PREDICTING SENSORY COHESIVENESS, HARDNESS AND SPRINGINESS OF SOLID FOODS FROM INSTRUMENTAL MEASUREMENTS

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ABSTRACT

The sensory evaluation of cohesiveness, hardness and springiness of 15 solid food samples was performed by eight trained assessors. The rheologic response of the 15 samples was estimated by performing cyclic compression tests and stress–relaxation tests.

From the force–deformation curves of the first two cycles of the compression test, texture profile analysis parameters related to cohesiveness, hardness and springiness were calculated. Young's modulus (E), strain (d_i) and stress (s_i) at peak as well as irrecoverable strain (r_i) and irrecoverable work (L_i) were monitored during the first five cycles. From the stress–relaxation response, Peleg's linearization model parameters, K_1 and K_2, were estimated by best-fit regression. These parameters were used for predicting sensory attributes.

Hardness and springiness were both accurately predicted by rheologic properties, while cohesiveness prediction was less representative.

PRACTICAL APPLICATIONS

This study contributes to enhance the knowledge in the research area of sensory instrumental correlation. Also, the research allows to better understanding that no single instrument is able to measure all texture attributes adequately. In fact, the results demonstrate that both stress–relaxation and cyclic compression tests need to be performed for the correct prediction of sensory responses.

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KEYWORDS

Cyclic compression test, partial least squares, sensory analysis, stress–relaxation test

INTRODUCTION

Texture is the sensory and functional manifestation of the structural, mechanical and surface properties of foods detected through the senses of sight, hearing, touch and kinesthetics (Szczesniak 2002). It depends on the product's physical and physicochemical properties and on the unique, complex features of the human senses (Peleg 1987); according to Bourne (2002), texture of foods derived from their structure. Texture is also widely recognized as an important quality attribute for product acceptability affecting consumer perception.

According to an engineering approach of food processing, texture attributes are a measure of performance when food interacts with the consumer. They are the result of structure and composition that are obtained by submitting the ingredients to a sequence of operations, which comprise a given food process. From this point of view, like the performance of any other engineering material, the texture attributes of foods can be described by intrinsic material properties, which, according to existing theories, can even be defined by adequately selecting ingredient compositions and food process parameters.

According to Aguilera and Stanley (1999), food processes are controlled ways to preserve, transform, destroy or create structures. Preserving structure is a major objective in postharvest technology of plant material; transforming structure is central to the food processing industry; the controlled destruction of structure in food processing occurs whenever reducing the size of materials is required for further processing; the creation of structure is a major task in product development and improvement (Aguilera 2000).

Understanding the relationship between food texture perception and food structure is of increasing importance for companies wishing to produce texturally attractive food products (Wilkinson *et al.* 2000). This study is complicated by the dynamic nature of texture perception and by the presence of large individual differences in oral processes. Thus, a multidisciplinary approach is required, integrating three research areas: sensory science, physiology and food structure research, i.e., the study of rheologic parameters, microstructure and other relevant food engineering properties.

The stimuli of texture perception are primarily of a mechanical nature. Therefore, to establish a relationship between perceived texture and food characteristics, it is essential to understand the mechanics or the rheology of food deformation (Peleg 1987). The most recurrent parameters among solid food texture attributes are hardness, springiness, cohesiveness and friability. Hardness is a textural characteristic estimated during the first mastication; strength is applied on the food product in an approximately linear way and can be satisfactorily reproduced instrumentally through a uniaxial compression test (Shama and Sherman 1973). Uniaxial compression testing gives valuable information related to the mechanical characteristics of food subjected to breakup; such information assumes a major role if compared with data obtained from the sensory analysis, in finding which instrumental parameters better predict texture sensory results. Among textural parameters, hardness is the one that shows a good correlation between sensory and instrumental data (Szczesniak 1998).

Good correlations have also been found between instrumental strength and fracturability (Nunez *et al.* 1986), and between strength related to different deformations and hardness (Wium *et al.* 1997).

Several studies have been conducted to relate sensory and instrumental measurements (Meullenet *et al.* 1998; Drake *et al.* 1999; Lee *et al.* 1999; Toscas *et al.* 1999; Liu *et al.* 2000; Sesmat and Meullenet 2001; Truong *et al.* 2002; Adhikari *et al.* 2003). In the work of Breuil and Meullenet (2001), texture evaluation was performed on 29 types of cheese to relate sensory properties and instrumental parameters obtained from uniaxial compression, puncture and penetration tests. It was found that hardness, springiness and cohesiveness of mass were best predicted by instrumental data from cone penetration tests. Benedito *et al.* (2000) studied textural characteristics through uniaxial compression, puncture tests and sensory analysis as a way to improve Mahon cheese texture evaluation, and observed that the elastic module of compression and slope in puncture testing appears correlated to sensory hardness and elasticity. Visual, manual and oral texture attributes for Reggianito grating cheese were related to parameters obtained from compression tests by Hough *et al.* (1996); it was found that strain is the instrumental parameter which best correlated with sensory texture. Meullenet and Gross (1999) evaluated six textural attributes from 24 different foods, obtained by an experienced panel. Their study aimed to define a predictive model to evaluate textural sensory characteristics, based on instrumental parameters inferred by uniaxial and double compression tests. It was found that hardness, cohesiveness and fracturability were accurately predicted, whereas springiness, cohesiveness of mass and chewiness were unsatisfactorily predicted. Yuan and Chang (2006) correlated texture profile analysis (TPA) hardness and springiness of tofu with sensory parameters, and found linear instrumental and sensory correlations, whereas Szczesniak *et al.* (1963) reported a nonlinear relationship between sensory hardness ratings and texturometer hardness values.

The present work aimed to investigate the relationships between mechanical textural sensory attributes (hardness, cohesiveness and springiness) and instrumental measurements from cyclic compression and stress–relaxation tests, using 15 food samples.

MATERIALS AND METHODS

Food Samples

Food products used for this study (Table 1), consisting of well-known commercial brands to ensure availability, were purchased in local supermarkets. The samples were chosen to represent a wide range of texture characteristics.

Sample Preparation

In order to achieve comparable results with data related to different food categories, sample size was standardized for both sensory and instrumental analysis. For most samples analyzed, 15-mm diameter and 15-mm height cylinders were prepared with a special metal cable cylinder, while candy samples, because of their cylindric shape and dimensions, were used in unmodified form. Rectangular toffee candy samples (19-mm wide, 15-mm thick and 10-mm high) were cut in order to obtain samples 15-mm wide and

TABLE 1.
BRAND NAMES OF FOODS EXAMINED IN THIS STUDY

Food samples
Big fruit candy – “Dofour”
Sliced white bread – “Mulino Bianco”
Candy – “Fruit Joy”
Jelly candy – “Gelly”
Firm egg white – “Ovito”
Galbanino cheese – “Galbani”
Little loaf – “Mulino Bianco”
Madeleines – “Le Petit di Playtime”
Mini Babybel cheese – “Bel”
Angel cake – “Bisconova”
Sandwiches – “Mulino Bianco”
Toffee candy – “Elah”
Trolly kiss candy – “Trolly”
Würstel without skin – “Wuoi Citterio”
Würstel without skin – “Wuoi Citterio” (raw)

TABLE 2.
DESCRIPTION OF SENSORY ATTRIBUTES AND EVALUATION TECHNIQUES USED ON VARIOUS FOODS

Attributes	Definitions	Evaluation techniques
Cohesiveness	Mechanical textural attribute relating to the degree to which a food can be deformed before it breaks.	Compress the sample with molars and evaluate the amount of deformation before rupture
Hardness	Mechanical textural attribute relating to the force required to compress the sample.	Compress the sample with molars and evaluate the required force
Springiness	Mechanical textural attribute relating to the rapidity and degree of recovery from a deforming force.	Compress the sample partially with fingers and evaluate the degree and rapidity of recovery

thick and 10-mm high. Würstel samples were boiled for 5 min and egg samples for 20 min. Both sensory and instrumental analysis were carried out at room temperature.

Sensory Analysis

Analysis was performed by means of a panel composed by eight trained assessors in an International Organization for Standardization 8589:1998 compliant sensory analysis location. Food hardness, cohesiveness and springiness were evaluated by using a continuous structured scale (10 cm), without reference. Every sample was tested in a randomized design with three replications. Attribute definition and evaluation techniques used are described in Table 2.

Instrumental Analysis

Cyclic compression and stress–relaxation tests were performed by means of an Instron Universal Testing Machine (mod. 4467, Instron Ltd., High Wycombe, GB, U.K.).

Cyclic Compression Tests. Cyclic compression tests were performed using a 60-mm diameter piston and with load bearing cells (10 N, 1 kN) chosen according to the attainable maximum load on samples during test execution. Data were acquired through Instron Series IX software. Tests were performed with a crosshead speed of 50 mm/min, imposing 50% as maximum deformation for the first cycle, with preventive confirmation of breakup within such a range of the examined foods. Five compression/decompression cycles were performed.

Stress–relaxation Tests. Stress–relaxation tests were performed, imposing a deformation from 2% to 16% so that the deformation was included in the linear viscoelasticity region, achieved with a crosshead speed of 100 mm/min. Stress was registered during 5 min. Every test was replicated 15 times for each different food sample.

Data Analysis

From the force–deformation curves of the first two compression test cycles, TPA parameters related to cohesiveness (A_2/A_1), hardness (S_1) and springiness (d_2/d_1) were calculated according to Bourne (1978).

Young's modulus (E), strain (d_i) and stress (S_i) at peak as well as irrecoverable strain (r_i) and irrecoverable work (L_i) were acquired during the five cycles of experimental cyclic compression tests. Irrecoverable work (L_i) was obtained by the difference between compression work and recoverable work. From the stress–relaxation response, Peleg's linearization model parameters, K_1 and K_2, were estimated by best-fit regression (Peleg and Calzada 1976).

Statistical Analysis

Sensory and instrumental data were submitted to analysis of variance and Duncan's test ($P \leq 0.05$) to assess significant differences related to texture characteristics among different products. Sensory and instrumental data were correlated by linear and nonlinear regression, and by partial least squares (PLS) regression analyses.

Partial least squares regression is a statistical modeling technique used to compare two sets of data by seeking out latent variables common to both data sets (Martens and Martens 1986). If several sensory variables are predicted at the same time from a set of instrumental variables, PLS_2 is used, whereas the PLS_1 solution is performed when each sensory variable is predicted separately. In this case, instrumental parameters were used as predictors of all three sensory variables (PLS_2 option).

Relative ability of prediction (RAP) was used in order to estimate the model's predictive quality (Meullenet and Gross 1999). It was calculated, for each sensory characteristic, as follows

$$RAP = \frac{\left(s_{\text{tot}}^2 - RMSEP\right)}{\left(s_{\text{tot}}^2 - s_{\text{ref}}^2\right)} \tag{1}$$

where s_{tot} is the SD of the sensory scores across all samples for a particular attribute; $RMSEP$ is a measure of the average difference between predicted and measured response values; and s_{ref} is a measure of the uncertainty of the analysis because of sensory judgments (Wendin and Hall 2001).

Analysis of variance was performed by means of an SPSS v10.1 software package (SPSS Inc, Chicago, IL), nonlinear regression analysis by means of the Jandel table curve software v1.0 (Jandel Scientific, San Rafael, CA) and PLS regression by using SIMCA-P 10 statistical software (Umetrics AB, Umeå, Sweden).

RESULTS AND DISCUSSION

Sensory Analysis

The results of the sensory analysis are shown in Figs. 1–3 (Duncan's test, $P \leq 0.05$). Cohesiveness, hardness and springiness showed significant variation among the food samples analyzed.

The hardness and springiness (Figs. 2 and 3) of the examined foods are uniformly distributed on the evaluation scale, while for cohesiveness (Fig. 1), the opposite can be observed; trolly, toffee and Fruit Joy candies samples are

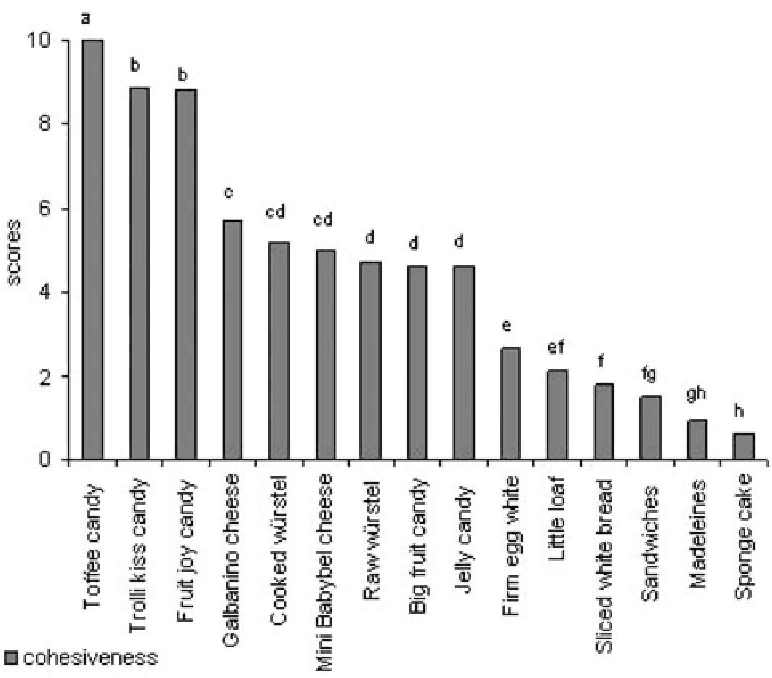

FIG. 1. AVERAGE SENSORY COHESIVENESS SCORES FOR VARIOUS FOODS
Different letters indicate significant differences (Duncan's test, $P \leq 0.05$).

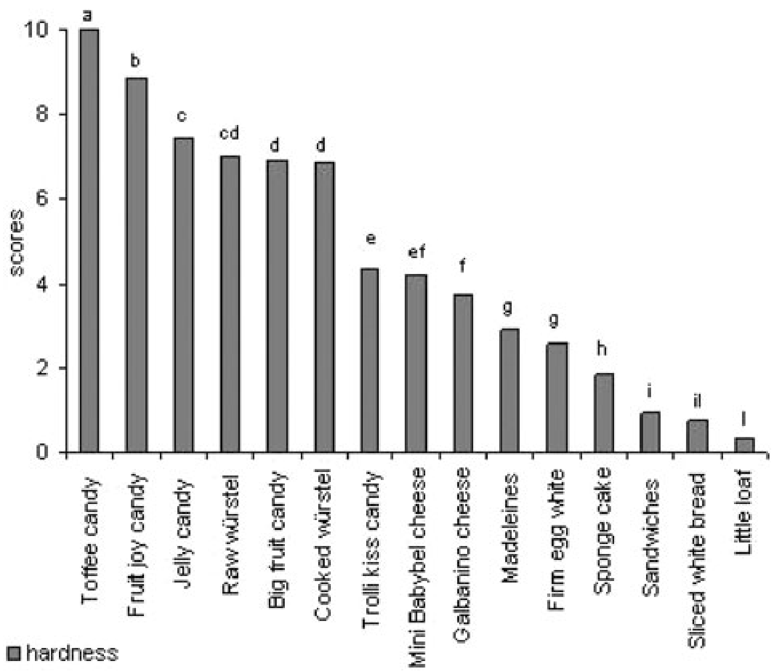

FIG. 2. AVERAGE SENSORY HARDNESS SCORES FOR VARIOUS FOODS
Different letters indicate significant differences (Duncan's test, $P \leq 0.05$).

more cohesive than other samples; the samples positioned in the central part of the evaluation scale (galbanino and Mini Babybel cheeses, cooked and raw würstel, big fruit and jelly candies) give quite similar cohesiveness values.

Instrumental Analysis

Cyclic Compression Test. In Fig. 4, the sensory characteristics are measured against the TPA parameters. From the TPA parameters, only sensory hardness was successfully correlated with TPA parameters ($R^2 = 0.875$). Indeed, no correlation was found between cohesiveness and TPA cohesiveness and between springiness and TPA springiness.

From the force–deformation curves, Young's modulus (E), strain (d_i) and stress (S_i) at peak as well as irrecoverable strain (r_i) and irrecoverable work (L_i) were also monitored during the five compression test cycles. A typical cyclic compression/decompression curve is shown for the big fruit candy sample (Fig. 5), where all parameters monitored during the five cycles of the compression test are represented.

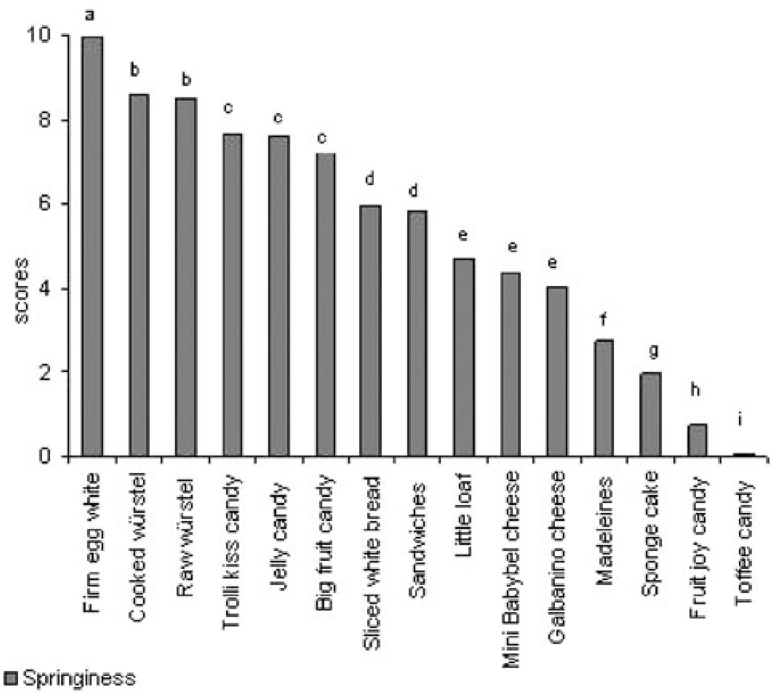

FIG. 3. AVERAGE SENSORY SPRINGINESS SCORES FOR VARIOUS FOODS
Different letters indicate significant differences (Duncan's test, $P \leq 0.05$).

A mathematical model was fitted in order to describe every parameter Y, with the exception of E, as a function of cycle number:

$$\log Y = C_i \times n^{A_i} \qquad (2)$$

In the above equation, C_i is the parameter value for $n = 1$, and A_i is an index of the parameter decay rate. The n value corresponds to the cycle number ($n = 1, 2, 3, 4, 5$).

Both the observed and predicted values of stress at peak, irrecoverable strain and irrecoverable work for big fruit candy, Mini Babybel cheese and cooked würstel samples are shown in Fig. 6. The same behavior was observed for all mechanical parameters and for all food samples; the results of parameters C_i and A_i, according to Eq. (2), are presented in Table 3. From the R^2 values, it is evident that the model was able to correctly describe the mechanical behavior of all samples.

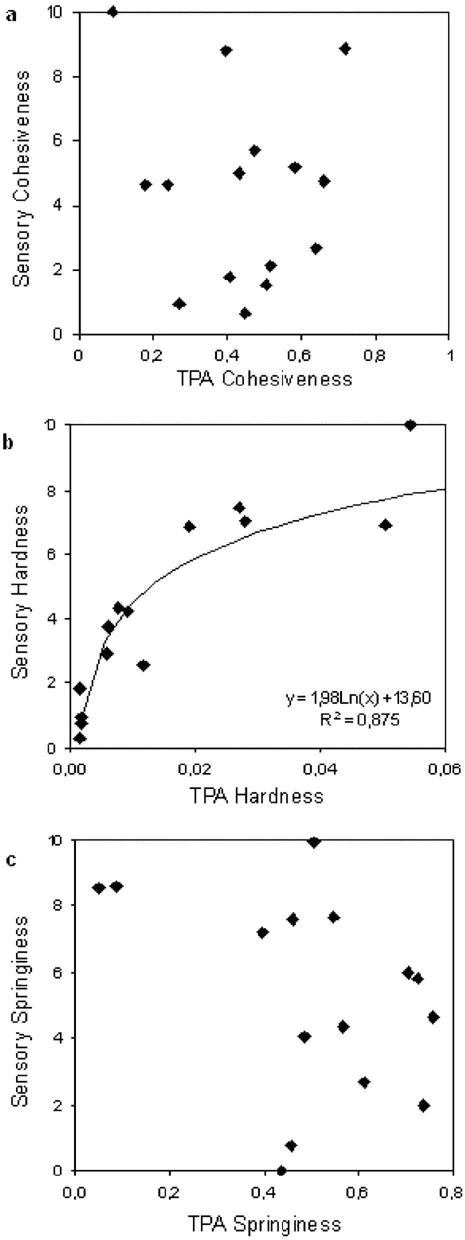

FIG. 4. SENSORY VARIABLES VERSUS TEXTURE PROFILE ANALYSIS (TPA) PARAMETERS

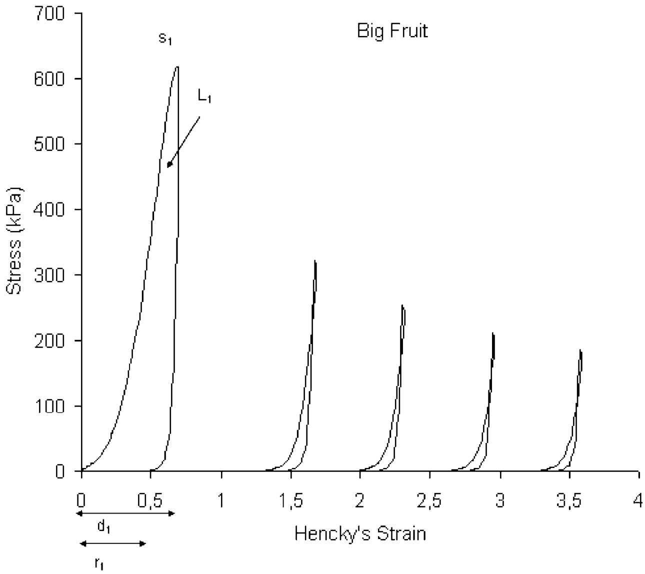

FIG. 5. EXAMPLE OF CYCLIC COMPRESSION/DECOMPRESSION CURVE (BIG FRUIT CANDY)

S_1, stress at peak; L_1, irrecoverable work; d_1, strain; r_1, irrecoverable strain.

Toffee candy showed the highest Young's modulus (E), whereas the angel cake sample had the lowest. The toffee sample also had the highest decreasing speed of strain at peak (A_1) in the five testing cycles, whereas the slowest speed emerged in the würstel samples; the Fruit Joy sample had the highest stress value at peak at the first cycle (C_2), while the bakery products had the lowest. The decay rate of stress at peak during the five test cycles is indicated by A_2. The fastest rate was found in firm egg white, big fruit and toffee candies. The stress at peak of the trolly candy showed the slowest decay rate. The toffee sample showed the highest irrecoverable strain (C_3) during the first compression/decompression cycle and also had the highest decay rate of the parameter (A_3). However, A_3 did not describe the differences among the samples analyzed. Firm egg white and raw würstel samples showed the lowest values of C_3. Fruit Joy candies showed the highest value of irrecoverable work at the first cycle (C_4), whereas the bakery products, except for the madeleines, exhibited the lowest. The toffee sample showed the highest decay rate of irrecoverable work (A_4), and the sandwiches showed the lowest.

Stress–relaxation Test. Stress–relaxation test results were normalized with respect to stress at initial time as $\sigma(t) = \sigma(t)/\sigma(t_0)$, in order to better

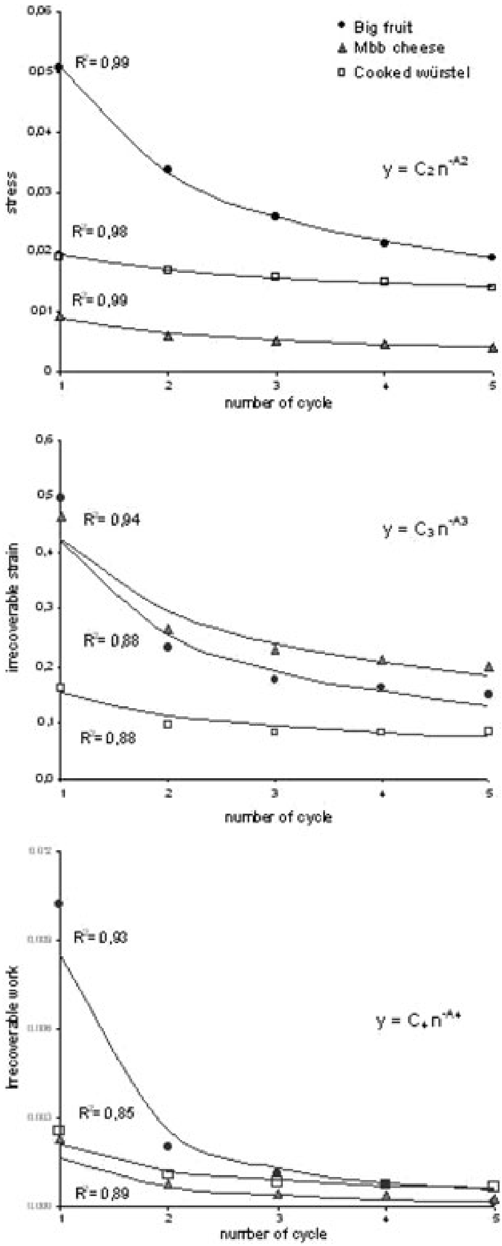

FIG. 6. STRESS AT PEAK, IRRECOVERABLE STRAIN AND IRRECOVERABLE WORK DATA FITTING
Mbb, Mini Babybel.

TABLE 3.
MECHANICAL PARAMETERS OBSERVED FOR FOOD PRODUCTS

Food samples	E	C_1*	A_1	R^2	C_2	A_2	R^2	C_3	A_3	R^2	C_4	A_4	R^2
Big fruit candy	0.0430_d	0.5_a	0.544_d	0.95	0.0510_c	0.616_d	0.99	0.420_{fg}	0.718_c	0.88	0.0085_d	1.711_{cd}	0.93
Sliced white bread	0.0059_a	0.5_a	0.219_b	0.94	0.0019_a	0.216_a	0.99	0.328_e	0.329_a	0.94	0.0004_a	1.135_b	0.95
Firm egg white	0.0036_a	0.5_a	0.106_a	0.93	0.0100_{ab}	0.560_d	0.83	0.109_a	0.427_{ab}	0.76	0.0005_a	0.810_b	0.91
Fruit Joy candy	0.4880_e	0.5_a	0.492_{cd}	0.90	0.1890_d	0.158_a	0.85	0.487_h	0.507_b	0.84	0.0374_f	0.920_b	0.90
Galbanino cheese	0.0118_b	0.5_a	0.351_c	0.88	0.0061_{ab}	0.318_b	0.98	0.394_f	0.592_b	0.88	0.0013_b	0.936_b	0.94
Jelly candy	0.0057_a	0.5_a	0.374_c	0.86	0.0275_b	0.254_a	0.99	0.420_{fg}	0.559_b	0.83	0.0048_c	1.460_c	0.90
Little loaf	0.0040_a	0.5_a	0.111_a	0.92	0.0015_a	0.173_a	0.99	0.174_b	0.102_a	0.72	0.0003_a	0.836_b	0.92
Madeleines	0.0372_c	0.5_a	0.275_b	0.95	0.0057_{ab}	0.411_c	0.98	0.332_e	0.346_a	0.84	0.0016_b	1.333_c	0.89
Mini Babybel cheese	0.0120_b	0.5_a	0.358_c	0.97	0.0089_{ab}	0.497_c	0.98	0.426_{fg}	0.520_b	0.94	0.0016_b	1.330_c	0.89
Angel cake	0.0022_a	0.5_a	0.168_a	0.91	0.0017_a	0.299_b	0.99	0.285_d	0.121_a	0.86	0.0003_a	1.050_b	0.95
Sandwiches	0.0026_a	0.5_a	0.146_a	0.97	0.0018_a	0.201_a	0.98	0.167_b	0.267_a	0.75	0.0003_a	0.018_a	0.86
Toffee candy	2.4664_f	0.5_a	0.967_e	0.99	0.0520_c	0.553_d	0.97	0.634_i	1.043_d	0.99	0.0160_e	2.130_d	0.89
Trolly candy	0.0034_a	0.5_a	0.143_a	0.86	0.0070_{ab}	0.091_a	0.90	0.228_c	0.378_a	0.72	0.0008_a	0.719_b	0.96
Cooked würstel without skin	0.0067_a	0.5_a	0.119_a	0.95	0.0193_{ab}	0.193_a	0.99	0.153_b	0.440_{ab}	0.88	0.0021_b	0.781_b	0.85
Raw würstel without skin	0.0121_b	0.5_a	0.102_a	0.97	0.0278_b	0.114_a	0.99	0.114_a	0.564_b	0.96	0.0024_b	0.854_b	0.89

Means within a column with a different subscript are significantly different (Duncan's test, $P \leq 0.05$).
* Max strain at the first cycle was the same for all the samples.
E, Young's modulus; n, cycle number; C_i, parameter value for $n = 1$; A_i, index of decay rate; $i = 1$, max strain; $i = 2$, max stress; $i = 3$, irrecoverable strain; $i = 4$, irrecoverable work.

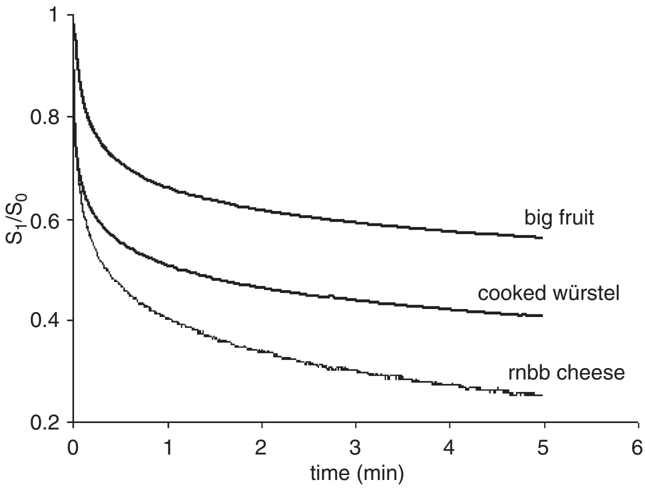

FIG. 7. EXAMPLES OF STRESS–RELAXATION CURVES
$S(t)/S_0$, normalized stress; S_1, stress at peak; S_0, stress recorded at the initial time; mbb, Mini Babybel.

compare the different samples analyzed. Figure 7 shows an example of a stress–relaxation curve for three food samples. The curves show a slope decreasing as time increases. This means that the stress–relaxation speed is higher at the beginning, and decreases as time progresses. From this figure, one can observe that big fruit, cooked würstel and Mini Babybel cheese samples behave as a typical viscoelastic solid, because stress for long testing times assumed nonzero values. All food samples tested showed a similar behavior (see Table 4).

The curves obtained were fitted through Peleg's model. This is a simplified approach in representing the relaxation curves of food materials, resulting in a linear regression function, as follows

$$t/Y(t) = K_1 t + K_2 \tag{3}$$

where $Y(t) = [F_0 - F(t)]/F_0$, $1/K_1$ is related to the initial stress decay rate and $1/K_2$ to a hypothetical asymptotic level nonrelaxed at long times.

In Table 4, parameters K_1 and K_2 are shown for all food samples. All food samples, except for the Mini Babybel cheese, showed a higher K_1 than K_2. Moreover, this cheese had the lowest K_1 value of all, indicating the presence of a higher viscoelastic feature with respect to the other. By contrast, raw würstel and big fruit candy samples showed the highest K_1 values.

TABLE 4.
PELEG'S MODEL PARAMETERS

Food samples	K_1	K_2	R^2
Big fruit candy	1.960_e	0.330_e	0.998
Sliced white bread	1.488_{cd}	0.157_c	0.999
Firm egg white	1.540_d	0.330_e	0.997
Fruit Joy candy	1.030_b	0.024_a	0.999
Galbanino cheese	1.185_b	0.222_d	0.999
Jelly candy	1.294_{bc}	0.062_b	0.999
Little loaf	1.431_c	0.209_d	0.985
Madeleines	1.389_c	0.104_c	0.999
Mini Babybel cheese	0.002_a	0.342_e	0.998
Angel cake	1.413_c	0.123_c	0.999
Sandwiches	1.492_{cd}	0.168_c	0.999
Toffee candy	1.044_b	0.029_a	0.999
Trolly candy	1.356_c	0.091_{bc}	0.999
Cooked würstel without skin	1.696_d	0.225_d	0.998
Raw würstel without skin	1.960_e	0.328_e	0.997

Means within a column with different subscripts are significantly different (Duncan's test, $P \leq 0.05$).

Fruit Joy and toffee candies had the lowest K_2 values, showing a high initial stress–relaxation speed, and thus indicating a structure unable to withstand the energy applied. A high K_2 value, obtained by Mini Babybel, firm egg white and big fruit samples, reflects a low response to relaxation.

Prediction of Sensory Attributes from Instrumental Parameters

The total percent variance explained by the first two components of PLS analysis was 66.85, and the individual percent variances were 53.66 for cohesiveness, 77.35 for hardness and 69.52 for springiness. The *RAP* indices were 0.78, 0.85 and 0.82 for cohesiveness, hardness and springiness, respectively. Thus, hardness was the best predicted sensory attribute, followed by springiness and cohesiveness. Indeed, cohesiveness showed the lowest *RAP*. Loadings for the first two PLS components are shown in Fig. 8.

As for the explanatory variables, on the first component, Peleg's model parameters (K_1 and K_2) were opposed to parameters relative to cyclic compression (A_i, C_i and E). Instead, C_3, A_2, A_1 and E were opposed to the other parameters on the second component.

All sensory variables were positively related on the second component, but while hardness and cohesiveness were also positively related on the first component, springiness was negatively related. PLS analysis also indicates that hardness and cohesiveness were related to each other.

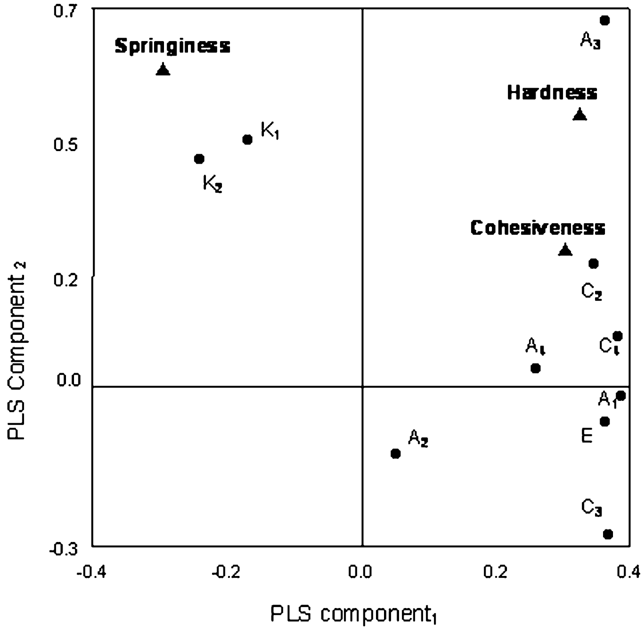

FIG. 8. LOADINGS FOR THE FIRST TWO PARTIAL LEAST SQUARES (PLS) COMPONENTS
●, *X* variables; ▲, *Y* variables.

The most influential instrumental parameters were identified for every sensory characteristic. In particular, K_1 and K_2 were significant contributors to the model; they were found to be the most important parameters involved in the prediction of springiness. This means that the stress–relaxation test is a valid method to predict the springiness of foods, as it provides a measure of their viscoelastic properties. Both K_1 and K_2 contributed positively; higher K_1 and K_2 values resulted in higher predicted values for springiness. Springiness scores were also negatively related to C_3 and A_2, which represent, respectively, the irrecoverable strain during the first compression test cycle and the stress decay rate at peak during the five cycles. These findings are consistent with the sensory definition of springiness (see Table 2).

Instead, the most predictive parameter of hardness was A_3, which has to be interpreted as an index of irrecoverable strain decay rate during the compression cycles. This finding is not consistent with the sensory evaluation technique for hardness (see Table 2) which did not involve any chewing of samples. Hence, the relation between sensory hardness and the irrecoverable strain decay rate was unexpected. It may be observed that C_2 also gave a good relation with hardness, which confirms that the TPA method predicts sensory hardness quite well (Meullenet *et al.* 1998; Antoniou *et al.* 2000; Adhikari *et al.* 2003; Chao-Chi Chuang and Yeh 2006). Indeed, C_2 is the stress value at peak at the first cycle; hence, it corresponds to the S_1 TPA parameter.

The prediction of cohesiveness was found to be less accurate than the other sensory characteristics. C_2, C_4 and A_4 were the most predictive parameters of cohesiveness. All the parameters contributed positively (i.e., samples that show high values of C_2, C_4 and A_4 had high cohesiveness). C_2 represents the amount of stress at peak of the first compression cycle, whereas C_4 and A_4 are, respectively, the amount of irrecoverable work of the first cycle and the decay rate of irrecoverable work.

PLS analysis also showed that Young's modulus (E) is of little value in predicting the sensory characteristics analyzed. This finding conflicts with that of Wium *et al.* (1997) who reported that both oral and nonoral firmness of feta cheese were well predicted from E, and with that of Breuil and Meullenet (2001) who reported that Young's modulus was positively correlated with the sensory hardness scores of different cheeses.

In Fig. 9, the graphs of observed variables versus predicted from instrumental measurements by the PLS regression analysis are shown. The position on the graphs of the different samples confirms a good relation between instrumental parameters and sensory hardness; even sensory springiness was predicted quite well by the PLS model, whereas cohesiveness was not so accurately predicted.

CONCLUSIONS

The major finding of this study is that both stress–relaxation and cyclic compression tests need to be performed for the correct prediction of sensory responses. TPA is unable to predict the examined sensory characteristics, except for hardness, which showed a good nonlinear relation with the TPA parameter.

As a sensory attribute, hardness as well as springiness is predicted well by means of the instrumental parameters used. Instead, the instrumental prediction of cohesiveness is not so accurate. This may be because of the fact that analyzed samples are not uniformly distributed on a sensory cohesiveness scale and that the instrumental methods used do not break the samples, whereas the sensory evaluation technique of cohesiveness concerns the rupture of the samples.

As the samples analyzed in this study reflect a very large pattern of instrumental measures, further investigation on the prediction ability of such parameters on samples with smaller differences in instrumental measures will be conducted.

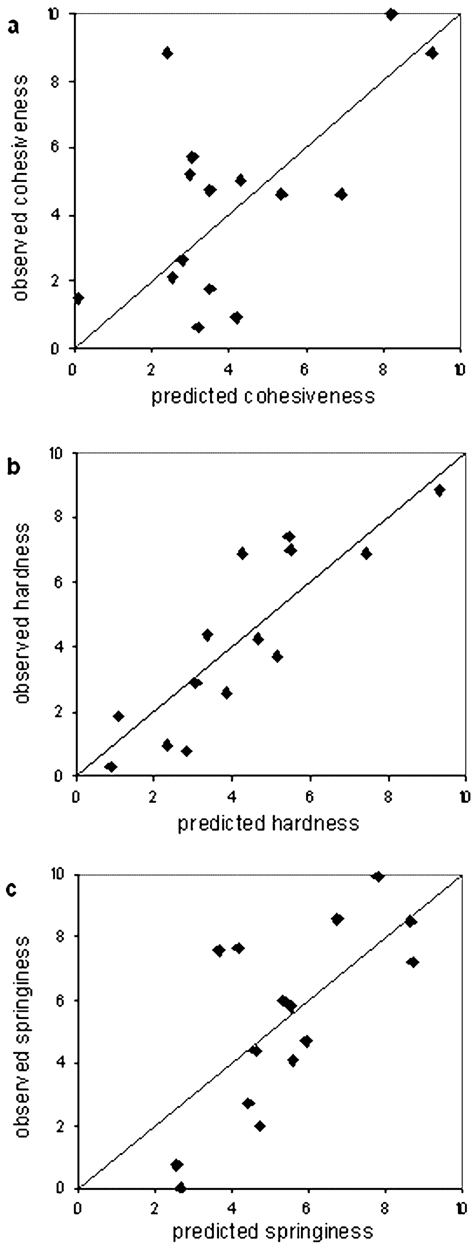

FIG. 9. PREDICTED VERSUS OBSERVED SENSORY VARIABLES

In addition to this study, future research in this area will focus on the investigation of appropriate instrumental methods to predict sensory cohesiveness.

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