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Principal component analysis to study the effect of temperature fluctuations during storage of frozen potato

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Abstract The effects of temperature fluctuation ranges, number of fluctuations carried out, and packaging during frozen storage on the texture of potato tissue in terms of compression, shear, and tension rheological parameters were assessed through data generated according to a factorial design using principal component analysis (PCA). Five ranges of fluctuation (–24 °C to –18 °C, –18 °C to –12 °C, –12 °C to –6 °C, –24 °C to –12 °C and –18 °C to –6 °C) applied 2, 4, 8, 16, 24, and up to 32 times on unpacked and pre-packed frozen potatoes, were considered. The controls were unpacked and prepacked frozen tissues thawed immediately without undergoing any fluctuation. In addition, several geometrical, technological, and chemical parameters were determined. PCA showed that maximum shear force, F_s was the best rheological parameter for differentiation of the structural damage and softening occurring in the tissue at each treatment, which was closely related to its duration, TT_d. PCA did not permit complete discrimination between the five fluctuation ranges, but it clearly separated samples subjected to –18 °C/–6 °C from those subjected to –24 °C/–18 °C. Frozen samples undergoing up to four fluctuations formed a separate cluster from those undergoing a higher number. Analysis also clearly separated unpacked from pre-packed samples in response to slower freezing rates reached in the latter.

Key words Potato · Temperature fluctuations · Principal component analysis · Rheological parameters · Frozen storage

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Introduction

The storage stage offers the greatest potential for quality maintenance of either refrigerated or frozen foods [1–5]. Consequently, a precise knowledge of food storage temperatures and conditions is needed to maintain quality with in satisfactory ranges. Effects of storage temperature and oscillations in these temperatures on quality of refrigerated foods has been evaluated to identify optimum storage conditions for domestic refrigeration [6]. Optimization of quality in the storage of frozen foods is considerably more difficult because of the low temperatures which must be maintained throughout the cold chain. Temperature abuse is most likely to occur at the retail point of the distribution chain [7].

Effects of temperature and temperature fluctuation during distribution and sale on quality and stability of frozen prepared foods including different meats and fish has been studied [8]. Sensory evaluation indicated no significant difference in texture, flavor, or color after a certain period of constant temperature storage for all samples with different numbers of freeze-thaw cycles in shipping temperatures of –18 °C, –12 °C, and –6 °C for 18 h and thawing times of 40, 80, and 120 min at 20 °C. However, studies on three different temperature variations in cold cabinet showed that a temperature variation of –12 °C to –5 °C would result in serious freezer burn and considerable amounts of frost on product surface, with a much shorter shelf-life than with temperature variations of –15 °C to –9 °C and –19 °C to –13 °C.

Fluctuating temperature had detrimental effects on the texture of frozen potato, even in the region of –24 °C and –18 °C, with the lowest rheological properties used to measure firmness of tissue in samples subjected to fluctuations between –18 °C and –6 °C. [4, 9]. Growth of ice crystals by recrystallization was shown to be the major factor in determining structural damage in unpacked samples, whereas the higher structural deterioration in pre-packed samples was associated with greater drying of the tissue by sublimation of ice on the sample surface, the damage caused by recrystallization and sublimation being cumulative [3, 4].

Prediction of quality changes under temperature fluctuations is also important in conserving energy by optimizing storage temperature. Lai and Heldman [10] applied kinetic models to analysis of time-temperature-tolerance (TTT) data for frozen food storage using kinetic parameters to describe quality degradation in frozen foods. Alvarez and Canet [5] pointed out the potential of kinetics parameters calculated for rheological properties as firmness indicators to distinguish between temperature fluctuation ranges of –24 °C to –18 °C and of –18 °C to –6 °C, proposing the term "frozen storage firmness" to describe the amount of firmness that is resistant to degradation after freezing with four temperature fluctuations during frozen storage and final thawing of potato tissue.

Our results [4, 5, 9] have shown the influence of packaging on frozen tissue quality. Freezing and temperature fluctuations cause greater damage to pre-packed than to unpacked samples. Because packaging is essential, at least in the distribution and sale stages, more studies of the effect of packaging materials on temperature fluctuation of frozen food are required [11].

Principal component analysis (PCA) is used to study interdependencies and underlying relationships between variables [12], being widely applied in studies on semisolid or liquid products, such as wine and apple juices [13–15]. PCA is also used to analyze sensory properties of fruit and vegetables, trying to find their relationships with instrumental objective measurements [16–18]. There have been few processed food studies using this technique concerning such drastic thermal treatments as those entailed in the production of frozen vegetables. The aim of this study was to apply PCA to test its effectiveness in describing and distinguishing between different fluctuation ranges and number of fluctuations carried out on unpacked and pre-packed potato tissue during frozen storage, and to look for the rheological parameter which can best be used as a texture measurement when checking the effect of temperature fluctuations during frozen storage.

Materials and methods

Test material. The potato samples (*Solanum tuberosum*, L., *cv. Monalisa*) came from Segovia (Spain) and consisted of potatoes having weights (in grams) within the confidence interval ($153.83 \leq \mu \leq 186.56$) and specific weights (g/cm^3) within the interval ($1.0635 \leq \mu \leq 1.0796$); $P \leq 0.01$. The material was stored in a chamber (4 °C and 85% relative humidity) during the experiment. The number of days that each batch of potatoes had been in storage prior to test was considered as a technological parameter which could influence the results (Table 1).

Freezing, temperature fluctuations and thawing processes. Samples were frozen by forced convection with liquid nitrogen vapor in an Instron programmable chamber (model 3119–05, –70 °C/+250 °C) at –60 °C until their thermal center reached –18 °C. Once this temperature was reached, the chamber was controlled by product thermal center temperature, and 0 (i.e., only freezing and thawing processes and controls), 2, 4, 8, 16, 24 and up to 32 fluctuations varying from –24 °C to –18 °C, –18 °C to –12 °C, –12 °C to –6 °C, –24 °C to –12 °C, and –18 °C to –6 °C ranges were induced in unpacked and pre-packed samples. Once the fluctuations had been completed, the product was thawed by forced convection with air at +20 °C. For pre-packed samples, polyethylene bags were used, sealed under light vacuum (–0.05 MPa) on a Multivac packing machine. Air and product temperature were monitored by K-type thermocouples (NiCr/NiAl; –200 °C to +1000 °C) using a hardware and software system developed together with the LabWindows/CVI package (C for Virtual Instrumentation) for the automation of the thermal process control [19]. The software permitted real-time data-gathering, storage and calculation of either freezing and thawing rates (R_f and R_t, respectively) or exact duration of each treatment carried out. The total duration of each treatment (including freezing, a given number of temperature fluctuations in the given ranges, and thawing processes) varied significantly according to the fluctuation range concerned and depending on whether or not the treatment had been performed in pre-packed or unpacked samples [5]. Total duration of each thermal treatment carried out (TT_d), the duration of one temperature fluctuation (TF_d), and the freezing and thawing rates at each treatment were considered as technological parameters in the PCA analysis (Table 1).

Mechanical tests. Compression, shear, and tension tests were performed using an Instron Food Testing Instrument Model 4501 [4, 5, 9]. Ten replicates were performed for each of the mechanical tests. Cylindrical specimens (diameter 25.40 mm, height 10 mm) were compressed between parallel plates at a deformation rate of 200 mm min^{-1}. This test allowed for the measurement of the bioyield point [B_c (N)], the maximum compression force [F_c (N)], the compression ratio (representing the level of the first linear zone with respect to the maximum breaking point of the force-deformation curve at which there was deviation from linearity) [R (dimensionless)], the apparent modulus of elasticity [E_c (MPa)], and the energy required for breaking per unit of volume [U_c (µJ mm^{-3})]. Shear tests were performed on cylindrical specimens (diameter 25.40 mm, height 10 mm) using a shear cell [9, 20] at a deformation rate of 400 mm min^{-1} to give the maximum shear force [F_s (N)], the maximum shear stress [σ_s (MPa)], the modulus of rigidity [G_s (kPa)], and the shear energy required for breaking per unit of volume [U_s (µJ mm^{-3})]. The tension test was performed on 5-mm-thick bone shaped specimens (75 mm long, 20 mm wide at the retaining ends and 8 mm wide at the neck) at a deformation rate of 100 mm min^{-1}, using a cell consisting of two compressed-air clamps (0.15 MPa) fitted to the specimen ends by filter paper to prevent slippage and failure, to give the maximum tension force [F_t (N)], the maximum tension stress [σ_t (MPa)], the apparent modulus of elasticity [E_t (MPa)], the energy required for breaking per unit of volume [U_t (µJ mm^{-3})], and the maximum tension deformation [D_t (mm)]. Altogether, there were 14 different rheological parameters (Table 1).

Moisture content. Determinations were made by drying samples in a Philips microwave oven (model M-718, 700 W) with output power at 70%. Weighing was performed on a Mettler AT 100 analytical balance with a metering precision of 0.00001 g. The initial weight of each sample was approximately 5 g. Samples were weighed every 5 min until a constant weight was attained [21]. Ten determinations were performed for each treatment and moisture content was considered as a chemical parameter in the PCA analysis (Table 1).

Principal components analysis. PCA was used to study interdependencies and underline relationships between variables in order to reduce the number of variables representing the rheological, geometrical, technological, and chemical aspects, aiming at simplification without loss of relevant information, and at im-

Table 1 Variables considered in the analysis. Supplementary variables (*)

Aspect	Symbol	Variable	Unit
	F_c	Maximum compression force	(N)
	B_c	Bioyield point	(N)
	R	Compression ratio	*Dimensionless*
	E_c	Apparent modulus of elasticity in compression	(MPa)
	U_c	Compression energy required for breaking per unit of volume	(μJ mm^{-3})
	F_s	Maximum shear force	(N)
	σ_s	Maximumshear stress	(MPa)
Rheological	G_s	Modulus of rigidity	(KPa)
	U_s	Shear energy required per unit of volume	(μJ mm^{-3})
	F_t	Maximum tension force	(N)
	σ_t	Maximumtension stress	(MPa)
	E_t	Apparent modulus of elasticity in tension	(MPa)
	U_t	Tension energy required for breaking per unit of volume	(μJ mm^{-3})
	D_t	Maximum tension deformation	(mm)
Geometrical	V_{cs}	Volume decrease of cylindrical specimens	(%)
	V_{bs}	Volume decrease of bone shaped specimens	(%)
	R_f	Freezing rate	(°C min^{-1})
	R_t	Thawing rate	(°C min^{-1})
	TT_d	Total thermal treatment duration	(min)
Technological	TF_d	Temperature fluctuation duration	(min)
	Days	Days in refrigerated storage before the treatment	(days)
	Range	Fluctuation range levels (*)	*Dimensionless*
	Number	Number of temperature fluctuations levels (*)	*Dimensionless*
	Pack	Packaging levels (*)	*Dimensionless*
Chemical	*Mo*	Moisture content	(%)

provement of the associated understanding via identification of new, uncorrelated variables. The STAT-ITCF software (Bordeaux, France) used for calculation of principal components was applied to the multivariate data pertaining to 62 averages (5 fluctuation range levels × 6 number of fluctuation levels × 2 packaging levels plus two controls).

Results and discussion

The 25 selected variables used to characterize the treatments were gathered in four aspects and designated by the abbreviations shown in Table 1. In the analysis, the factors fluctuation range, number of fluctuations applied and packaging were considered as supplementary variables. Although not directly used to derive the principal components, their projections on the factorial planes enable one to gain knowledge of their effect and their relationship with the measured variables. The data matrix used in the PCA was constructed from values that had been standardized by centering and reduction to make them independent of the units of measurement employed [12].

For initial rheological parameters from compression tests, the highest correlation was between the apparent modulus of elasticity E_c and energy required for breaking U_c ($r=0.929$), indicating that these parameters were redundant and measure the same physical effect in the tissue. An earlier investigation showed that maximum compression force was the most sensitive mechanical property to detect the effect of the temperature fluctuation range, varying this property with the number of fluctuations with the greatest level of significance [4]. Compression parameters were also most significantly affected by the effects of the precooling and the freezing rate at freezing temperatures [22], representing either the loss of cell turgor pressure or of elastic response tissue in treatments which involved freezing [9, 20].

In shear tests, the highest correlation was found between maximum force F_s and energy U_s, (r = 0.914) and in tension tests the highest correlation was established between maximum force F_t and maximum stress σ_t ($r=0.962$). Correlations between rheological parameters derived from different mechanical tests were also quite high. The highest correlation was between maximum compression force F_c and shear energy U_s ($r=0.903$). When taking into account only the results from the most extreme fluctuation ranges (i.e., –24 °C/–18 °C and –18 °C/–6 °C), shear force F_s was found to be the best rheological parameter to define the softening of potato tissue by fluctuation using two-phase models [5]. Results from earlier investigations show that the best mechanical test to use will depend on the type of effect that is studied and the purpose of the measurement [9, 23].

When considering correlations between rheological parameters and variables representing the other aspects, geometrical parameter V_{cs} presented the highest negative correlation with F_c ($r=-0.676$) whereas V_{bs} correlated better with s_t ($r=-0.710$). However, technological parameters correlated better with shear rheological parameters, so that thermal treatment duration TT_d showed a strong correlation ($r=-0.790$) with U_s, and temperature fluctuation duration TF_d correlated well

(r=–0.799) with s_s. Also, moisture content Mo correlated strongly with the modulus of rigidity G_s (r=0.749). Rheological shear parameters may be considered the best to correlate with the variables representing the different aspects considered.

PCA revealed that five principal components (PC-1 to PC-5) explained almost 88% of the variance between the data, although the first two principal components explain 70% of the total variance (Table 2). Table 3 shows the rotated orthogonal PC loadings. The loading for each measured variable represents its relative contribution to a principal component. Variables with the highest loadings for each PC are marked in boldface, indicating that this PC is dominated by these particular variables. Figure 1A,B shows the projection of all the variables studied (supplementary variables are in boldface) on the coordinate grid defined by the first and second factorial axes and their projection on the coordinate grid defined by the first and third factorial axes, respectively. Total variation explained in Fig. 1A is 69.9%, whereas total variation explained by the first and third axes is slightly lower (67.6%). Circles gather the best represented variables, which are the ones close to the borders of the circles. Figure 2 shows the projection of the observations (thermal treatments carried out) on the plane defined by the first and second components.The following conclusions may be drawn from the statistical data:

The first PC, which explains almost 60% of the total variance, presents negative and high correlations (Table 3), in descending order, with rheological parameters F_s, F_c, U_s, U_c, F_t, E_t, E_c G_s, U_t, σ_s, σ_t, and B_c (for abbreviations see Table 1). Shear and compression forces therefore correlated best with PC-1. This first PC also presents positive and high correlations with technological variables TF_d and TT_d, as well as with geometrical parameters V_{bs} and V_{cs} (angle between projections close to 180°, Fig. 1A). Finally, PC-1 presents a negative high correlation with moisture content, Mo. This means that the greater the decrease of sample volume with respect to the original volume, the lower either the mechanical strength of the tissues or the final moisture

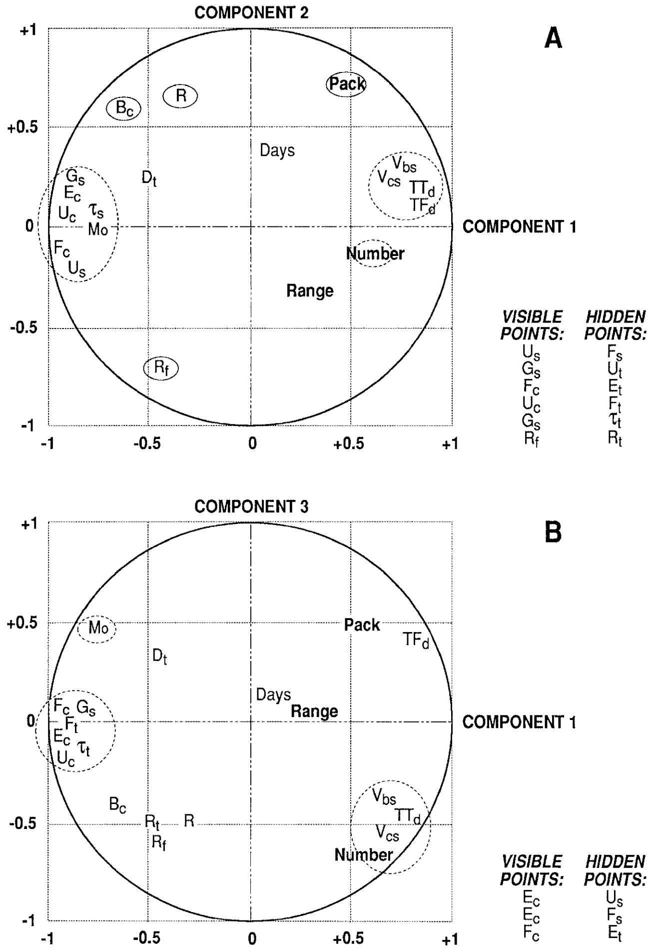

Fig. 1 Projection of the variables on the coordinate grid defined by the first and second factorial axes (**A**) and projection of the variables on the coordinate grid defined by the first and third factorial axes (**B**)

Table 2 Total variation explained by the five principal components (PC-1 to PC-5)

Variation explained (%)				
PC-1	PC-2	PC-3	PC-4	PC-5
59.1	10.8	8.5	4.7	4.4

Table 3 Rotated orthogonal principal component (PC) loadings of the variables studied. The highest PC loadings for each factor are in **boldface**. Supplementary variables (*). For abbreviations, see Table 1

Variables	*PC-1*	*PC-2*	*PC-3*	*PC-4*	*PC-5*
F_c	**−0.9419**	−0.1030	0.0692	0.0821	0.0559
B_c	**−0.6520**	0.5497	−0.3604	−0.2128	0.1079
R	−0.3017	**0.6923**	−0.4253	−0.2817	0.1350
E_c	**−0.9182**	0.2151	−0.0346	−0.0139	−0.1496
U_c	**−0.9325**	0.0768	−0.1342	−0.0257	−0.1207
F_s	**−0.9464**	−0.1208	−0.0106	−0.0646	−0.0734
σ_s	**−0.8528**	0.0997	−0.2431	−0.1168	−0.2285
G_s	**−0.8859**	0.2563	0.0792	−0.0761	0.1616
U_s	**−0.9382**	−0.1555	−0.0133	−0.0916	0.0135
F_t	**−0.9306**	0.1128	0.0011	0.2237	0.0230
σ_t	**−0.8400**	0.2342	−0.0909	0.3429	0.0211
E_t	**−0.9290**	−0.0814	0.0609	0.0338	0.1725
U_t	−0.8670	0.2324	0.1358	0.2572	−0.0527
D_t	−0.4496	0.2426	0.2885	**0.6226**	0.2724
V_{cs}	**0.6462**	0.2439	−0.4577	0.0860	−0.1318
V_{bs}	**0.6947**	0.3056	−0.3191	0.2247	−0.0714
R_f	−0.4802	**−0.6549**	−0.4837	−0.0070	0.2611
R_t	−0.5069	**−0.6261**	−0.4519	0.0426	0.3120
TT_d	**0.7743**	0.2261	−0.3960	0.2706	0.0312
TF_d	**0.7846**	0.1425	0.4266	−0.0469	0.0943
Days	0.1052	0.4267	0.1808	−0.2330	**0.7141**
Mo	**−0.7765**	0.0072	0.4856	−0.2469	−0.0518
Range (*)	0.2965	−0.2528	0.1049	−0.2834	0.2305
Number (*)	**0.6196**	−0.0806	−0.5714	0.2904	0.1194
Pack (*)	0.5121	**0.6354**	0.4647	−0.0259	−0.2674

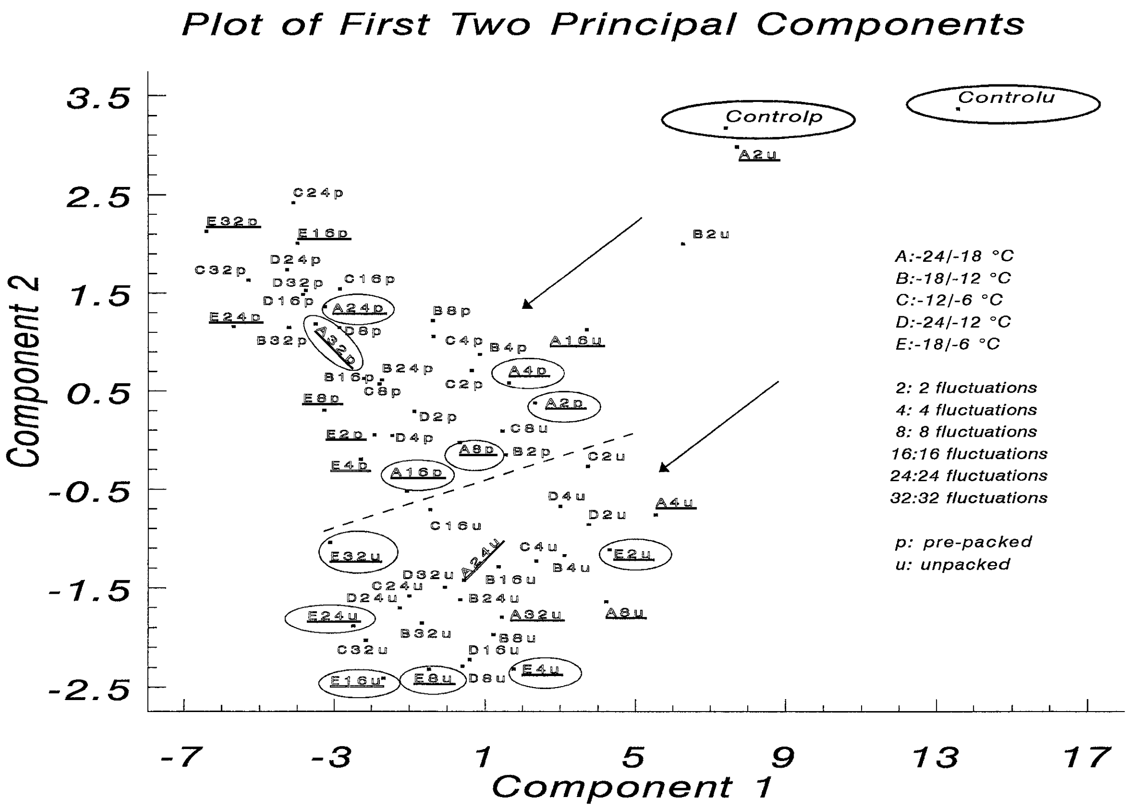

Fig. 2 Projection of the observations on the plane defined by the first and second factorial axes as functions of the three factors studied (*Range*, *Number*, *Pack*)

content after thawing. The longer the thermal treatment or a fluctuation lasted, the greater the mechanical damage undergone by the tissue and the lower the mechanical strength, confirming previous findings [4]. The longest treatment subjected pre-packed samples to 32 fluctuations between –18 °C and –6 °C, attaining temperatures very close to the zone of maximum ice crystal formation; this accelerates melting of small ice crystals, thus increasing the amount of available water, which refreeze immediately, causing enlargement of the big crystals at the expense of the small crystals. The number of the latter consequently decreases and their average size increases through migratory recrystallization [24], which accounts for the tissue softening.

The factorial axis associated with PC-1 is the axis which of all the imaginable axes best represents the similarities and differences between the observations [12] and distinguishes samples with higher rheological parameters and lower volume reductions from samples with lower rheological parameters and larger volume reductions. PC-1 gathers all the rheological parameters, except D_t, and the geometrical, chemical, and two technological parameters. According to the correlations obtained, PC-1 may be identified chiefly with the rheological aspect representing an index of the mechanical behavior of the tissue, which undergoes more structural damage as the duration of the thermal treatment is increased by means of a greater fluctuation range and/or a larger number of fluctuations.

Samples controlp and controlu were not subjected to fluctuations; these had the highest rheological and chemical parameters and the lowest treatment durations and volume decreases. These gave outlying values quite distant from the points for the other treatments, especially unpacked control (Fig. 2). The treatments involving two fluctuations between –24 °C and –18 °C and between –18 °C and –12 °C in unpacked samples (A2u and B2u, respectively) were quite close to the controls, indicating that less softening was produced by the lowest number of fluctuations in the narrowest ranges, which involved lower temperatures (designated A and B).

The greatest contribution to PC-1 from the supplementary variables was made by the factor Number (number of temperature fluctuations carried out). Its projection within the plane (Fig. 1A) shows the large influence that this factor had either on the rheological parameters or on the moisture content (angle between projections close to 180 °C).

In fact the movement of the individuals along PC-1 (see arrows in Fig. 2) indicates loss of firmness and moisture through the increase in the numbers of fluctuations applied, which is accompanied by an increase in the loss of sample volume. Unpacked samples subjected to fluctuations between –18 °C and –6 °C and pre-packed samples subjected to fluctuations between –24 °C and –18 °C are circled. The movement of these points along PC-1 indicates high loss of firmness from the corresponding controls up to four temperature fluctuations. Also, although there was greater softening with larger numbers of fluctuations, the observations for 8, 16, 24 and 32 fluctuations are distributed within a narrower range along the negative PC-1 axis. This explains the relatively low apparent correlation of *Number* with PC-1, even with it being the factor that had most significantly affected tissue softening, confirming previous results. In an earlier study [5] it was shown how, in potato tissue, plots of log (rheological parameters) vs number of fluctuations exhibit two distinct regions. Conventional chemical kinetic theory was used to express tissue softening by freezing and frozen storage through two pseudo-kinetic mechanisms, which were qualitatively similar to those found for thermal softening of vegetables [25]. As few as four fluctuations are enough to cause such damage to the structure that the tissue softening remains practically constant if the number of fluctuations is increased [4]. Figure 2 shows how PC-1 segregates two clusters, separating the samples which had undergone up to four or eight fluctuations (to the right of the graph) from those subjected to a higher number (left of the graph). There is no clear segregation in the five fluctuation ranges between 8, 16, 24, and 32 due to very slow softening of the tissue, which remains practically constant after four fluctuations. Certainly, four fluctuations defines the onset of slower tissue softening.

PC-2 (which explains just over 10% of the total variance) gathers the technological parameters freezing rate R_f and thawing rate R_t, and also the compression ratio R. Freezing and thawing rates presented positive r values with the rheological parameters, indicating that they decreased with the decrease in both rates in the thermal treatments. The highest correlation was with shear energy U_s. Both rates presented a strong positive correlation ($r=0.954$). Their projections in Fig. 1A are so close that one variable occludes the other, which means that the slower the freezing the slower the thawing. PC-2 gathers two technological variables which correlated negatively with the duration of the thermal treatment TT_d and the duration of a fluctuation TF_d. Hence, PC-2 may be identified mainly with the technological aspect.

Freezing and thawing rates depended on whether samples were treated packed or unpacked. Note the position of the supplementary variable *Pack* (representing packaging levels) on the plane formed by the first two components (Fig. 1A). *Pack* was the variable that best correlated ($r=0.6354$) with PC-2. It follows from its projection in the correlation circle that there was a strong relation between the packaging and the process rates R_f and R_t (angle between projections close to 180°). Packaging slows down freezing and thawing processes, and consequently rheological parameters are reduced in response to the structural damage caused to the tissue by slow freezing [26]. The technological aspect of the second principal component can be seen in the representation of individuals, where the points representing the packed samples (at the top of the graph) formed a separate cluster distinct from the group representing the unpacked samples (bottom of the graph; unpacked A16u and C8u were two exceptions). Also, the points representing the packed samples are situated more to the left along PC-1 than the corresponding unpacked samples, reflecting a greater degree of softening resulting from lower freezing rates. This is more readily apparent if we compare the positions on the plane of the points representing the same treatments in packed and unpacked samples (e.g., A4u A4p).

PC-3 and PC-4 did not present high r values with any of the variables (Table 3). The projections of the technological variable compression ratio, R and geometrical variables are less well represented on the plane formed by the first and third principal components (Fig. 1B). PC-4 presents a positive correlation ($r=0.6226$) with maximum tension deformation D_t. This rheological parameter was unrelated to any other of the variables studied. PC-5 was formed mainly by the technological parameter “days in refrigerated storage” (*Days*). This fact also indicates the absence of any linear relationship between this variable and those well correlated under the first principal components plane, showing that any effect of the time that the potatoes were stored before treatment was not significant for the rheological parameters measured in the tissues after treatment. Alvarez et al. [27] found that, under the same storage conditions, cell turgor pressure of potato tissue decreased during the first 2 weeks, increased between 4 and 8 weeks, finally decreasing up to 8 weeks. Results suggest that under freezing treatments the effects of stored times on the texture of potato are not detected.

The level of representation of an original variable within the first and second PC plane (Fig. 1A) can be measured by means of the cumulative determination coefficient, defined as commonalities (Table 4). Of the rheological parameters, maximum shear force F_s was the one best explained by the first two principal components and may therefore be considered the best suited to measure tissue firmness in this study. Explanation of geometrical variables was moderate (with low percentages), and of the technological variables the best explained was total treatment duration TT_d. Finally, it is worth noting the difference in percentage explanation for the supplementary variables. The degree of explanation of the variable *Range* (representing the levels of the “fluctuation ranges” factor) was very low. Points for the five fluctuation ranges applied (see Fig. 2) did not form clearly separate clusters. However, the samples corresponding to the range –18 °C to –6 °C (designated E and underlined in the graph) fell in the left side of the graph, indicating that these samples gave the lowest values for the rheological parameters in response to the increased structural damage and softening caused by these fluctuations. On the other hand, most of the sam-

Table 4 Percentage of each variable explained by the first two factorial axes. Supplementary variables (*). For abbreviations, see Table 1

Variables	Percentage explained
F_c	89.77
B_c	72.72
R	57.03
E_c	88.95
U_c	87.55
F_s	**91.03**
σ_s	73.72
G_s	85.06
U_s	90.44
F_t	87.88
σ_t	76.05
E_t	86.96
U_t	80.56
D_t	26.01
V_{cs}	47.71
V_{bs}	57.60
R_f	65.95
R_t	64.89
Days	19.32
TT_d	**82.54**
TF_d	80.49
Mo	60.31
Range (*)	15.18
Number (*)	39.04
Pack (*)	66.60

ples subjected to fluctuations in the range –24 °C to –18 °C (designated A and underlined in the graph) are situated on the right of the graph, indicating that these were the samples with the highest rheological parameters. These two fluctuation ranges produced the most significant differences in the final tissue firmness. No significant differences were observed among samples subjected to fluctuations in the other three ranges (designated B, C, and D in Fig. 2) [4, 5]. The supplementary variable *Number* (representing the levels of the factor "fluctuations applied") was reasonably well explained by the first two principal components, indicating rapid softening of the tissue for four fluctuations and slower softening for larger numbers of fluctuations. The supplementary variable *Pack* (representing the levels of the factor "packing") is well explained by the first two principal components, with clear separation of the relative positions of packed and unpacked samples in the first factorial plane.

The results show that the plane formed by the first two principal components gathers the relative positions of the samples in accordance with the four aspects studied, while the rheological, geometrical, and chemical aspects are gathered by the first principal component, PC-1. This component segregated the samples that had been subjected to up to four temperature fluctuations from those subjected to a higher number. The second principal component PC-2, representing the technological aspect, clearly segregated packed and unpacked samples on the basis of their response to the lower freezing rate in samples packed before thermal treatment. PCA has confirmed the results of previous studies, and on that basis we intend to apply, and propose for others, this statistical technique for determining the effects that the thermal treatments used in the vegetable processing industry have on texture.

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References

1. Reid DS (1983) Food Technol 37:110–113, 115
2. Reid DS (1990) Food Technol 44:78–82
3. Canet W (1989) Quality and stability of frozen vegetables. In: Thorne S (ed) Developments in food preservation, vol 5. Elsevier, London, pp 1–50
4. Alvarez MD, Canet W (1998) Z Lebensm Unters Forsch A 206:52–57
5. Alvarez MD, Canet W (1999) Eur Food Res Technol (2000) 210:273–279
6. Dong SJ, Mee RK, Joong HA, Kwang YC, Young HC, Seung UK, Kwan HP (1996) Korean J Food Sci Technol 28:632–637
7. Hall LP (1979) IFST-Proceedings 12:267–276
8. Huang CC, Chang PY (1987) Food Sci-China 14:361–372
9. Alvarez MD (1996) Caracterización reológica de tejidos de patata tratados térmicamente. Cinéticas de ablandamiento. PhD thesis, Universidad Politécnica de Madrid, Madrid
10. Lai DJ, Heldman DR (1983) J Food Process Eng 6:179–200
11. Zuritz CA, Sastry SS (1986) J Food Sci 51:1050–1056
12. Piggot JR, Sharman, K (1986) Methods to aid interpretation of multidimensional data. In: Piggot JR, Sharman K (eds) Statistical procedures in food research. Elsevier Science, London, chap 6, pp 181–232
13. Silva ML, Macalta FX (1999) Z Lebensm Unters Forsch A 208:134–143
14. Varela F, Calderón F, González MC, Colomo B, Suárez JA (1999) Eur Food Res Technol 209:439–444
15. König T, Schreider P (1999) Z Lebensm Unters Forsch A 208:130–133
16. Barreiro P, Ruiz-Altisent M (1997) Medida instrumental de la harinosidad en manzana. 11 Congreso Iberoamericano de Ciencias Hortícolas. Vilamoura 11–15 March 1997
17. Barreiro P, Ortiz C, Ruíz-Altisent M, De Smedt V, Schotte S, Andani, Z, Wakeling I, Beyts PK (1998) J Texture Stud 29:509–525
18. Cuppett S, Deleon A, Parkhurst A, Hodges L (1997) J Food Quality 20:127–144
19. Rico R, Alvarez MD, Canet W (1995) Eurofach Electrón 18(231):60–65
20. Canet W (1980) Estudio de la influencia de los tratamientos térmicos de escaldado, congelación y descongelación en la textura y estructura de patata (*Solanum tuberosum*, L.). Ph D thesis, Universidad Politécnica, Madrid
21. Canet W (1988) J Microwave Power EE 23:231–236
22. Alvarez MD, Canet W (1997) Z Lebensm Unters Forsch A 205:282–289
23. Alvarez MD, Canet W (1998) Z Lebensm Unters Forsch A 207:55–65
24. Fellows P (1994) Congelación. In: Fellow P (ed) Tecnología del procesado de los alimentos. Principios y prácticas. Acribia S.A. Zaragoza, pp 391–419
25. Bourne MC (1987) J Food Sci 52:667–668, 690
26. Alvarez MD, Canet W, Tortosa ME (1997) Z Lebensm Unters Forsch A 204:356–364
27. Alvarez MD, Saunders DEJ, Vincent JFV (1999) Eur Food Res Technol (2000) 210:331–339