 0.2 mm/s trials with respect to those conducted at 1.0 mm/s. Nevertheless, sound events

Table 3
Acoustic properties values, evaluated with two different tests on raw and roasted hazelnut kernels, by the compression axis and test speed.

Product	Speed mm/s	Compression (flat probe)				Shear (non-sharp single blade probe)			
		x	y	z	*Sign.*^{b}	x	y	z	*Sign.*^{b}
Acoustic maximum peak [dB (SPL)]									
Raw	0.2	92.0 ± 9.3^{aB}	87.4 ± 7.8^{aA}	87.6 ± 8.6^{A}	*	93.2 ± 4.0^{cB}	91.1 ± 6.2^{bAB}	88.1 ± 8.9^{bA}	**
	1.0	92.2 ± 7.3^{aB}	89.4 ± 8.0^{aAB}	87.7 ± 7.2^{A}	*	80.3 ± 5.8^{bB}	77.9 ± 8.2^{aAB}	75.9 ± 8.1^{aA}	*
	10.0	96.2 ± 7.4^{bB}	93.4 ± 8.1^{B}	89.3 ± 7.2^{A}	***	68.7 ± 8.0^{aA}	76.4 ± 8.7^{aB}	76.3 ± 6.4^{aB}	***
	Sign.^{a}	*	**	ns		***	***	***	
Roasted	0.2	90.3 ± 9.6^{AB}	92.5 ± 6.5^{aB}	87.8 ± 8.8^{aA}	ns	76.5 ± 6.6	76.1 ± 6.9^{ab}	78.8 ± 7.7^{b}	ns
	1.0	92.8 ± 7.3	92.4 ± 8.7^{a}	90.4 ± 8.6^{ab}	ns	75.1 ± 6.5^{A}	78.6 ± 6.8^{bB}	74.3 ± 6.4^{aA}	*
	10.0	93.0 ± 5.9^{A}	97.4 ± 6.2^{bB}	93.6 ± 7.4^{bA}	**	75.1 ± 9.8	74.2 ± 9.2^{a}	73.5 ± 9.8^{a}	ns
	Sign.^{a}	ns	**	**		ns	*	**	
Sign.^{c}		ns, ns,*	**, ns,*	ns, ns,*		***,***,**	***, ns, ns	***, ns, ns	
Positive acoustic energy [dB (SPL) × s]									
Raw	0.2	26.6 ± 14.4^{b}	27.3 ± 13.3^{b}	25.7 ± 12.0^{b}	ns	164.2 ± 87.7^{b}	172.7 ± 107.1^{c}	149.2 ± 94.0^{c}	ns
	1.0	219.4 ± 16.8^{cC}	211.2 ± 19.5^{cB}	184.4 ± 10.3^{cB}	***	160.6 ± 35.2^{bB}	110.2 ± 35.3^{bA}	99.7 ± 28.5^{bA}	***
	10.0	14.4 ± 2.8^{a}	13.1 ± 2.8^{a}	13.2 ± 2.2^{a}	ns	2.6 ± 1.0^{aA}	5.0 ± 3.5^{aB}	5.7 ± 3.6^{aB}	***
	Sign.^{a}	***	***	***		***	***	***	
Roasted	0.2	76.3 ± 50.2^{bB}	82.0 ± 82.3^{bB}	34.4 ± 22.6^{bA}	***	91.1 ± 64.5^{b}	72.4 ± 50.3^{b}	66.1 ± 55.9^{b}	ns
	1.0	212.8 ± 24.4^{cC}	194.7 ± 25.1^{cB}	171.3 ± 18.8^{cA}	***	185.5 ± 19.7^{cC}	173.8 ± 18.0^{cB}	153.8 ± 17.7^{cA}	***
	10.0	19.1 ± 4.9^{a}	19.6 ± 3.5^{a}	19.5 ± 3.1^{a}	ns	3.0 ± 1.2^{a}	3.4 ± 1.6^{a}	3.0 ± 1.0^{a}	ns
	Sign.^{a}	***	***	***		***	***	***	
Sign.^{c}		***, ns,***	***,**,***	*,***,***		***,***, ns	***,***,*	***,***,***	
Acoustic peak number [−]									
Raw	0.2	175.1 ± 90.0^{b}	172.0 ± 71.4^{b}	158.6 ± 65.8^{b}	ns	370.6 ± 160.9^{c}	389.0 ± 149.3^{c}	456.2 ± 199.3^{c}	ns
	1.0	13.5 ± 6.3^{aA}	17.4 ± 10.3^{aA}	23.7 ± 10.8^{aB}	***	119.2 ± 28.9^{b}	130.3 ± 31.8^{b}	119.3 ± 27.4^{b}	ns
	10.0	20.2 ± 3.4^{a}	19.0 ± 3.4^{a}	18.6 ± 3.2^{a}	ns	6.4 ± 2.8^{aA}	10.4 ± 4.8^{aB}	10.8 ± 4.8^{aB}	***
	Sign.^{a}	***	***	***		***	***	***	
Roasted	0.2	350.8 ± 144.0^{bB}	323.9 ± 161.1^{cB}	200.6 ± 77.1^{cA}	***	385.8 ± 147.6^{cB}	326.3 ± 130.1^{bAB}	285.2 ± 118.5^{bA}	**
	1.0	20.8 ± 15.7^{aA}	32.7 ± 19.3^{bB}	44.1 ± 23.6^{bC}	***	36.8 ± 23.2^{b}	41.5 ± 19.8^{a}	39.9 ± 20.4^{a}	ns
	10.0	17.1 ± 4.7^{aB}	15.9 ± 3.4^{aAB}	14.4 ± 3.3^{aA}	**	6.5 ± 3.0^{a}	7.7 ± 3.4^{a}	6.7 ± 2.4^{a}	ns
	Sign.^{a}	***	***	***		***	***	***	
Sign.^{c}		***,**,**	***,***,***	*,***,***		ns,***, ns	*,***,**	***,***,***	
Average acoustic peak emission [dB (SPL)]									
Raw	0.2	48.4 ± 1.2^{a}	48.6 ± 1.1^{a}	49.0 ± 1.7^{a}	ns	55.6 ± 2.6^{B}	55.0 ± 2.4^{aB}	53.0 ± 2.1^{aA}	***
	1.0	72.3 ± 4.4^{cB}	70.0 ± 6.0^{cB}	66.4 ± 5.7^{bA}	***	57.2 ± 3.8^{B}	53.6 ± 3.9^{aA}	53.4 ± 3.6^{aA}	***
	10.0	65.7 ± 3.2^{bA}	65.9 ± 3.8^{bA}	67.9 ± 4.0^{bC}	*	55.9 ± 3.8^{A}	58.4 ± 3.6^{bB}	59.9 ± 3.9^{bB}	***
	Sign.^{a}	***	***	***		ns	***	***	
Roasted	0.2	49.6 ± 1.5^{aB}	49.8 ± 1.9^{aB}	48.2 ± 1.4^{aA}	***	51.1 ± 3.5^{a}	49.6 ± 2.8^{a}	49.8 ± 2.9^{a}	ns
	1.0	66.7 ± 6.7^{bB}	63.2 ± 5.4^{bA}	61.3 ± 5.5^{bA}	***	57.7 ± 4.5^{b}	57.4 ± 3.8^{b}	56.5 ± 3.9^{b}	ns
	10	66.9 ± 6.6^{bA}	69.0 ± 5.5^{cAB}	70.1 ± 4.6^{cB}	*	58.1 ± 5.5^{b}	59.0 ± 5.1^{b}	58.3 ± 4.1^{b}	ns
	Sign.^{a}	***	***	***		***	***	***	
Sign.^{c}		***,***, ns	**,***,**	*,***,*		***, ns,*	***,***, ns	***,***, ns	

Values are expressed as average ±standard deviation ($n = 40$). Different lowercase letters within the same column indicate significantly different values among test speeds results in the same product-test type conditions (Tukey-b test, $p < 0.05$). Different uppercase letters within the same row indicate significantly different values between analysis axis results (Tukey-b test, $p < 0.05$).
x, y, z = compression or shear axis.
[a]: *, **, *** and "ns" means significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between values obtained with different test speeds.
[b]: *, **, *** and "ns" means significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between values obtained with different analysis axes.
[c]: *, **, *** and "ns" means significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between raw and roasted values for each of the three test speeds considered (0.2, 1.0, and 10.0 mm/s, respectively).

recorded at 0.2 mm/s test speed had a very low average intensity compared to the other speed conditions, evidencing little but continuous fractures during the compression/shear test. Some differences were found between raw and roasted hazelnuts in the average peak emission, but the most discriminating parameter between the two groups was the number of detected peaks: a general increase was found from raw to roasted kernels in compression tests, while a different trend was observed in shear tests. Anyway, test speed accounted for the biggest changes.

Another parameter, the positive acoustic energy, could be also linked to the moisture content and to the crispness parameter of a series of samples (Aboonajmi et al., 2015). Slower (and therefore long) compression tests accounted for low positive acoustic energy. The difference found between 1.0 and 10.0 mm/s measurements, although seems to be wide, just reflects the shorter test time.

As previously noted, the analysis of acoustic emission at 10.0 mm/s reduced the information acquired. Therefore, it is not the best condition for the evaluation of the acoustic properties, but it can be useful when only the general perception is required (i.e. few peaks or maximum peak detection) particularly for mechanical-sensory tests, with maximum acoustic peak and (positive) acoustic energy being the candidate instrumental parameters to be correlated with crispness/crunchiness perceptions. In addition, the acquisition at 250 points per second is adequate for the evaluation of force events, but for the acoustic measurements in very fast tests a higher acquisition rate, when possible, is favorable.

3.3. Sample variability and minimum number of samples

While the instrumental mechanical-acoustic test can be considered fast, the analysis of several different batches composed by 40 hazelnut kernels may require long times. A optimization of the analysis method was carried out calculating the minimum number of samples (i.e. sample size) advisable for each of the tested conditions, according to the formula described by van Belle (2008). The results are shown in Table 4, based on the coefficient of variation (CV) calculated from the values found in Tables 2 and 3 (40 hazelnut kernels observation).

Table 4
Calculated minimum sample number needed to obtain a theoretical 10% average deviation on the mechanical and acoustic parameters.

Parameter	Product	Speed mm/s	Calculated min. Sample number – Compression test			Calculated min. Sample number – Shear test		
			x	y	z	x	y	z
Rupture force [F1, N]	Raw	0.2	48	28	32	**24**	51	31
		1.0	**19**	25	36	29	45	33
		10.0	44	44	34	49	65	58
	Roasted	0.2	76	55	69	56	77	41
		1.0	59	44	**38**	65	77	75
		10.0	79	45	40	**40**	85	49
Rupture slope [E1, N/mm]	Raw	0.2	20	45	29	**28**	38	41
		1.0	**16**	32	24	82	41	47
		10.0	17	33	37	83	100	89
	Roasted	0.2	33	32	58	**34**	65	95
		1.0	47	56	**31**	53	140	170
		10.0	**31**	34	32	68	171	255
Rupture energy [W1, mJ]	Raw	0.2	168	**82**	131	**76**	134	90
		1.0	102	121	148	82	134	97
		10.0	377	191	190	91	143	143
	Roasted	0.2	223	160	221	200	279	**156**
		1.0	220	139	**75**	233	180	621
		10.0	330	180	229	173	438	414
Total energy [Wtot, mJ]	Raw	0.2	39	33	27	50	69	62
		1.0	**18**	21	22	46	67	**38**
		10.0	52	86	24	51	136	71
	Roasted	0.2	47	44	45	105	**71**	168
		1.0	106	61	43	93	102	113
		10.0	109	149	**42**	142	84	132
Acoustic maximum peak [dB (SPL)]	Raw	0.2	<8	<8	<8	<8	<8	<8
		1.0	<8	<8	<8	<8	<8	9
		10.0	<8	<8	<8	10	10	<8
	Roasted	0.2	9	<8	<8	<8	<8	<8
		1.0	<8	<8	<8	<8	<8	<8
		10.0	<8	<8	<8	13	12	13
Positive acoustic energy [dB (SPL) × s]	Raw	0.2	211	171	157	206	278	286
		1.0	<8	<8	<8	**35**	74	60
		10.0	28	34	21	116	353	291
	Roasted	0.2	312	727	311	361	348	515
		1.0	10	12	**9**	9	**<8**	10
		10.0	48	24	19	121	151	74
Acoustic peak number [–]	Raw	0.2	191	125	125	136	107	138
		1.0	158	254	150	43	43	**39**
		10.0	**21**	24	22	139	152	145
	Roasted	0.2	122	179	107	106	115	125
		1.0	413	253	208	287	165	189
		10.0	55	**34**	38	152	139	**95**
Average acoustic peak emission [dB (SPL)]	Raw	0.2	<8	<8	<8	<8	<8	<8
		1.0	<8	<8	<8	<8	<8	<8
		10.0	<8	<8	<8	<8	<8	<8
	Roasted	0.2	<8	<8	<8	<8	<8	<8
		1.0	<8	<8	<8	<8	<8	<8
		10.0	<8	<8	<8	<8	<8	<8

Values calculated accordingly to van Belle (2008) using the coefficient of variation values from Tables 2 and 3, obtained on 40 observations. Lowest values in the same test type, parameter, and product are in boldface.

A lower calculated number of samples was generally required for the analysis of raw hazelnuts rather than of the roasted products. Acceptable values, sometimes less than 20, were found for the rupture force (F1), rupture slope (E1), and total energy (Wtot) mechanical parameters, particularly for the x-axis measurements carried out at 1.0 mm/s. The rupture energy (W1) parameter showed a high variability in almost all the test conditions, although the x-axis analysis of raw products in the shear test marked the lowest results, probably due to the test design limited only on the fracture event (as discussed in section 3.1.1). However, this effect on roasted products was not evidenced.

Regarding acoustic tests, a flat 10% estimated deviation for all the parameters was not found completely satisfactory: the peak emission parameters showed very low deviations, but in contrast positive acoustic energy and peak number parameters required higher estimated deviation values. However, lower sample size results were found for the positive acoustic energy parameter using 1.0 mm/s as test speed, generally with low influence of the test axis. The acoustic peak number parameter, for the considerations expressed in section 3.2, accounted for a lower calculated sample number when analyzing at 10.0 mm/s in compression tests.

3.4. Correlation study on the obtained parameters

Pearson's correlation tests were performed on the results, with the main aim to investigate a possible influence of the sample height limited to the x-axis observations, and hence the possible normalization between the force parameters and the sample height, which could be useful in the comparison of different hazelnut kernel samples. The correlations were carried out separately for each test speed, product, and test type combination ($n = 40$ for each trial).

No significant correlations between the mechanical parameters and the sample height were found in the samples analyzed using a test speed of 10.0 mm/s. In addition, no significant correlations were found between rupture force (F1) and sample height in compression tests, as also previously found by Demir and Cronin (2004) using 10 mm/min (about 0.17 mm/s) as test speed. The only significant correlation between rupture force (F1) and sample height parameters was found in 1.0 mm/s roasted kernels shear test, although a low correlation coefficient was achieved ($R = 0.342$; $p = 0.031$).

Negative correlations between sample height and the rupture slope (E1) parameter were found when analyzing raw hazelnut kernels at 1.0 mm/s (compression: $R = -0.524$, $p = 0.001$; shear: $R = -0.692$, $p < 0.001$). A correlation was found also in the roasted kernels analysis, but only for the compression test, with the acoustic peak number (0.2 mm/s test speed: $R = 0.345$, $p = 0.027$; 1.0 mm/s test speed: $R = -0.426$, $p = 0.006$), however the different sign between the test speed trials showed a different response influenced by the test condition.

In compression tests, sample height and positive acoustic energy were correlated in four out of six cases, with strong positive correlations when using 1.0 mm/s as test speed (raw $R = 0.920$, $p < 0.001$; roasted $R = 0.876$, $p < 0.001$).

The possibility of a linkage between mechanical and acoustic parameters was also investigated, limitedly to the x-axis measurements: in general very poor correlations were found, the only strong one was found between the rupture slope (E1) and the maximum acoustic peak ($R = 0.562$; $p < 0.001$) when analyzing roasted hazelnut kernels at 0.2 mm/s compression test speed. This was foreseeable, as less elastic kernels (higher E1 parameter) could break intensely and so release a high acoustic emission during the first or subsequent breakages; however, at this time there is not sufficient specific evidence to confirm this.

3.5. Method application: mechanical-acoustic properties of hazelnuts under different storage conditions

The resulting test speed condition discussed in the section 3.3 (1.0 mm/s test speed) limited to compression test was applied in the evaluation of the compressive behavior of raw hazelnuts during 12-months storage. All the three kernel compression axes were considered in separate tests, however since the x-axis seemed to give less variable results in the previous test comparison it was considered as the main analysis axis. The sample size of 20 kernels was chosen in accordance with the calculated values shown in Table 4, where rupture force (F1), rupture slope (E1), and total energy (Wtot) mechanical parameters obtained a calculated minimum sample number of 19, 16, and 18, respectively. Also some acoustic parameters showed very low calculated minimum sample numbers (below 10) when expecting a maximum 10% variability. Following the sample size choice, the acoustic peak number parameter was not calculated because of the very high sample size required for getting useful results.

The x-axis analysis storage trial results are shown in Table 5. All the storage conditions maintained well the mechanical characteristics of the kernels until 8 months of storage, with no or little significant differences in mechanical parameters from the beginning and at 4 months.

After 12 months of storage, the in-shell condition showed a important decrease in kernel rupture force (F1) and slope (E1), in relation to the previous points. While the rupture energy (W1) didn't significantly change between points, the raw kernels sustained a higher deformation, gaining elasticity and lowering their rupture slope ratio. It is worth to remember that this storage condition was kept at ambient temperature (10–25 °C in the experiment), which was sensibly higher with respect to the other conditions temperature (5 °C, and the frozen trial kept at −25 °C). In previous studies, the variations of temperature from 4 °C to 10 °C in short 12-days storage showed differences both in sensory and instrumental firmness values, these parameters resulted well-maintained at lower temperatures (Moscetti et al., 2012). Lower firmness and higher elasticity characterizing the 12-months in-shell condition represent a loss in texture structure and may affect the sensory quality, although the presence of the shell during storage in this particular condition could aid in the protection from rancid sensory perceptions (San Martín et al., 2001).

The importance of the changes occurred in the in-shell trial could be also evidenced by the acoustic maximum peak parameter, which fell down by almost 10 units between the previous points and the 12-months point. In-shell was the only storage condition where this happened, although not significant decreases were found for all conditions: in particular, a decrease from around 100 to 94–95 dB (SPL) occurred in all the trials kept under vacuum.

The other considered acoustic parameters showed very important changes during storage. The 12-months point accounted for the highest differences between storage conditions. In particular, the refrigerated condition in 99% N_2, 1% O_2 atmosphere resulted the most different from the others, with higher values of positive acoustic energy and average peak emission. Moreover, the highest acoustic maximum peak average value at 12-months point was registered in this storage condition, although it resulted not significantly different from the other conditions tested except for the in-shell trial.

A previous study carried out on the same hazelnut cultivar highlighted that the in-shell ambient temperature condition showed lower rupture slope values with respect to shelled (kernels) refrigerated samples, however the important loss of structure discussed here from 8 to 12-months storage in the in-shell samples was not evidenced (Ghirardello et al., 2013).

The results of the other two compression axes tested (y-axis in Supplementary Table 6, z-axis in Supplementary Table 7) evidenced similar trends with respect to the x-axis, but when the y-axis was analyzed a significant difference in rupture slope evolution was found, generally showing a decrease in all the tested conditions from the beginning to the 12-months storage point. When analyzing each storage condition separately, it was confirmed the decrease in rupture slope parameter and the increased specific deformation from 8-months to 12-months storage points in the in-shell storage samples, while for the z-axis a non-significantly different force trend was shown for each tested condition.

4. Conclusions

The study investigated the use of different test parameters in the evaluation of mechanical and acoustic properties of hazelnut kernels, and the subsequent application of the parameters with less results variability in a storage trial. Compression and shear resulted to be very different instrumental tests and they have particular peculiarities which should be considered when setting up a test. The compression test, more common in literature, may better characterize the kernel, while the shear test seems to be usable in relation to sensory tests, particularly applying higher test speeds.

Different test speeds gave results not directly comparable. The test speed setting should be defined on the basis of the experimental plan; for sensory imitative correlations, speed of 10 mm/s or more should be advised. Regarding analysis axis, x-axis measures were favorable, also because they resulted in less variable results (lower CV).

Therefore, the less variable conditions for mechanical-acoustic characterization of hazelnut kernels resulted: compression test,

Table 5
Storage trial mechanical and acoustic properties results (1.0 mm/s compression, x-axis).

Parameter (x axis)	Months	In shell, Ambient T, 60–80% RH	Refrigerated, 5 °C, 55% RH	Refrigerated 5 °C, 99% N_2, 1% O_2	Refrigerated, 5 °C, Under vacuum	Refrigerated, 5 °C, Under vacuum, Nitrogen flush	Frozen, −25 °C, Under vacuum	*Sign.*[b]
Specific deformation [%]	0	17.2 ± 3.9^{a}	17.2 ± 3.9	17.2 ± 3.9	17.2 ± 3.9	17.2 ± 3.9	17.2 ± 3.9	ns
	4	14.2 ± 3.7^{a}	15.4 ± 3.1	16.8 ± 3.3	16.8 ± 4.0	16.1 ± 4.2	15.2 ± 3.9	ns
	8	15.3 ± 3.6^{aA}	15.3 ± 3.9^{A}	19.2 ± 5.6^{B}	15.0 ± 3.3^{A}	14.8 ± 3.2^{A}	15.0 ± 5.1^{A}	**
	12	24.7 ± 5.7^{bB}	15.7 ± 3.6^{A}	15.6 ± 3.8^{A}	14.8 ± 3.2^{A}	15.8 ± 2.4^{A}	15.1 ± 5.0^{A}	***
	Sign.[a]	***	ns	ns	ns	ns	ns	
Rupture force [F1, N]	0	86.7 ± 14.5^{b}	86.7 ± 14.5	86.7 ± 14.5	86.7 ± 14.5	86.7 ± 14.5	86.7 ± 14.5	ns
	4	83.9 ± 18.9^{b}	82.3 ± 12.7	89.7 ± 16.8	89.0 ± 24.1	82.5 ± 21.4	78.4 ± 19.6	ns
	8	83.3 ± 20.4^{b}	87.8 ± 18.7	93.8 ± 21.0	81.9 ± 13.6	80.0 ± 17.2	76.3 ± 21.3	ns
	12	54.1 ± 20.0^{aA}	79.4 ± 17.5^{B}	84.6 ± 18.1^{B}	75.3 ± 15.4^{B}	81.7 ± 14.4^{B}	78.9 ± 21.9^{B}	***
	Sign.[a]	***	ns	ns	ns	ns	ns	
Rupture slope [E1, N/mm]	0	40.4 ± 5.1^{b}	40.4 ± 5.1^{ab}	40.4 ± 5.1	40.4 ± 5.1	40.4 ± 5.1	40.4 ± 5.1	ns
	4	45.4 ± 5.2^{bB}	40.7 ± 5.4^{abAB}	41.3 ± 5.9^{AB}	41.6 ± 9.7^{AB}	38.5 ± 6.0^{A}	39.6 ± 5.0^{A}	*
	8	42.3 ± 12.5^{b}	43.5 ± 5.3^{b}	37.7 ± 6.4	42.7 ± 7.2	42.9 ± 6.6	39.3 ± 4.6	ns
	12	15.6 ± 3.6^{aA}	38.7 ± 5.1^{aB}	42.3 ± 5.2^{B}	40.0 ± 6.2^{B}	39.7 ± 4.9^{B}	38.7 ± 6.4^{B}	***
	Sign.[a]	***	*	ns	ns	ns	ns	
Rupture energy [W1, mJ]	0	98.3 ± 46.5	98.3 ± 46.5	98.3 ± 46.5^{ab}	98.3 ± 46.5	98.3 ± 46.5	98.3 ± 46.5	ns
	4	75.7 ± 32.9	85.7 ± 33.8	99.4 ± 36.3^{ab}	100.2 ± 51.3	93.6 ± 51.6	80.5 ± 39.9	ns
	8	80.0 ± 30.1^{A}	92.7 ± 40.3^{A}	131.2 ± 82.8^{bB}	79.3 ± 31.4^{A}	76.6 ± 34.9^{A}	80.0 ± 51.1^{A}	**
	12	90.8 ± 49.4	81.8 ± 38.9	82.6 ± 34.2^{a}	70.2 ± 29.1	81.5 ± 26.2	87.2 ± 63.4	ns
	Sign.[a]	ns	ns	*	ns	ns	ns	
Total energy [Wtot, mJ]	0	509 ± 74^{b}	509 ± 74^{ab}	509 ± 74	509 ± 74	509 ± 74^{b}	509 ± 74	ns
	4	519 ± 144^{b}	526 ± 99^{b}	518 ± 81	515 ± 99	507 ± 106^{b}	466 ± 94	ns
	8	461 ± 129^{b}	504 ± 122^{ab}	528 ± 88	493 ± 144	485 ± 121^{ab}	447 ± 114	ns
	12	295 ± 51^{aA}	427 ± 127^{aB}	452 ± 131^{B}	432 ± 131^{B}	423 ± 102^{aB}	511 ± 100^{B}	***
	Sign.[a]	***	*	ns	ns	*	ns	
Acoustic maximum peak [dB (SPL)]	0	97.5 ± 6.9^{b}	97.5 ± 6.9	97.5 ± 6.9	97.5 ± 6.9^{ab}	97.5 ± 6.9	97.5 ± 6.9	ns
	4	98.4 ± 5.2^{b}	96.5 ± 9.4	101.7 ± 6.8	96.6 ± 8.8^{ab}	98.9 ± 7.9	97.9 ± 7.1	ns
	8	96.9 ± 7.3^{b}	99.6 ± 7.1	100.2 ± 5.9	100.8 ± 7.7^{b}	100.6 ± 5.0	100.1 ± 8.2	ns
	12	87.3 ± 9.4^{aA}	95.8 ± 8.0^{B}	99.8 ± 6.9^{B}	94.0 ± 8.6^{aB}	95.0 ± 7.8^{B}	94.9 ± 7.0^{B}	***
	Sign.[a]	***	ns	ns	ns	ns	ns	
Positive acoustic energy [dB (SPL) × s]	0	259 ± 19^{a}	259 ± 19^{a}	259 ± 19^{a}	259 ± 19^{a}	259 ± 19^{a}	259 ± 19^{a}	ns
	4	354 ± 30^{cC}	301 ± 24^{bB}	297 ± 22^{bB}	258 ± 24^{aA}	266 ± 19^{abA}	250 ± 20^{aA}	***
	8	388 ± 42^{d}	389 ± 36^{c}	407 ± 37^{d}	389 ± 42^{c}	378 ± 45^{c}	398 ± 29^{c}	ns
	12	303 ± 18^{bA}	303 ± 36^{bA}	334 ± 30^{cB}	290 ± 24^{bA}	288 ± 36^{bA}	309 ± 33^{bA}	***
	Sign.[a]	***	***	***	***	***	***	
Average acoustic peak emission [dB (SPL)]	0	53.2 ± 1.3^{a}	53.2 ± 1.3^{a}	53.2 ± 1.3^{a}	53.2 ± 1.3^{ab}	53.2 ± 1.3^{a}	53.2 ± 1.3^{ab}	ns
	4	58.7 ± 2.7^{bC}	54.7 ± 1.3^{bB}	55.2 ± 3.1^{abB}	52.3 ± 1.7^{aA}	52.0 ± 1.4^{aA}	52.1 ± 1.5^{aA}	***
	8	59.3 ± 3.4^{bAB}	58.8 ± 2.5^{cA}	62.5 ± 6.4^{cB}	60.8 ± 3.2^{cAB}	59.5 ± 3.0^{cAB}	62.0 ± 4.5^{cAB}	*
	12	54.5 ± 1.0^{aA}	54.7 ± 1.9^{bA}	56.9 ± 1.4^{bB}	54.3 ± 1.2^{bA}	54.7 ± 2.2^{bA}	54.5 ± 1.1^{bA}	***
	Sign.[a]	***	***	***	***	***	***	

Values are expressed as average ± standard deviation ($n = 20$). Different lowercase letters within the same column indicate significantly different values among storage months results (Tukey-b test, $p < 0.05$). Different uppercase letters within the same row indicate significantly different values between storage conditions (Tukey-b test, $p < 0.05$).
The initial point was the same for all the conditions tested.
[a]: *, **, *** and "ns" means significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between values obtained in different points (storage months).
[b]: *, **, *** and "ns" means significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between values obtained in different storage conditions.

1 mm/s test speed, analysis on the x-axis. A calculated minimum sample number of 20 samples was sufficient to provide meaningful results under these instrumental conditions, except for rupture energy and acoustic peak number parameters.

The storage trial evidenced a good mechanical response of stored kernels with no or little differences for all the storage conditions except for in-shell at ambient temperature, while acoustic tests could require further studies to set up and possibly link to sensory characteristics. The instrumental joint mechanical-acoustic test can aid, in a future perspective, in the evaluation of instrumental-sensory correlations, particularly for the hazelnut kernel crispness-crunchiness perceptions assessment.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jfoodeng.2015.10.037.

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