DATA ANALYSIS OF PENETROMETRIC FORCE/DISPLACEMENT CURVES FOR THE CHARACTERIZATION OF WHOLE APPLE FRUITS

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ABSTRACT

*The objective of the present study was to compare two chemometric approaches for characterizing the rheological properties of fruits from puncture test force/displacement curves. The first approach (*parameter approach*) computed six texture parameters from the curves, which were supposed to be representative of skin hardness, fruit deformation before skin rupture, flesh firmness and mechanical work needed to penetrate the fruit. The second approach (*whole curve approach*) used the whole digitized curve (300 data points) in further data processing. Two experimental studies were compared: first, the variability of the rheological parameters of five apple cultivars; second, the rheological variability that was characterized as a function of storage conditions. For both approaches, factorial discriminant analysis was applied to discriminate the fruits based on the measured rheological properties. The qualitative groups in factorial discriminant analysis were either the apple cultivar or the storage conditions (days and temperatures of storage). The tests were carried out using cross-validation procedures, making it possible to compute the number of fruits correctly identified. Thus the percentage of correct identification was 92% and 87% for using the parameter and the whole curve approaches, respectively. The discrimination of storage duration was less accurate for both approaches giving about 50% correct identifications. Comparison of the percentage of correct classifications based on the whole curve*

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and the parameter approaches showed that the six computed parameters gave a good summary of the information present in the curve. The whole curve approach showed that some additional information, not present in the six parameters, may be appropriate for a complete description of the fruit rheology.

KEYWORDS

Apple, digitized curve, factorial discriminant analysis, penetrometry, puncture test, storage, texture

INTRODUCTION

Firmness is an important parameter of fruit quality. Operators on U.S. and European markets often require thresholds values of firmness making it possible to grade the fruits according to their maturity. For apples, other textural properties like hardness, crunchiness and juiciness play an important role in the appreciation of the product by the consumers (Harker *et al.* 1997). All these properties depend on different characteristics of fruit cells or tissue turgidity, cell size, wall composition and integrity. Sensory analyses are the best method to estimate all these parameters and to take into account simultaneously the effects of all involved cellular components. However, sensory analyses are difficult to apply on large series of samples. For this reason, physical measurements based on rheological properties of tissues have been used for a long time to evaluate texture.

The most common method for assessing apple fruit firmness is the *puncture test*. With this test the maximal penetration force is measured that is required to let a cylindrical probe penetrate in the apple flesh up to a predetermined depth. It is often performed manually (Duprat *et al.* 1995; Johnston *et al.* 2001a; Harker *et al.* 2002; Hoehn *et al.* 2003). Sophisticated devices allow a motorized penetration of the probe into the fruit, at a defined speed and the record of the complete force versus displacement curve. Such tests can be carried out with or without apple skin, leading to the acquisition of different pieces of information. Several authors propose to extract various texture parameters from the force-deformation curves (Duprat *et al.* 2000; Mehinagic *et al.* 2003). Chen *et al.* (1995) and Duprat *et al.* (2000) tried to summarize the texture parameters with a small set of numerical values calculated from the penetrometric curve. In these studies, the authors considered the entire force-displacement curve as an indicator of both flesh and skin properties.

Wu and Abbott (2002) carried out a mathematical analysis of the penetrometric curves for characterizing fruit variability and built a mathematical model representing the relaxation forces as a logarithmic function. In this way, they obtained a high correlation (coefficient of determination, $r^2 = 0.77–0.97$) between firmness and the relaxation force at specific relaxation time. This result predicted skin hardness of fruit from penetrometric measurements.

Mehinagic *et al.* (2003) studied the relationship between fruit texture characterized by sensory analyses and texture parameters extracted from the penetrometric curves. Sensory *crunchiness* could be partly predicted from penetrometric measurements by several parameters called *F*f (flesh firmness), *Grad* (stiffness measured by penetrometry) or *W*f (mechanical work measured during flesh penetration). In another study, Mehinagic *et al.* (2004) showed that the prediction of sensory attributes could be improved by a linear regression that included several of these parameters. These last results showed the possible relationship between sensory perception and the measurement by objective instrumental methods for assessing apple texture characteristics.

The extraction of texture parameters from the penetrometric curves is not a straightforward operation. Most authors have used simple physical models and have considered that their models naturally led to the calculation of a small set of physical parameters. In spite of the significant correlations obtained between some sensorial analyses of texture and parameters extracted from the force/displacement curves, it is difficult to conclude that these parameters are able to fully characterize the texture. Another possible approach, which is the aim of the present study, is to process the whole digitized curve by chemometric methods in order to extract the more relevant information, without *a priori* hypothesis. Two methods of discrimination of the texture of apples from the force/displacement curves were compared. The first one is based on the chemometric analysis of the whole curve and the second relies on the extraction of six parameters (as described by Duprat *et al.* [2000]) from each curve. In order to take into account the complexity and diversity of the texture components, two sources of texture variability were studied: genetic variability among five apple cultivars and storage conditions. In previous work Johnston *et al.* (2001b) showed a linear and negative relation between firmness measurement and temperature of storage.

MATERIALS AND METHODS

Sample Collection

Apple fruits were collected at maturity in experimental orchards in the area of Angers (France). The first set (experiment A) designed to be the representative of the studied genetic variability included 110 fruits belonging to two early harvested apple cultivars: *Elstar* (*El*) and *Gala* (*Ga*) and three late harvested cultivars: *Goldrush* (*Gh*), *Pinova* (*Pi*) and *Topaz* (*Tz*).

The second set (experiment B) was designed for studying the texture variation occurring during storage. A total amount of 180 fruits of two cultivars, *Ga* and *El*, were split into two batches (90 fruits by batch) after a first period of cold storage (2C during 4 months). The first batch was kept at room temperature (20C), whereas the second one was kept in the cooled room. At time 0, 8, 14, 21, 28 days, 10 fruits were taken from each batch for penetrometric measurements.

Penetrometric Measurement

The texture of the unpeeled apples was measured on the equatorial side of the fruit. Four measurements were carried out on each fruit by varying the orientation at intervals by about 90°. A TA-XT2 Texture Analyzer (Stable Microsystems, Surrey, U.K.) fitted with a probe of 4 mm diameter was used. The probe was moved from the surface of the fruit to a depth of 10 mm at a speed of 3.3 mm/s and the force was recorded every 0.01 s. Each force/displacement curve included 300 data points. Six numerical values called texture parameters were computed from the force/displacement curve (Fig. 1). The maximal force (*F*s) represents the force required to puncture the apple skin. *F*s represents the skin strength. The probe displacement (*D*p), expressed in mm, indicates the probe position at *F*s. It allows the calculation of fruit deformation before the skin rupture. Stiffness (*Stif*), defined by [*F*s/*D*p], is the slope of the first part of the curve measured from the beginning of the acquisition until *F*s is reached. Work 1 (*W*1) is the mechanical work needed to reach the rupture point, estimated by the area under the curve up to the skin rupture point. The flesh firmness (*F*f) is the average values of the forces measured after the skin rupture. In a similar way, work 2 (*W*2) is the work measured after the skin rupture. These texture parameters were automatically computed from each curve using a specific software (Texture Exponent 32, Stable Microsystems, U.K.).

Data Analysis

The relative importance of the whole curve (300 data points) and the extracted texture parameters (six values) was compared. In the following, these two approaches are referred as the “whole curve” and the “parameter” approaches.

Factorial discriminant analyses (FDAs) were carried out both on the digitized curves and on the texture parameters. A given digitized force/displacement curve formed a vector $\boldsymbol{x}_i$ of 300 elements. The vectors such as $\boldsymbol{x}_i$ with $i = 1, 2, \ldots, n$ were gathered in a matrix $\boldsymbol{X}$ dimensioned $n \times 300$. Because of the collinear nature of the columns of $\boldsymbol{X}$, it was impossible to

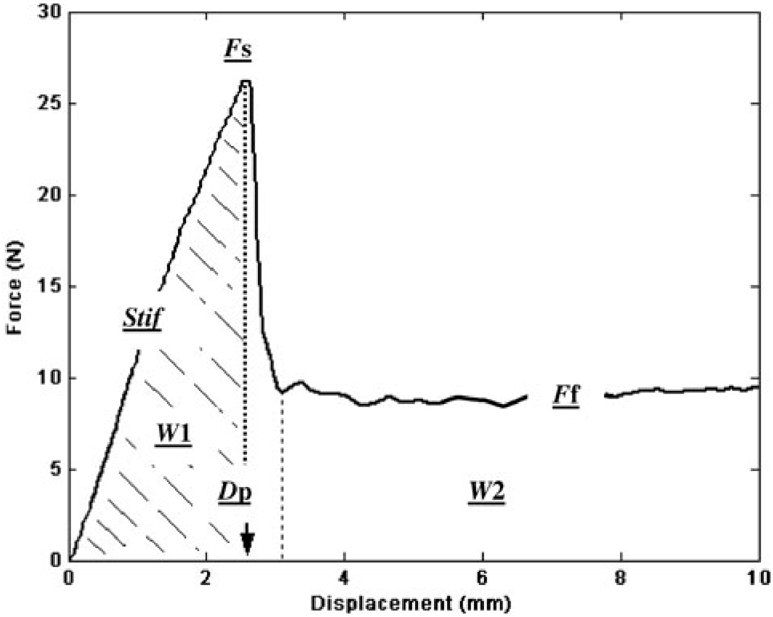

FIG. 1. PENETROMETRIC FORCE/DISPLACEMENT CURVE AND PARAMETERS EXTRACTED
*F*s (skin strength), *Stif* (stiffness), *W*1 (work 1), *D*p (displacement), *F*f (flesh firmness) and *W*2 (work 2).

directly apply FDA. In order to cope with this collinearity, a modified version of FDA, was applied according to Bertrand *et al.* (1990).

In FDA, the qualitative groups to be discriminated were the *cultivars* (experiment A) and the *durations of storage* for each cultivar stored at a given temperature (experiment B). In experiment B, FDA was separately carried out for each of the two tested cultivars. The qualitative groups were the storage durations for each temperature conditions. There were thus for each cultivar 4 storage durations (8, 14, 21, 28 days) $\times$ 2 temperature conditions making 8 qualitative groups. The starting point (day 0) was the same for both temperatures, giving a single group. There were thus 9 qualitative groups to be discriminated.

A criterion of the efficiency of the FDAs was the proportion of correctly identified observations in validation sets. These validation tests were carried out by dividing the data matrices into a training and a validation set. The FDA model was computed on the calibration set. The observations of the validation set were then classified using the established model. The observations correctly identified in the validation set were counted and expressed as a percentage of correctly classified fruits. Such validation tests were independently carried out 10 times, placing two-thirds of the observations in the calibration set and the remaining ones in the validation set. The comparison between the whole curve and the parameter approaches was based on the discrimination accuracy appreciated by the percentage of correct classifications. FDA computes a few set of discriminant scores, which are some linear combinations of the original variables. The discriminant scores are new "synthetic variables" calculated with the goal of discriminating the observations. The correlation between the discriminant scores and the predictive variables is of interest. For this purpose, the correlation coefficients between the discriminant scores and the original variables (six parameters or 300 digitized data points of the whole curve) were computed. For the whole curve approach, it was impossible to show 300 correlation coefficients. For this reason, the correlations were graphically represented as a curve giving the correlation coefficients of the force, at each displacement, with a given discriminant score. Such curves could be drawn for each of the calculated discriminant scores.

All the statistical procedures were carried out using the Matlab environment (The MatWorks, Inc., 3 Apple Hill Drive, Natick, MA 01760-2098 U.S.A.).

RESULTS AND DISCUSSION

Texture Variability Related to the Cultivars

Texture Parameters. The studied data matrix of experiment A included a total of 440 penetrometric measurements (110 fruits $\times$ 4 repetitions).The discriminant ability of the texture parameters was evaluated from the percentage of correct classifications in the validation sets (about 1450 individual observations were eventually placed in the validation set). FDA allowed 83, 84, 100, 94 and 97% of correct identification for *El*, *Ga*, *Gh*, *Pi* and *Tz* cultivars, respectively. We noticed that the confusion generally occurred between early harvested cultivars (*El* and *Ga*) on one side and late harvested ones (*Gh*, *Pi* and *Tz*) on the other side, but not within these two groups.

Factorial maps of FDA performed with the six parameters as variables are shown in Fig. 2. Three groups were visible on the first two discriminant scores: {*Gh*, *Pi*, *Tz*}; *El* alone; *Ga* alone (Fig. 2A). The third component (Fig. 2B) made it possible to separate *Gh*, *Pi*, *Tz*. The correlation coefficients between the discriminant scores and the textures parameters, reported in Table 1, showed that *F*f and *Stif* were the two most important parameters that explained the discrimination between the mentioned groups on the two first discriminant scores. *F*s was the most highly correlated with the third discriminant score.

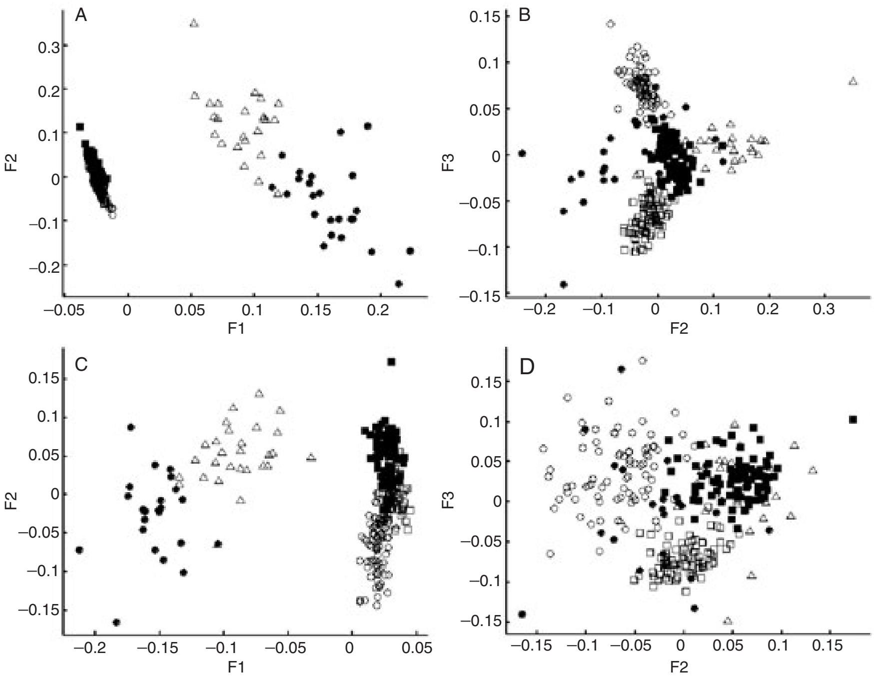

FIG. 2. FACTORIAL DISCRIMINANT ANALYSIS OF CULTIVARS
(A) First and second discriminant scores (parameter approach); (B) second and third discriminant scores (parameter approach); (C) first and second discriminant scores (whole curve approach); (D) second and third discriminant scores (whole curve approach). △, *El*; ●, *Ga*; ○, *Tz*; ■, *Pi*; □, *Gh*.

TABLE 1.
CORRELATION COEFFICIENTS BETWEEN THE DISCRIMINANT SCORES AND THE TEXTURE PARAMETERS. (DISCRIMINATION OF CULTIVARS)

	*F*s	*D*p	*W*1	*Stif*	*F*f	*W*2
F1	0.74	0.80	0.89	0.71	0.99	0.78
F2	–0.28	0.19	–0.16	–0.46	–0.02	–0.28
F3	–0.54	–0.30	–0.24	–0.49	–0.15	–0.49

F1, F2, F3: the ranks of the discrimant scores.

This parameter was able to discriminate cultivars *Gh*, *Pi*, *Tz*. The cultivars thus differed according to their flesh and skin properties. All texture parameters showed higher values for *Ga* than *El* and the three late cultivars (*Gh*, *Pi*, *Tz*). Among the six parameters, *F*f was the most correlated to the first factorial

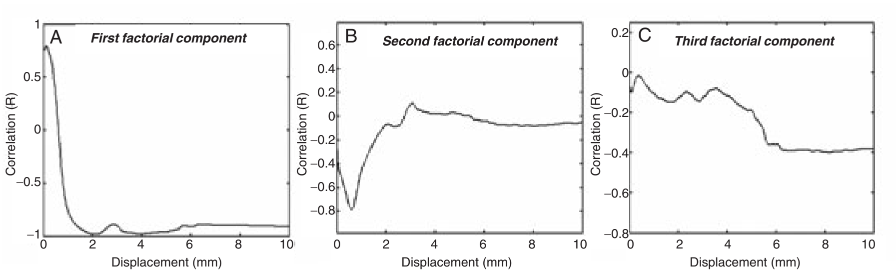

FIG. 3. CORRELATION COEFFICIENTS OF THE DISCRIMINANT SCORES WITH THE FORCE AS THE FUNCTION OF THE DISPLACEMENT OF THE PROBE (DISCRIMINATION OF THE CULTIVARS)

Correlation coefficient with (A) the first discriminant score (B) the second discriminant score (C) the third discriminant score.

score showing that the flesh firmness was the main characteristic that differed between *Ga*, *El* and the group constituted by the three late cultivars. According to FDA, *Gh*, *Pi*, *Tz* did not show any differences in their flesh firmness.

According to the third factorial score, it was possible to separate the three late cultivars. Three texture parameters were correlated with this third factorial score: *F*s ($r = -0.54$), *Stif* ($r = -0.49$) and *W*2 ($r = -0.49$). Thus, *Gh*, *Pi*, *Tz* were separated ones from the others according to their skin hardness (*F*s), Stiffness (*Stif*) and also according to *W*2, which represents the work needed to penetrated the apple flesh.

Digitized Curves. The accuracy of discrimination using the whole curves was slightly lower than the one given by the parameters approach: 68, 83, 94, 95 and 96% of *El*, *Ga*, *Gh*, *Pi* and *Tz* cultivars, were correctly classified here.

The factorial maps of the FDA performed on the digitized curves are shown on Fig. 2C,D. The first factorial component made it possible to separate three groups of cultivars. The second and the third components allowed the discrimination of the three late cultivars. The scores projection on the second plane (the second and the third factorial component) was quite different in comparison with the projection obtained with the parameter approach.

Figure 3 presents the correlation of the discriminant scores with the force as a function of the probe displacement. The first factorial component allowing the discrimination between *Ga*, *El* and the three other cultivars was highly correlated with the force at probe displacement between 2 and 10 mm ($|R| > 0.75$). The region of the force/displacement curve between 4 and 10 mm corresponded to the *F*f parameter, which correctly discriminated the same groups in the parameter approach. However, the region between 2 and 4 mm did not correspond to the same rheological information, but to a complex region where the apple skin rupture generally occurred. The whole curve approach had thus emphasized the interest of this region of the curve, which had seldom been studied in previous works. The second and the third discriminant scores, which separated three cultivars (*Tz*, *Pi* and *Gh*), showed high values of *R* around 1 mm ($|R| > 0.8$) and between 6 and 10 mm ($|R| > 0.4$). The first region of the curve (around 1 mm) probably gives the same information as the one associated with the *Stif* parameter, which is measured on the same part of the curve.

Texture Variability Related to the Storage Conditions

The texture changes occurring during storage in cold room (CR) and in shelf life (SL) were analyzed separately for *El* and *Ga* cultivars. The studied data matrix included a total of 720 penetrometric measurements (180 fruits × 4 repetitions).

Texture Parameters. The storage durations at two temperatures were considered as qualitative groups to be tentatively discriminated using FDA (Table 3). The percentage of correctly classified observations was lower for fruits stored in CR than in SL conditions for both cultivars. On average, 27% of *Ga* and *El* cultivars stored in CR were correctly classified, whereas 54 and 43% of the same cultivars were correctly identified in SL. These results are in accordance with the current knowledge of the effect of temperature on the rheological properties of fruits. It is well known that the effect of low storage temperature is to reduce the texture change in fruits.

Figure 4A,B show the factorial maps according to the first two discriminant scores of FDA for *El* and *Ga*. The fruits stored in CR did not show large variations according to the storage durations. The effect of time is clearly associated with the first discriminant score: on this axis, the fruits in SL conditions are correctly ranked according to the days of storage, including the starting point (0 day). In CR, only *El* showed some weak changes, related to the storage duration, according to the second discriminant score. The second scores had an important role in the discrimination of the three last storage durations (14, 21 and 28 days of storage) for fruits stored in SL.

According to the first factorial scores, the most important parameter involved in the discrimination of the duration effect was *Stif*. The *R*-values between the first discriminant scores and *Stif* was equal to –0.99 and –0.97, for the FDA applied on *Ga* and *El*, respectively (Table 2). *Ff* and *W*2 also showed a strong correlation with the first discriminant score, particularly for *El* cultivar. The second factorial scores were mainly correlated with *D*p with $R = 0.66$ and 0.45 for *Ga* and *El*, respectively (Table 2).

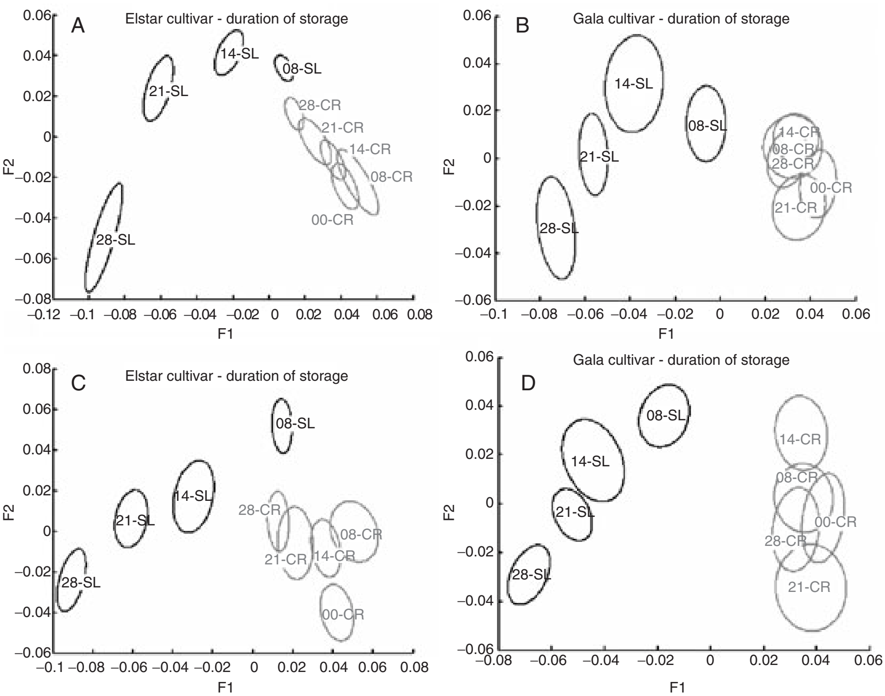

FIG. 4. FACTORIAL DISCRIMINANT ANALYSIS OF STORAGE CONDITIONS
(A) and (B), parameter approach; (C) and (D), whole curve approach. The ellipses present the confidence intervals of the barycenter at a probability threshold of 0.05. The number in each ellipse represents the duration of storage (days). CR, cooled room; SL, shelf life.

TABLE 2.
CORRELATION COEFFICIENTS BETWEEN THE DISCRIMINANT SCORES AND THE TEXTURE PARAMETERS. (CONDITIONS OF STORAGE)

	*F*s	*D*p	*W*1	*Stif*	*F*f	*W*2
Gala cultivar						
F1	–0.79	–0.04	–0.51	–0.99	–0.71	–0.78
F2	0.31	0.66	0.42	–0.11	0.13	0.14
Elstar cultivar						
F1	–0.40	0.62	0.17	–0.97	–0.87	–0.94
F2	0.14	0.45	0.26	–0.12	0.14	–0.04

F1, F2: the ranks of the discrimant scores.

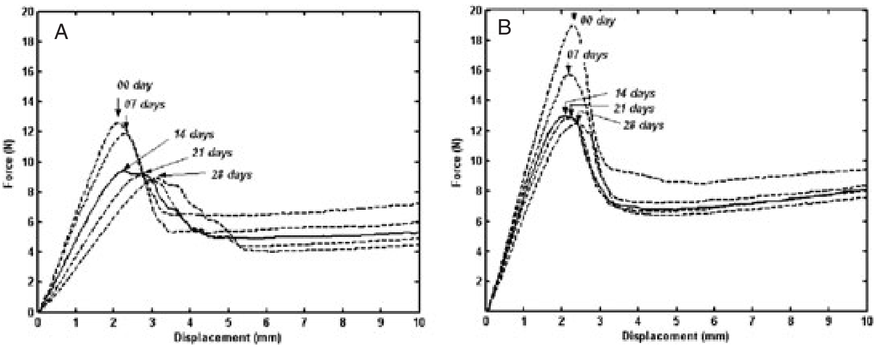

FIG. 5. FORCE/DISPLACEMENT CURVES AVERAGED ACCORDING TO STORAGE CONDITIONS

Fruits from cultivars *El* (A) and *Ga* (B) stored at 20C for varying duration of storage.

The behavior of the two cultivars during storage were slightly different. The variations of *F*s and *D*p did not show the same pattern according to the storage duration for *Ga* and *El*. *F*s of *Ga* steadily decreased all over the storage whereas such a diminution was observed only until the 14th day of storage for *El*. The fruit deformation measured before apple skin rupture showed no marked variations for *Ga* whereas this parameter increased between the 14th and 28th days for *El*. The force/displacement curves averaged according to cultivars and storage durations show the differences between these two behaviors (Fig. 5A,B). It is clear that the *D*p was markedly dependent on storage time for *El*, but not for *Ga*. As previously studied by Grotte *et al.* (2001), apple skin could play an important role in the overall decrease of apple firmness stored in SL. In this work we showed that apple hardness, measured with skin, could have an cultivar-dependent evolution for fruits in SL.

Digitized Curves. Figure 4C,D show the factorial maps according to the first two discriminant scores of FDA for *El* and *Ga*. The fruits stored in CR did not show large variations according to the storage durations whereas time effect is clearly associated with the first discriminant score. Table 3 presents the results of the cross-validation tests of discrimination. The percentages of correctly classified fruits were lower in CR than in SL conditions for both cultivars. On average, 38 and 40% of the *Ga* and the *El* stored in CR were correctly classified according to the days of storage. The same figures were 53 and 57% for the SL conditions. The discrimination accuracy using digitized curves was thus, slightly better than the accuracy obtained using the parameter approach. Figure 6 represents the curve of the correlation coefficients of the

TABLE 3.
PERCENTAGE OF FRUITS CORRECTLY DISCRIMINATED ACCORDING TO THE STORAGE CONDITIONS. (RESULT OF CROSS-VALIDATION TESTS)

	Elstar		Gala	
	Cooled room (%)	Shelf life (%)	Cooled room (%)	Shelf life (%)
Parameter approach				
0 day	33	33	43	43
8 days	53	48	30	43
14 days	8	48	13	38
21 days	18	60	33	30
28 days	23	60	18	60
Mean value	27	54	27	43
Whole curve approach				
0 day	43	43	48	48
8 days	45	60	28	63
14 days	30	54	45	45
21 days	33	53	38	53
28 days	38	45	43	65
Mean value	38	53	40	57

discriminant scores with the force measured at each probe displacement. The first scores were highly correlated with the forces measured at the beginning of the probe displacement (before 2 mm) and at the end of the curve (after 4 mm for *Ga* and 5 mm for *El*). In a more central region of the curve, the correlation coefficients decreased for both cultivars. This means that the discriminations of the storage conditions were mainly based on those regions of the penetrometric curves where the rupture of the skin did not occur. The elasticity of the whole fruit and the rheological characteristics of the flesh therefore played an important role in the discrimination. The discriminant scores computed in FDA are linear combination of the variables. They are not really adapted for identifying parameters such as *F*s; which are local maxima and not directly detectable using linear methods.

The correlation coefficients associated with the second discriminant scores obtained with *Ga* and *El* were comparable. A correct correlation between the second factorial scores and the force was visible in the region curve around 3 and 4 mm for *Ga* and *El*, respectively (Fig. 6B,D). This region curve corresponded to the apple skin rupture. This result is in agreement with those obtained with the parameter approach, which showed a high correlation of flesh and skin parameters such as *Stif*, *F*f, *W*2 and *F*s with the first discriminant scores and *D*p with the second scores (cf. "Texture Parameters" section).

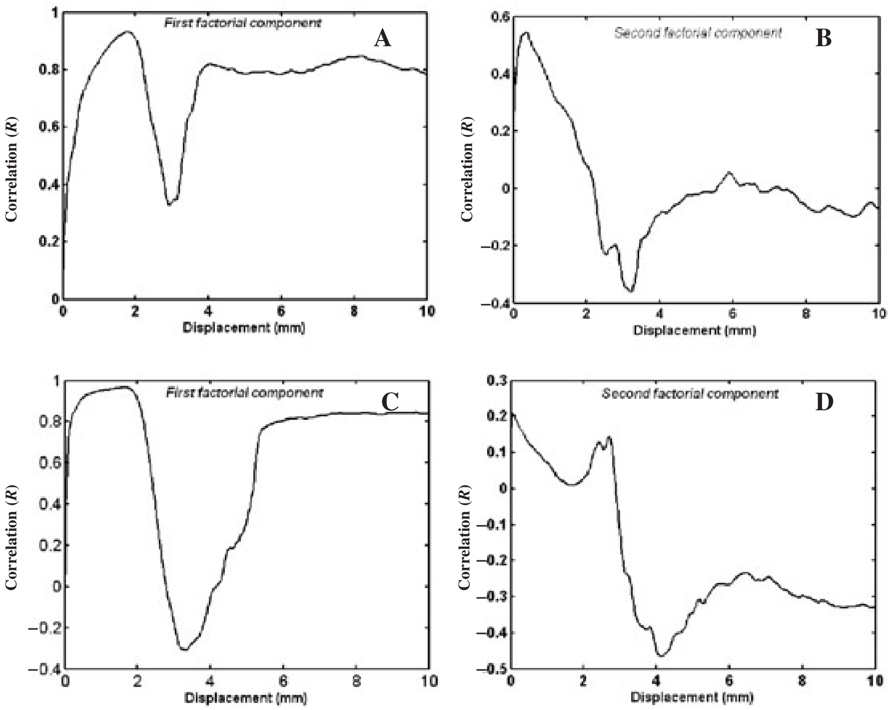

FIG. 6. CORRELATION COEFFICIENTS OF THE DISCRIMINANT SCORES WITH THE FORCE AS THE FUNCTION OF THE DISPLACEMENT OF THE PROBE (DISCRIMINATION OF THE STORAGE CONDITIONS)

(A) and (B): Correlations with the first and the second discriminant scores for *Ga*. (C) and (D): Correlations with the first and the second discriminant scores for *El*.

CONCLUSION

The use of factorial methods such as FDA appears to be appropriate for characterizing the rheological variability of fruits according to the nature of the cultivars and to the storage conditions. The two developed approaches (whole curve or parameter approaches) are complementary. The computation of FDA on the whole penetrometric curves led to slightly more accurate results than the ones obtained from the parameter approach. The whole curve approach also allows the identification of regions of the penetrometric curves, which were related to a given characteristic of the fruit (elasticity of the skin, properties of the flesh, . . .). The analysis of the whole curve also shows that some regions of the penetrometric curve were not taken into account when using only six calculated parameters: the region of the curve just after the skin rupture and before reaching the plateau was not summarized by one of the extracted parameters. It could therefore be relevant to have a specific descriptor for this region. The parameter approach was slightly less accurate than the whole curve approach, but the rheological properties of fruits were summarized by six numbers against 300 in the case of the whole curve approach. It can be, therefore, concluded that the extracted parameters correctly summarized the main information of the force/displacement curve. Moreover, the six extracted parameters appear to have rather clear meanings in terms of physics and rheology.

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