Mechanical behaviour of hazelnuts used for table consumption under compression loading

Nadia Valentini,[1*] Luca Rolle,[2] Caroline Stévigny[2,3] and Giuseppe Zeppa[2]

[1] Dipartimento di Colture Arboree, Università degli Studi di Torino, Via Leonardo da Vinci, 44 10095 Grugliasco, Italy
[2] DIVAPRA Sezione Industrie Agrarie, Università degli Studi di Torino, Via Leonardo da Vinci, 44 10095 Grugliasco, Italy
[3] Unité d'Analyse Chimique et Physico-Chimique des Médicaments, Université catholique de Louvain, UCL-7230-CHAM, Av. E. Mounier, 72, 1200 Bruxelles, Belgium

Abstract: Nuts of four hazelnut varieties and five new selections used for table consumption were compressed at the moisture content of 6% wet basis to measure shell resistance to breakage. Rupture force, rupture energy and nut specific deformation were measured under three compression loading positions. Physical parameters of nuts were also evaluated to relate them to the data obtained by compression test measurements. Rupture force and nut specific deformation are the most discriminant parameters that can be used to describe the behaviour under compression, while rupture energy values show fewer differences among the considered varieties. The values of force required to break nut shell ranged from 322.2 to 769.3 N. The lowest values of force were generally obtained along the *y*-axis, the transverse axis containing the major dimension at right angles to the longitudinal axis. Nut specific deformation ranged from 3.35 to 11.76%. Correlations between physical and texture parameters showed that values of force, energy and deformation were dependent on different parameters that varied in the three considered axis. The most used varieties, Ennis and Barcelona, showed high mean values of force rupture to break shell and low deformability, while Tonda Giffoni and Tonda Bianca were easy to break. Among the new selections, L35 and B6, with mean values of force rupture less than 428 N and values of nut specific deformation higher than 8%, were suitable for table consumption.

Keywords: *Corylus avellana* L.; hazelnut; in-shell nuts; texture analysis; mechanical behaviour; rupture force, rupture energy and deformation

INTRODUCTION

According to the Food and Agriculture Organization (FAO), the world's hazelnut or filbert (*Corylus avellana* L.) production is about 759 000 Mt a year (average 2000–2004).[1] Most hazelnuts are processed industrially, but 5% of the production is dedicated to direct table consumption ('in-shell' nuts).[1] Concerning this last market, the biggest producer is the USA (approximately 10 000 t), followed by Italy, France and Turkey.[2]

Nutritional benefits of hazelnut consumption have been reported by some authors. Raw hazelnut kernel is a rich source of oil and vitamins.[3] The oil represents 60–70% of the dry weight of the kernel with oleic being the main fatty acid followed by linoleic and palmitic; they represent together over 95% of total fatty acids in hazelnut.[4] Consumption of this nut appears to decrease the risk of heart disease, certain cancers and other chronic diseases.[5]

USA researchers have selected new varieties especially for direct consumption (Ennis,[6] Royal, Jumbo), while the European varieties are both used for processing and the fresh market. New selections for direct table consumption were obtained by breeding from the Department of Arboriculture and Pomology of Turin University, Italy.[7] A sensory analysis of these Italian selections showed that taster preference was for large nuts, with good shell appearance and high organoleptic quality of the kernel.[8] Also, easy shell breaking seems to be an important parameter for nuts and deserves to be investigated. In preliminary studies we have evaluated the mechanical behaviour of diverse varieties dedicated to processing[9] and to table consumption.[10]

Numerous works have been dedicated to texture parameters regarding different varieties of nuts. Braga *et al*. studied the mechanical behaviour of macadamia nut under compression as a function of moisture content, nut size and compression load position.[11] More recently, Koyuncu *et al*. investigated the effect of some physical parameters, such as shell thickness and geometric mean diameter, on breakage characteristics of walnut.[12] Concerning hazelnut, Aydin evaluated some physical properties of nuts, including rupture strength,[13] and Güner *et al*. analysed four Turkish varieties of hazelnut dedicated to processing, under compression loading, and evaluated the effects of shell moisture and compression axis.[14]

* Correspondence to: Nadia Valentini, Dipartimento di Colture Arboree, Università degli Studi di Torino, Via Leonardo da Vinci 44, 10095 Grugliasco, TO, Italy
E-mail: nadia.valentini@unito.it
(*Received 3 March 2005; revised version received 1 September 2005; accepted 2 February 2006*)
Published online 19 April 2006; DOI: 10.1002/jsfa.2486

The objective of this work was to define the effects of hazelnut variety and compression loading position on the rupture force, rupture energy and nut specific deformation of some hazelnut varieties used for table consumption and five new Italian selections. In addition, relationships between texture parameters and physical properties of the nuts at different compression loading positions were analysed.

MATERIALS AND METHODS

Nut samples

Barcelona (BA), Ennis (EN), Tonda Bianca (TB) and Tonda Giffoni (TG) varieties and B6, B59, C10, L35 and L39 selections[7] of hazelnut used for table consumption were used for this study.

Nuts of three plants for each variety were individually collected in September 2002 in an experimental orchard with a completely randomized design located in Cravanzana at 550 m above sea level (Cuneo district, Northwest Italy). The nuts were manually harvested directly from the ground when the natural drop reached 80–90%.

Samples of 2 kg for each variety were sun-dried until they reached a moisture content of 6% wet basis (wb). In-shell moisture contents of 6–8% are considered optimum for nut storage and commerce.[15] The moisture content was determined according to the AOAC 925.40 method.[16]

Before texture analysis, nuts were visually inspected and those with damaged shells were discarded. For each variety, 90 nuts (30 nuts for each plant) were randomly selected and analysed (10 fruits for each nut dimension).

Physical properties of the nut

Nut weight was determined on each single nut. The three nut and kernel dimensions length (L), width (W) and thickness (T) were measured using a calliper which had an accuracy of 0.1 mm. The ratios of the nut dimensions were also calculated as T/L, W/L and T/W. Shell thickness (Ts) of each nut was measured

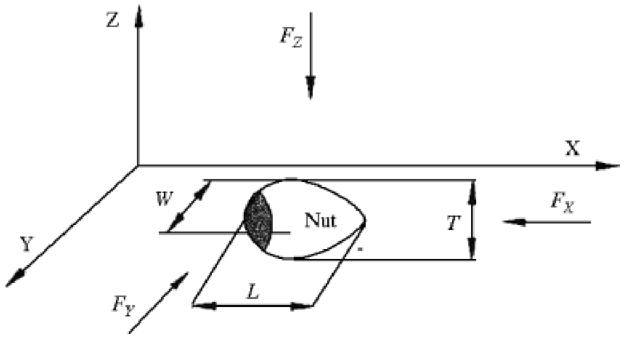

Figure 1. Representation of the three axes and three perpendicular dimensions of nuts: x-axis, the longitudinal axis through the hilum (length, L); y-axis, the transverse axis at right angles to the longitudinal axis containing the major dimension (width, W); z-axis, the transverse axis containing the minimum dimension (thickness, T); F_x, F_y and F_z: axial forces (from Güner *et al.*[14]).

Table 1. Physical measurements of nuts and kernels

Cultivar and selection	Nut weight (g)	V_n (cm^3)	V_k (cm^3)	ΔV (%)	SI_k	Nut L (mm)	Nut W (mm)	Nut T (mm)
B59	3.34 ± 1.42^{cd}	5.26 ± 0.42^{c}	1.65 ± 0.24^{cd}	68.58 ± 3.96^{ab}	0.77 ± 0.05^{cd}	21.74 ± 0.86^{c}	23.48 ± 0.63^{b}	19.65 ± 0.64^{d}
B6	3.42 ± 1.58^{cd}	6.23 ± 0.68^{b}	1.92 ± 0.37^{abc}	69.22 ± 4.29^{ab}	0.78 ± 0.08^{cd}	23.60 ± 1.17^{b}	23.43 ± 1.00^{b}	21.47 ± 0.77^{b}
BA	3.33 ± 1.35^{cd}	4.11 ± 0.25^{d}	1.70 ± 0.16^{bcd}	58.57 ± 3.38^{c}	0.90 ± 0.06^{b}	20.67 ± 0.84^{d}	21.05 ± 0.52^{e}	18.03 ± 0.58^{f}
C10	4.10 ± 1.60^{a}	6.21 ± 0.62^{b}	1.98 ± 0.52^{ab}	68.12 ± 4.90^{ab}	0.75 ± 0.06^{cd}	25.89 ± 1.11^{a}	22.80 ± 0.91^{bc}	20.06 ± 0.80^{cd}
EN	3.74 ± 1.63^{abc}	6.06 ± 0.53^{b}	2.03 ± 0.32^{a}	66.41 ± 5.45^{ab}	0.66 ± 0.06^{e}	25.85 ± 0.88^{a}	21.92 ± 0.82^{d}	20.39 ± 0.77^{c}
L35	3.88 ± 1.62^{a}	6.84 ± 0.57^{a}	2.02 ± 0.46^{a}	70.38 ± 7.15^{a}	0.82 ± 0.13^{c}	23.7 ± 1.00^{b}	24.73 ± 0.80^{a}	22.27 ± 0.83^{a}
L39	3.51 ± 1.49^{bcd}	5.53 ± 0.45^{c}	1.81 ± 0.41^{abcd}	67.36 ± 6.69^{ab}	0.77 ± 0.08^{cd}	23.80 ± 1.09^{b}	22.27 ± 0.68^{cd}	19.91 ± 0.63^{cd}
TB	3.31 ± 1.36^{d}	5.13 ± 0.42^{c}	1.75 ± 0.44^{abcd}	64.68 ± 5.48^{b}	0.73 ± 0.05^{de}	23.51 ± 0.92^{b}	22.15 ± 0.79^{cd}	18.80 ± 1.14^{e}
TG	2.86 ± 1.34^{e}	3.54 ± 0.26^{e}	1.55 ± 0.14^{d}	56.15 ± 3.77^{c}	1.01 ± 0.09^{a}	19.37 ± 0.69^{e}	20.33 ± 0.67^{e}	17.18 ± 0.74^{g}

Average ± standard deviation. Values in the same column not followed by the same letter are significantly different ($P \leq 0.01$). BA = Barcelona; EN = Ennis; TB = Tonda Bianca; TG = Tonda Giffoni.

J Sci Food Agric **86**:1257–1262 (2006)
DOI: 10.1002/jsfa

in two different positions of the shell using the same calliper. The volume of the nut (V_n) and kernel (V_k) were calculated using an ellipsoid formula:

$$V = \left(\frac{4}{3}\right)\pi\left(\frac{L}{2}\right)\left(\frac{W}{2}\right)\left(\frac{T}{2}\right)$$

The 'empty volume' (ΔV) was calculated as the percentage of the nut volume (V_n) without the kernel volume (V_k):

$$\Delta V = \left[1 - \left(\frac{V_k}{V_n}\right)\right]100$$

The shape index of nut (SI_n)[17] and kernel (SI_k), the geometric mean diameter (D_p) and the sphericity (ϕ)[18] of the nut were calculated using the following formula:

$$SI = \frac{(W+T)}{2L} \qquad Dp = (L\ W\ T)^{1/3}$$

$$\phi = \left[\frac{(L\ W\ T)^{1/3}}{L}\right]100$$

Compression measurements

A Universal Testing Machine TA.HD® Texture Analyser (Stable Micro System, Godalming, Surrey, UK) was used to measure shell resistance to breakage. The test of compression was performed with a 100 kg loadcell using a P/75 flat circular plate of aluminium (75 mm of diameter) at 1 mm s^{-1} constant speed. The nut was placed on a HDP/90 perforated platform. The accuracy of the instrument was 0.0196 N for force and 1 μm for probe distance. The force–deformation curve was acquired as a graph and elaborated by a Texture Expert® software. Three replicates of 10 nuts for each variety were compressed along the three compression axes: x-axis (length), y-axis (width) and z-axis (thickness) according to Güner *et al.*[14] (Fig. 1).

The breakage characteristics of hazelnut were expressed according to Braga *et al.*,[11] as maximum force required to obtain shell rupture (N), energy required to deform the nut shell to rupture (J), and nut specific deformation (%).[19]

Statistical analysis

Data for morphological and compression measurements were analysed using Statistica software.[20] ANOVA and Tukey's mean comparison test were used. Pearson product–moment correlation coefficients were calculated for morphological and compression parameters.

RESULTS AND DISCUSSION

Physical properties of nuts

Tables 1 and 2 show the mean values and standard deviation of nut and kernel measurements. Kernel dimensions data were used to calculate the volume of the kernel and they are not reported in tables.

Nut weight varied from 4.10 g for C10 to 2.86 g for Tonda Giffoni. The volume of the nut had a maximum value of L35 (6.84 cm^3) and a minimum for Tonda Giffoni (3.54 cm^3), while the volume of kernels varies from 2.03 cm^3 for Ennis to 1.55 cm^3 for Tonda Giffoni. The percentage of 'empty volume' ranged from 70.38% for L35 to 56.15% for Tonda Giffoni. Considering the shape index of the kernel, Tonda Giffoni had the most rounded kernel (1.01) and Ennis the most elongated one (0.66).

Tonda Giffoni showed the lowest values for the three nut dimensions, while C10 had the highest value for nut length (25.89 mm) and L35 for nut width (24.73 mm) and thickness (22.27 mm). Considering the proportions of nut dimensions, T/L varied from 0.94 of L35 to 0.78 for C10, T/W varied from 0.93 for Ennis to 0.84 for B59 and Tonda Giffoni, and W/L from 1.08 for B59 to 0.85 for Ennis. Barcelona had the thickest shell (1.62 mm) while the lowest value was that of B6 (1.07 mm).

The shape index of the nut had the highest values (0.99) for L35 and B59 and the lowest value for Ennis (0.82). Nut sphericity ranged from 99.37 for L35 to 87.46 for Ennis. These two parameters showed similar information, as demonstrated by statistical analysis. L35 showed the maximum value of geometric mean diameter (23.54 mm).

Table 2. Physical measurements of nuts

Cultivar and selection	T/L	T/W	W/L	SIn	ϕ	Dp (mm)	Ts (mm)
B59	0.90 ± 0.03^{ab}	0.84 ± 0.02^{e}	1.08 ± 0.04^{a}	0.99 ± 0.03^{a}	99.24 ± 2.34^{a}	21.56 ± 0.57^{c}	1.26 ± 0.17^{c}
B6	0.91 ± 0.04^{ab}	0.92 ± 0.03^{ab}	0.99 ± 0.05^{c}	0.95 ± 0.04^{b}	96.70 ± 2.80^{b}	22.81 ± 0.82^{b}	1.07 ± 0.11^{d}
BA	0.87 ± 0.04^{bc}	0.86 ± 0.03^{de}	1.02 ± 0.05^{bc}	0.95 ± 0.04^{b}	96.19 ± 2.83^{b}	19.86 ± 0.40^{d}	1.62 ± 0.24^{a}
C10	0.78 ± 0.03^{e}	0.88 ± 0.03^{cd}	0.88 ± 0.04^{e}	0.83 ± 0.03^{d}	88.08 ± 2.36^{d}	22.79 ± 0.77^{b}	1.3 ± 0.16^{bc}
EN	0.79 ± 0.03^{e}	0.93 ± 0.03^{a}	0.85 ± 0.03^{e}	0.82 ± 0.03^{d}	87.46 ± 2.10^{d}	22.60 ± 0.65^{b}	1.22 ± 0.12^{cd}
L35	0.94 ± 0.04^{a}	0.90 ± 0.04^{abc}	1.04 ± 0.04^{ab}	0.99 ± 0.04^{a}	99.37 ± 2.54^{a}	23.54 ± 0.65^{a}	1.19 ± 0.15^{cd}
L39	0.84 ± 0.04^{cd}	0.89 ± 0.03^{bc}	0.94 ± 0.03^{d}	0.89 ± 0.04^{c}	92.24 ± 2.68^{c}	21.93 ± 0.59^{c}	1.09 ± 0.18^{d}
TB	0.80 ± 0.06^{de}	0.85 ± 0.06^{de}	0.94 ± 0.05^{d}	0.87 ± 0.05^{c}	91.03 ± 3.21^{c}	21.38 ± 0.58^{c}	1.43 ± 0.15^{b}
TG	0.89 ± 0.05^{b}	0.84 ± 0.04^{e}	1.05 ± 0.05^{ab}	0.97 ± 0.05^{ab}	97.68 ± 3.18^{ab}	18.90 ± 0.45^{e}	1.26 ± 0.18^{c}

Average ± standard deviation. Values in the same column not followed by the same letter are significantly different ($P \leq 0.01$). BA = Barcelona; EN = Ennis; TB = Tonda Bianca; TG = Tonda Giffoni.

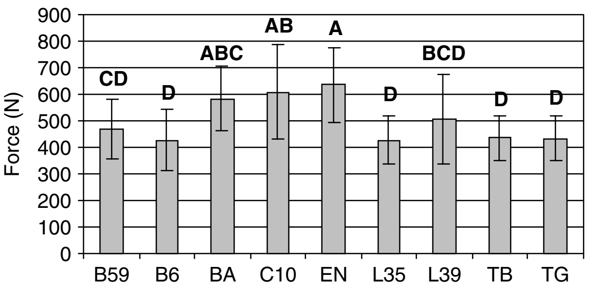

Figure 2. Values of force required to break shell. Average of the three axes ± standard deviation. Values not followed by the same letter are significantly different ($P \leq 0.01$). BA = Barcelona; EN = Ennis; TB = Tonda Bianca; TG = Tonda Giffoni.

Compression test values

The mean values of force rupture needed to break the shell of nine hazelnut cultivars are shown in Fig. 2. Ennis, C10 and Barcelona had values of force higher than 550 N and they were significantly different from B6, L35, Tonda Bianca and Tonda Giffoni, which had values less than 450 N.

Considering values obtained along each single axis, all varieties showed significant differences in force values except for Barcelona (Table 3). The lowest values of force required for shell rupture were those obtained along the *y*-axis for all the varieties except for L35. In contrast, Aydin[13] obtained the least values of force along the *x*-axis.

Values of force rupture to break the shell obtained for hazelnut varieties used for table consumption were higher than those reported by Güner *et al.*[14] in Turkish varieties used for processing. Actually, nuts analysed with the same moisture content (6% wb) and along the same axis (z) showed values ranging from 406.2 to 749.2 N for table consumption nuts, while Güner *et al.*[14] reported values from 148.7 to 247.7 N.

The force required to rupture the shell along the *x*-axis was positively related to nut length (Table 4) and negatively correlated with T/L and W/L ratio and the shape index of the nut and kernel. The highest value of force (769.3 N; Table 3) was found for Ennis, which had the most elongated nut and kernel (Tables 1 and 2). On the *y*-axis, values of force were positively correlated to shell thickness and nut weight. The lowest value of force was found for B6 (322.2 N; Table 3), which had the thinnest shell (Table 2). Instead, for walnut, Koyuncu *et al.*[12] reported that force increases linearly with shell thickness in all the compression positions. Along the *z*-axis, force was related to the same parameters found for the *x*-axis, except for the shape index of the kernel. In addition it was correlated with nut weight and the volume of the kernel.

The mean value of energy necessary for shell rupture varied from 0.43 J for B59 and C10 to 0.35 J for Barcelona. No significant differences were found among the varieties (Fig. 3).

Considering the three nut dimensions B6, Barcelona, Ennis, L35 and Tonda Bianca had significant differences between values of energy; Ennis

Table 3. Force required to break nut shell (N)

Axis	B59	B6	BA	C10	EN	L35	L39	TB	TG
x (length)	446.9 ± 81.3^{ab}	535.0 ± 79.9^{a}	654.0 ± 156.8^{a}	618.9 ± 128.6^{ab}	769.3 ± 60.6^{a}	359.2 ± 38.7^{b}	463.6 ± 53.2^{b}	522.3 ± 54.5^{a}	426.9 ± 81.5^{ab}
y (width)	392.9 ± 85.6^{b}	322.2 ± 66.1^{b}	561.0 ± 88.7^{a}	435.1 ± 79.8^{b}	523.1 ± 122.2^{b}	414.7 ± 97.4^{ab}	369.1 ± 79.1^{b}	391.9 ± 73.3^{b}	366.4 ± 53.5^{b}
z (thickness)	558.5 ± 107.2^{a}	426.4 ± 83.3^{ab}	518.3 ± 55.7^{a}	749.2 ± 154.5^{a}	642.3 ± 110.6^{ab}	504.4 ± 55.0^{a}	676.2 ± 164.2^{a}	406.2 ± 64.8^{b}	502.5 ± 52.1^{a}

Average ± standard deviation. Values in the same column not followed by the same letter are significantly different ($P \leq 0.01$). BA = Barcelona; EN = Ennis; TB = Tonda Bianca; TG = Tonda Giffoni.

J Sci Food Agric **86**:1257–1262 (2006)
DOI: 10.1002/jsfa

Table 4. Correlation coefficients between morphological and compression parameters

	Force			Energy			Nut specific deformation		
Axis	*x* (length)	*y* (width)	*z* (thickness)	*x* (length)	*y* (width)	*z* (thickness)	*x* (length)	*y* (width)	*z* thickness)
Nut weight	0.172	0.386***	0.579***	−0.141	0.453***	0.308**	−0.429***	0.098	−0.288**
Nut *L*	0.333**	0.167	0.445***	0.203	0.298**	0.077	−0.308**	0.114	−0.456***
Nut *W*	−0.232*	−0.002	0.050	−0.173	0.424***	0.305**	−0.119	0.261*	0.036
Nut *T*	−0.088	−0.03	0.084	0.047	0.325**	0.140	−0.152	0.209	−0.220*
SI_n	−0.526***	−0.210	−0.427***	−0.349**	−0.072	−0.123	0.228*	0.037	0.406***
Ts	0.247*	0.531***	0.132	−0.078	−0.015	0.193	0.152	−0.388***	0.207
D_p	0.046	0.070	0.240*	0.022	0.396***	0.188	−0.233*	−0.214*	−0.278**
SI_k	−0.285**	−0.056	−0.176	−0.284**	−0.022	0.154	0.106	0.085	0.383***
V_n	0.042	0.089	0.237*	0.003	0.414***	0.204	−0.243*	−0.217*	−0.261*
V_k	0.150	0.220*	0.336**	0.071	0.340***	0.331**	−0.212	0.109	−0.053
ΔV	−0.092	−0.139	−0.041	−0.020	0.150	−0.116	−0.282	0.159	−0.269*
Nut T/L	−0.472***	−0.243*	−0.366**	−0.298**	−0.078	−0.076	0.204	0.049	0.227*
Nut T/W	0.200	0.043	0.086	0.180	0.014	−0.112	−0.095	0.004	−0.389***
Nut W/L	−0.533***	−0.187	−0.409***	−0.360**	−0.080	−0.145	0.235	0.013	0.493***

*, **, *** Significant at $P \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$, respectively.

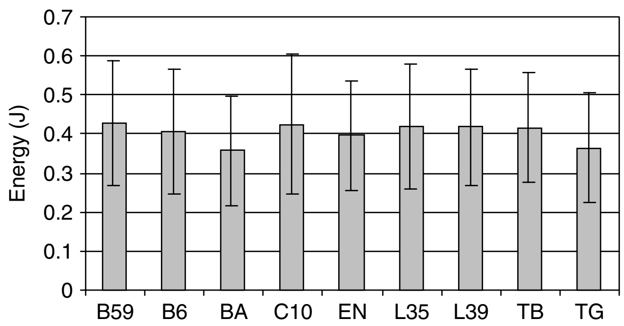

Figure 3. Values of energy required to deform nut shell to rupture. Average of the three axes ± standard deviation. Data do not show significant differences. BA = Barcelona; EN = Ennis; TB = Tonda Bianca; TG = Tonda Giffoni.

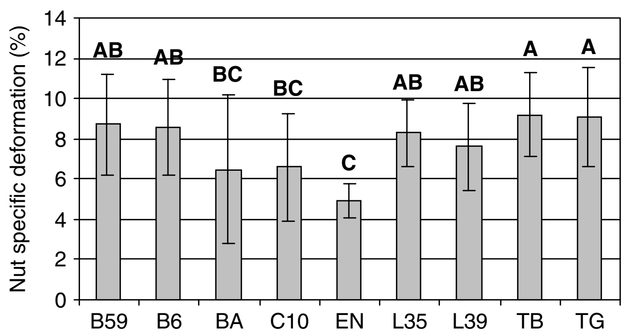

Figure 4. Values of nut specific deformation to shell rupture. Average of the three axes ± standard deviation. Values not followed by the same letter are significantly different ($P \leq 0.01$). BA = Barcelona; EN = Ennis; TB = Tonda Bianca; TG = Tonda Giffoni.

and Tonda Bianca had the highest values of energy along the *x*-axis (0.54 J) while L35 had the lowest one (0.26 J; Table 5). Actually, energy measured along the *x*-axis was negatively correlated to the shape index of the nut and kernel, and to T/L and W/L ratios (Table 4). Along the *y*-axis, the energy value was positively correlated to nut weight, nut and kernel volume, nut dimensions and geometric mean diameter. Except for C10 and L35, all varieties showed minimum values of shell rupture energy along the *y*-axis. Concerning the *z*-axis, energy is correlated only to nut weight, nut width and volume of the kernel.

Values of nut specific deformation showed wide variation among varieties. The mean value varied from 9.19% for Tonda Bianca to 4.89% for Ennis (Fig. 4). The least deformable nuts were those of Ennis, which had values less than 5.00%.

Barcelona and C10 had one dimension more deformable, respectively along the *z*- and *y*-axes (Table 6), while L35, Tonda Bianca and L39 showed one dimension that was less deformable (respectively *x*-, *y*- and *z*-axis). The other varieties did not show significant differences in values obtained from measurements carried out on the three different positions. The highest and the lowest values were found both in Barcelona (11.76% along the *z*-axis and 3.35% along the *y*-axis) and these results confirm the large differences in behaviour of the three nut positions. Deformability is negatively correlated with nut weight and length, considering the *x*-axis, and with shell thickness along the *y*-axis (Table 4). Barcelona showed the minimum value of deformability along the *y*-axis and the highest value of shell thickness. Regarding *z*-axis, deformability was correlated to more parameters, among which the most important were the shape of the nut and the kernel, nut length, T/W ratio and W/L ratio. Values of nut specific deformation were similar to those found by Güner *et al.*[14] for Turkish varieties.

CONCLUSIONS

The easy shell breaking could be considered as an important characteristic for hazelnuts used for table consumption. Results of the present work showed a large variability among hazelnut varieties and selections tested. The compressing loading position also had an important effect on breakage

Table 5. Energy required to deform nut shell to rupture (J)

Axis	B59	B6	BA	C10	EN	L35	L39	TB	TG
x (length)	0.41 ± 0.13^A	0.46 ± 0.18^a	0.30 ± 0.11^B	0.34 ± 0.12^A	0.54 ± 0.08^A	0.26 ± 0.05^B	0.45 ± 0.10^A	0.54 ± 0.09^a	0.38 ± 0.13^A
y (width)	0.38 ± 0.19^A	0.30 ± 0.11^b	0.23 ± 0.07^B	0.49 ± 0.13^A	0.29 ± 0.11^B	0.44 ± 0.17^A	0.38 ± 0.14^A	0.33 ± 0.12^b	0.32 ± 0.09^A
z (thickness)	0.50 ± 0.16^A	0.47 ± 0.16^a	0.51 ± 0.07^A	0.46 ± 0.24^A	0.38 ± 0.10^B	0.55 ± 0.11^A	0.42 ± 0.20^A	0.39 ± 0.11^b	0.41 ± 0.15^A

Average ± standard deviation. Values in the same column not followed by the same letter are significantly different for $P \leq 0.01$ (capital letters) and $P \leq 0.05$ (lower-case letters). BA = Barcelona; EN = Ennis; TB = Tonda Bianca; TG = Tonda Giffoni.

Table 6. Nut specific deformation to shell rupture (%)

Axis	B59	B6	BA	C10	EN	L35	L39	TB	TG
x (length)	8.64 ± 1.26^a	8.04 ± 3.29^a	4.36 ± 1.06^b	4.68 ± 2.16^b	5.08 ± 0.53^a	6.90 ± 0.65^b	8.65 ± 0.90^a	9.79 ± 1.47^a	9.53 ± 1.60^a
y (width)	7.73 ± 2.18^a	7.69 ± 0.95^a	3.35 ± 0.83^b	9.57 ± 0.90^a	4.34 ± 0.86^a	8.02 ± 1.24^a	8.88 ± 1.45^a	7.23 ± 1.45^b	7.96 ± 1.30^a
z (thickness)	9.53 ± 3.43^a	10.02 ± 1.76^a	11.76 ± 1.64^a	5.56 ± 1.61^b	5.24 ± 0.80^a	9.9 ± 1.24^a	5.42 ± 1.91^b	10.55 ± 1.61^a	9.86 ± 3.6^a

Average ± standard deviation. Values in the same column not followed by the same letter are significantly different ($P \leq 0.01$). BA = Barcelona; EN = Ennis; TB = Tonda Bianca; TG = Tonda Giffoni.

behaviour. Force required to break shell and nut specific deformation to shell rupture were the texture parameters that better discriminate varieties. These two parameters seem to be highly correlated. Values of texture parameters were highly influenced by the physical properties of the nuts, among which the most important were size and shape of the nut and the thickness of the shell. In conclusion, the most interesting varieties for easy breakage behaviour were Tonda Bianca and Tonda Giffoni, and B6 and L35 among the new selections.

REFERENCES

1 FAO website; www.fao.org [20 January 2005].
2 Germain E and Sarraquigne JP, *Le noisetier*. Ctifl Edition, Paris, pp. 14–16 (2004).
3 Stone D, Health benefits of hazelnuts. *Cereal Foods World* **45**:424–426 (2000).
4 Botta R, Gianotti C and Me G, Kernel quality in hazelnut cultivars and selections analysed for sugars, lipids and fatty acid composition. *Acta Hort* **445**:319–326 (1997).
5 Richardson DG, The health benefits of eating hazelnuts: implications for blood lipid profiles, coronary heart disease, and cancer risks. *Acta Hort* **445**:295–300 (1997).
6 Lagerstedt HB, 'Ennis' and 'Butler' filberts. *Hort Sci* **15**:833–835 (1980).
7 Valentini N, Me G, Vallania R and Zeppa G, New hazelnut selections for direct consumption. *Acta Hort* **556**:103–108 (2001).
8 Zeppa G, Rolle L, Gerbi V, Valentini N and Me G, Application of sensory analysis to characterize new selections of hazelnut. *Ind Aliment* **39**:1249–1257 (2000).
9 Valentini N, Zeppa G and Rolle L, Application of colorimetry, texture analysis and sensorial analyses in the characterization of Italian hazelnuts. *Frutticoltura* **65**:54–57 (2003).
10 Valentini N, Zeppa G and Rolle L, Characterization of hazelnut varieties by texture analysis. Proc. VI International Congress on Hazelnut. *Acta Hort* (in press).
11 Braga GC, Couto SM, Hara T and Almeida Neto JTP, Mechanical behaviour of macadamia nut under compression loading. *J Agric Engng Res* **72**:239–245 (1999).
12 Koyuncu MA, Ekinci K and Savran E, Cracking characteristics of walnut. *Biosyst Engng* **87**:305–311 (2004).
13 Aydin C, Physical properties of hazelnuts. *Biosyst Engng* **82**:297–303 (2002).
14 Güner M, Dursun E and Dursun IG, Mechanical behaviour of hazelnut under compression loading. *Biosyst Engng* **85**:485–491 (2003).
15 Westwood MN, *Temperate-zone Pomology. Physiology and Culture*. Timber Press, Portland, OR, p. 342 (1993).
16 AOAC, *Official Methods of Analysis*, 17th edn, no 925.40. Association of Official Analytical Chemists, Washington, DC (2000).
17 Fregoni M and Zioni E, Caratteristiche morfologiche, merceologiche e chimico-industriali dei frutti di alcune cultivar di nocciolo della Liguria. *Atti Convegno internazionale sul nocciolo*, pp. 125–156 (1962).
18 Mohsenin NN, *Physical Properties of Plant and Animal Materials*. Gordon and Breach, New York (1970).
19 Calzada J and Peleg M, Mechanical interpretation of compressive stress-strain relationships of solid foods. *J Food Sci* **43**:1087–1092 (1978).
20 StatSoft, *STATISTICA for Windows*. StatSoft, Tulsa, OK (1995).