MEASUREMENT OF FIRMNESS OF FRESH-CUT SLICED TOMATO USING PUNCTURE TESTS – STUDIES ON SAMPLE SIZE, PROBE SIZE AND DIRECTION OF PUNCTURE

MILZA M. LANA[1,2,6], LEOPOLD M.M. TIJSKENS[2,3], ANEMARIE DE THEIJE[2], MATTHIJS DEKKER[4] and DIANNE M. BARRETT[4,5]

[1]*Embrapa Hortaliças*
Caixa Postal 218, 70359970, Brasília-DF, Brazil

[2]*Horticultural Production Chains Group*
Wageningen University
Marijkeweg 22, 6709 PG, Wageningen, the Netherlands

[3]*Agrotechnology and Food Science Group*
PO Box 17, Wageningen, the Netherlands

[4]*Product Design and Quality Management Group*
PO Box 8129, Wageningen, the Netherlands

[5]*Department of Food Science & Technology*
University of California
1 Shields Avenue, Davis, CA 95616

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ABSTRACT

In order to investigate the firmness of tomato slices, two experiments were performed. In the first one, Monte Carlo simulation was used to study the variation in firmness within and between slices. Adding more slices and more measurements per slice reduced the SD, but in general, the efficiency of adding more slices was higher. In the second experiment, the firmness of tomato slices was measured by puncture test during storage, using one of three flat-tipped cylindrical probes (3.5-, 2.5- and 1.5-mm diameter) in two directions, along or perpendicular to the main axis of the fruit. Changes in firmness were studied by nonlinear regression analysis. The same model could be applied to all combinations of probe size and direction with the same correction for shear and compression. It suggests that shear and compression forces decay with storage time according to the same mechanism, irrespective of the measurement direction.

[6] Corresponding author. TEL.: +55-61-3385-9084; FAX: +55-61-3356-5744; EMAIL: milza@cnph.embrapa.br

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PRACTICAL APPLICATIONS

Methodologies for both firmness evaluation and data analysis were presented. Monte Carlo simulation was used to optimize the number of samples for firmness assays. After calculating the experimental SD from preliminary experimental results, simulations were performed with different numbers of replicates and measurements per replicate, to find an optimal experimental design where the SD is minimized. Using nonlinear regression, the effects on firmness of probe size, puncture direction in relation to the plant tissue and storage time can be analyzed simultaneously. The incorporation of a correction factor to account for differences in firmness due to probe size was proposed. The relative influence of shear (s) and compression force (c) on the observed force is estimated. Results of interest for the industry were presented, confirming previous findings that the firmness of ripened tomato slices measured by puncture analysis does not change significantly during short-term storage at low temperature.

KEYWORDS

Firmness measurement, fresh-cut tomato, modeling, Monte Carlo simulation, probe size, puncture, puncture direction, sampling, variation

INTRODUCTION

Firmness is a critical aspect of tomato quality. Appropriate measurement is necessary for quality control, as well as for postharvest research studies to develop procedures for preparation and handling of fresh-cut tomato slices (Wu and Abbott 2002). Previous results obtained by Lana *et al.* (2005) indicated that the firmness of fresh-cut red tomato slices did not change significantly during storage at low temperatures after processing. At temperatures lower than 8C, which is the maximum temperature recommended for fresh-cut fruit storage (Wiley 1994), the firmness of fresh-cut tomato slices at three different maturity stages did not change with storage time. This is not in agreement with the existing literature, where softening is considered an important cause of quality loss of fresh-cut fruit products (Varoquaux *et al.* 1990; Huber *et al.* 2001; Karakurt and Huber 2003). Additionally, fresh-cut tomatoes become translucent or water soaked during storage (Lana *et al.* 2005), which is expected to affect also the texture (Jackman *et al.* 1992; Soliva-Fortuny *et al.* 2002)). Hong and Gross (2000) reported that water-soaked tomato slices were 50% softer than slices that were not water soaked.

The most commonly used methods for the assessment of textural properties are those which apply large deforming forces (e.g., via puncture or compression), and are therefore destructive (Abbott 2004). Because of the empirical nature of these tests, however, they do not provide an understanding of food microstructure or force–deformation and failure mechanisms at the cellular level. The puncture and compression tests are both force-measuring methods, which measured values have the dimensions of mass, distance and time. They rely on measuring the force and/or deformation required to push or punch a probe into a food to a depth that causes irreversible damage or failure. Flat plate compression is a technique very similar to that of puncture, except that the perimeter effect is eliminated through the use of flat plates with an area exceeding that of the sample (Jackman *et al.* 1990).

For measuring the firmness of chilled injured fruits, Jackman *et al.* (1990) evaluated both methods and recommended the use of puncture tests for tomatoes rather than flat plate compression. Fresh-cut tomatoes are kept at chill injury-inducing temperatures, and therefore, a puncture test would seem most suitable for firmness measurements. Accordingly, there is a possibility that changes in some of the textural attributes of fresh-cut tomatoes stored at low temperatures and presenting water-soaked pericarp were not measured by the tests used in previous reports (Wu and Abbott 2002; Lana *et al.* 2005). In both cases, the tests were performed in the axial direction.

Barrett *et al.* (1998) carried out puncture tests on both tissue disks obtained from the equatorial region of tomato pericarp and single 6.35-mm-thick slices taken from the tomato fruit at the equator. Pericarp tissue disks were obtained using a 20-mm cork borer and were evaluated skin side down using a 5-mm probe. For slice evaluation, a 2.5-mm-diameter flat-tipped cylindrical probe and a 50-kg load cell were used for the measurement of outer pericarp, radial arm and columella tissues at the cut surface. These authors found that the puncture tests carried out on pericarp disks correlated well with flat plate compression tests on the whole fruit. The textural properties of fresh-cut tomato slices, as measured on the cut surface, varied substantially, but in general, the pericarp tissue was firmest, followed by the radial arms and columella tissue. This variability was largely related to difficulty in discriminating maturity differences in red tomatoes (Barrett *et al.* 1998).

In the present experiment, flat-tipped cylindrical puncture probes of different diameters applied to sliced fresh-cut tomatoes in two different directions were compared in order to determine which is more sensitive to measuring changes in the firmness of sliced fresh-cut tomatoes during storage. The hypothesis is that the use of smaller probes and the radial rather than axial direction will be a more sensitive test to measure changes in texture during refrigerated storage.

As mentioned earlier, the firmness of fresh fruits and vegetables typically exhibits a large variation between individual pieces, and even within the different tissues in the same individual piece (Lesage and Destain 1996). Sliced fresh-cut tomatoes show even more variation in firmness than intact fruits (Wu and Abbott 2002). In this article, a methodology for texture analysis based on Monte Carlo simulation is described in order to optimize the number of sliced tomato samples and the number of measurements per sample to be used in firmness measurements.

MATERIALS AND METHODS

Experiment 1 – Firmness Measurement Optimization for the Number of Fresh-cut Tomato Slices and Measurements per Slice

Harvesting and Processing. Tomato fruits (cultivar *Belissimo*) grown in commercial greenhouse conditions in Made, the Netherlands, were harvested at red maturity, between stages eight to nine following the tomato color chart from The Greenery (Barendrecht, the Netherlands) on March 2004, and were transported to Wageningen, the Netherlands. The tomato fruits were washed with drinkable water, sanitized in sodium hypochlorite solution (1 mg/l – pH 6.8) for 90 s and rinsed with drinkable water as described in (Lana *et al.* 2005).

The same day as harvest, the tomatoes were sliced in 7-mm-thick transversal slices, starting from the stem end. The first and the second slices were thrown away. The third slice was used to measure firmness. The fruits were sliced immediately before the firmness measurement in order to avoid any variation due to the time of storage after processing.

Firmness Evaluation. Firmness was measured using one of three flat-tipped cylindrical probes (3.5-, 2.5- and 1.5-mm diameter) in two directions: (1) axial – along the main axis of the fruit, and (2) radial – perpendicular to the main axis of the fruit as illustrated in Figs. 1 to 2, using a Zwick Universal Type Machine (Zwick, Ulm, Germany). For each combination of probe × direction, 10 slices (one central slice from each of 10 tomatoes) were used, and six measurements were carried out per slice. All the measurements were performed in the outer pericarp, avoiding the areas where the outer pericarp joins the radial arms. The axial measurements were carried out with the skin down, in contact with the surface of the plate. In all the measurements, the force necessary to cause a deformation of 3 mm was determined. Data were expressed as maximum force (F_{max}) to deform 3 mm, and deformation at break force (L_{max}).

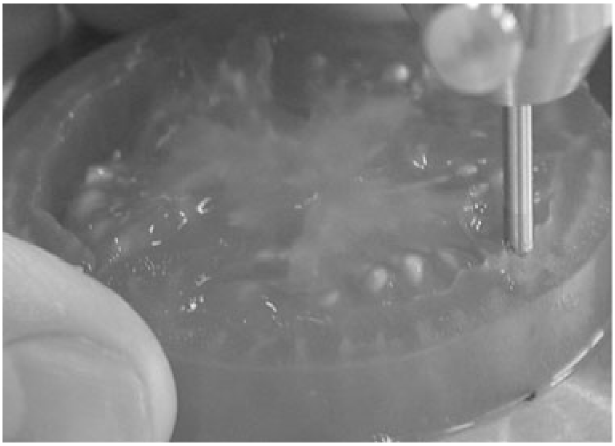

FIG. 1. MEASUREMENT OF FIRMNESS IN A TOMATO SLICE IN THE AXIAL DIRECTION, SHOWING THE DIRECTION OF PUNCTURE AND THE TISSUE PUNCTURED

Data Analysis. The variation within and between slices was used as input for Monte Carlo simulation to study the effect of sample type and number on the expected variability in the experimental results before performing experiment 2 that follows. After calculating the experimental SD from preliminary experimental results, assuming normal-distributed data, within a slice and between slices from different tomatoes, simulations were performed with different numbers of samples per slice and numbers of tomatoes, to find an optimal experimental design. For the different sample sizes (number of measurements carried out per slice and/or number of tomatoes used), the SDs were calculated for each simulated experiment and by doing this 1,000 times, the distribution in SDs could be estimated. By this analysis, the expected SD in the sample from a certain experimental design can be compared with the real SD that is present in the whole population.

Experiment 2 – Changes during Storage of Fresh-cut Sliced Tomatoes Evaluated Using Optimized Firmness Measurement

Harvesting, Processing and Storage. Tomato fruits (cultivar *Belissimo*) grown in commercial greenhouse conditions in Made, the Netherlands, were harvested at light red maturity, between stages 7 and 8, following the tomato color chart from The Greenery (Barendrecht, the Netherlands) on March 2004, and were transported to Wageningen, the Netherlands. The tomato fruits were washed, sanitized and sliced as described for experiment 1. The first and the

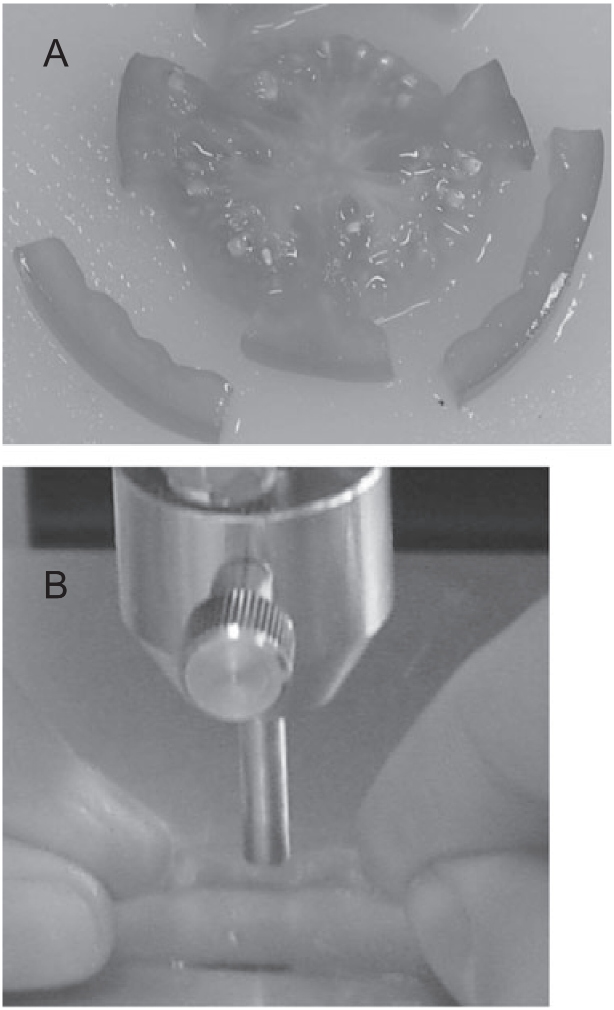

FIG. 2. PREPARATION OF THE SAMPLE (A) AND MEASUREMENT OF FIRMNESS (B) IN A TOMATO SLICE IN THE RADIAL DIRECTION, SHOWING THE DIRECTION OF PUNCTURE AND THE TISSUE PUNCTURED

second slices were thrown away. The next three slices were placed in a covered plastic Petri dish (diameter, 90 mm; height, 25 mm) and stored at 5 $\pm$ 0.6C until firmness measurement.

Firmness Evaluation. Firmness measurements were performed using three different flat-tipped puncture probes applied in two different directions, as described in experiment 1 on slices stored for 0, 2, 4, 6, 8, 10, 13 and 15 days. The firmness measurement was performed immediately after removing the slice from the storage chamber without equilibration to room temperature. On day zero, the slices were stored for 2 h at 5C to attain the same temperature the other slices would be at after the various storage times. The time required to cool the slices down to the storage temperature was monitored using an eight-channel thermocouple linked to a personal computer. For each combination of probe × direction, eight slices (one central slice from each of eight different tomatoes) were used, and three measurements were carried out per slice.

Statistical Analysis. Data were first analyzed by analysis of variance (ANOVA) using PROC GLM from Statistical Analysis System (SAS, Cary, NC), considering the probe size, direction and storage time as sources of variance. Later, a nonlinear regression analysis (GenStat, VSN International Ltd, Hemel Hempstead, U.K.) was conducted in order to study the changes with time, as described in the next section.

Model Development. The firmness was considered to consist of a variable part that changes according to a first-order mechanism, and a fixed part that is invariable for the circumstances under study. This resulted in the basic first-order model, as described in detail in Lana *et al.* (2005):

$$F = \left(F_0 - F_{fix}\right) \cdot e^{-k \cdot t} + F_{fix} \tag{1}$$

where

F = firmness at time t after harvest (in Newton);
F_0 = initial firmness at harvest (in Newton);
F_{fix} = invariable part of firmness (in Newton);
k = reaction rate constant at temperature t;
t = time (in days), counting from the moment of harvest.

Both parts depend for their magnitude on the surface area and perimeter of the puncture probes. To accommodate for the differences in this magnitude in firmness between the probes, the previous expression was multiplied by a correction factor, *cor*,

$$F = \left(\left(F_0 - F_{fix}\right) \cdot e^{-k \cdot t} + F_{fix}\right) \cdot cor \tag{2}$$

where the correction factor was calculated as follows:

$$\mathrm{cor} = (1 - f_{\mathrm{cs}}) \cdot \frac{\mathrm{area}}{\mathrm{area}_{ref}} + f_{\mathrm{cs}} \cdot \frac{\mathrm{perimeter}}{\mathrm{perimeter}_{ref}} \tag{3}$$

where area and perimeter were calculated from the probe diameter, and the subscript *ref* referred to a chosen reference diameter $Ø_{\mathrm{ref}}$, here 2.5 mm. The use of this reference system ensures that the different dimensions of area and perimeter are properly taken into account, while assuring at the same time a dimensionless correction factor.

The factor f_{cs} is a factor to be estimated. It represents the relative influence of shear force (f_{cs}) and compression force ($1 - f_{\mathrm{cs}}$) on the observed force. It describes the importance of shear force in the measured force data (for this product).

Data Analysis. Based on Eqs. (2) and (3), a nonlinear regression was performed (GenStat). The data (averaged per slice as well as individual) were analyzed in their entirety using time and probe dimension as explanatory variables (multivariate nonlinear regression analysis). The kinetic parameter k, the f_{cs} factor, the initial firmness (F_0) and the fixed firmness F_{fix} were estimated in common for all the data measured in both axial and radial directions.

RESULTS AND DISCUSSION

Experiment 1 – Firmness Measurement Optimization for the Number of Fresh-cut Tomato Slices and Measurements per Slice

Table 1 illustrates the results obtained when 10 fresh-cut tomato slices were measured with three different puncture probes, using two different directions of force application and six measurements per slice.

Using Monte Carlo simulation (data for the radial direction), the SD was calculated for each of the 1,000 simulated experiments, and then the distribution in SD was calculated for the total of 1,000 experiments. Figure 3 presents this distribution of SD for the 1.5-mm probe by showing the range in which 90% of the calculated SDs fall as a function of sample size. In 5% of the simulated experiments, a smaller SD distribution was present in the observed data and in 5% a larger one. In fact, this means that there is a 5% probability of finding an outlier outside the SD distribution that is larger than the ranges given in Fig. 3. The objective was to have a small SD with a reasonable amount of measurements.

The distribution in SDs for the 1.5-mm probe (Fig. 3) indicates that increasing the number of fresh-cut tomato slices is more efficient than increasing the number of measurements per slice. For example, the same SD

TABLE 1.
FIRMNESS OF FRESH-CUT SLICED TOMATOES EXPRESSED AS MAXIMUM FORCE TO DEFORM THE TISSUE 3 mm. VALUES CORRESPOND TO THE MEAN OF 60 MEASUREMENTS (10 SLICES AND SIX MEASUREMENTS PER SLICE)

Direction of force application	Probe diameter (mm)	Maximum force (N)	SD within slices	SD between slices
Radial	1.5	1.30	0.21	0.27
Radial	2.5	2.25	0.32	0.26
Radial	3.5	4.15	0.76	0.72
Axial	1.5	1.08	0.26	0.19
Axial	2.5	2.25	0.38	0.32
Axial	3.5	3.87	0.86	0.76

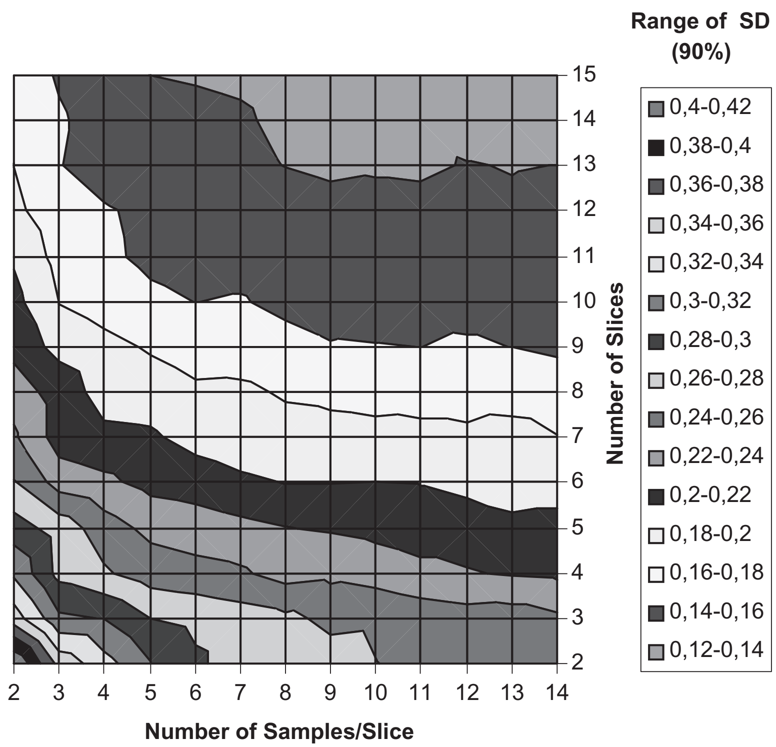

FIG. 3. DISTRIBUTIONS OF SD AS FUNCTION OF SAMPLE SIZES BY MONTE CARLO SIMULATION FOR 1.5-mm PROBE IN THE RADIAL DIRECTION

distribution range is obtained whether nine slices with three measurements per slice (27 measurements in total) or six slices with 12 measurements per slice (72 measurements in total) are used. For the other probes, similar graphs were obtained (data not shown). For the 2.5-mm probe, the contour lines were more symmetrical around the diagonal, and the distributions in SDs relative to the mean (2.25 N) were somewhat smaller. This more symmetrical behavior was also seen for the 3.5-mm probe; the distributions in SDs for this probe relative to the mean value (4.15 N) were in between the 1.5- and 2.5-mm probe.

The ultimate objective of this experiment was to determine how many fresh-cut tomato slices to use (e.g., how many individual tomatoes) and how many measurements to take in each slice. From the obtained results, it can be concluded that adding more slices and more measurements per slice reduces the distribution in SDs, but in general, the efficiency of adding more tomatoes is higher. Similar results were reported by Lesage and Destain (1996), where the variability between the tomatoes was somewhat higher than the variability within a fruit. In addition, the effect of adding more measurements per slice levels off when more measurements or tomatoes are added. Using the 2.5-mm probe as an example (Figs. 4A,B), it can be argued that using 8–10 tomatoes and three to six measurements per slice removes most of the possibility of getting outliers, other than the SD of the entire population of one treatment of around 0.4 for the 2.5-mm probe. In 90% of the cases, the observed SD will be in between 0.27 and 0.53 for eight tomatoes and three measurements per slice using the 2.5-mm probe.

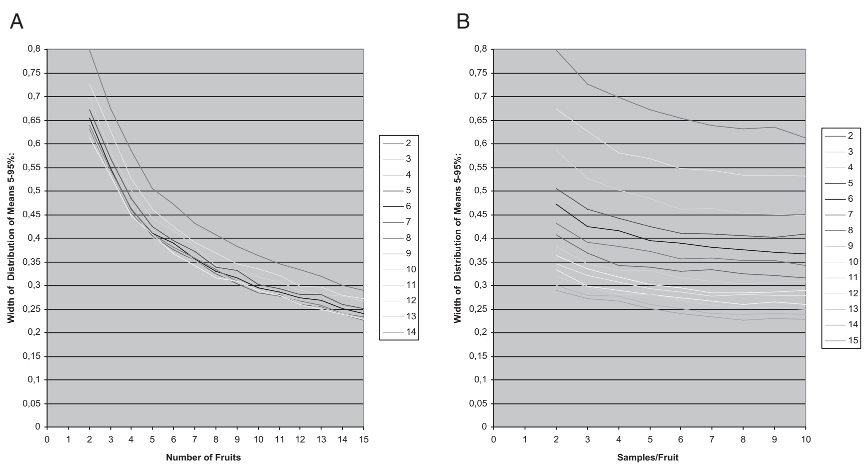

FIG. 4. SD DISTRIBUTION FOR NUMBER OF MEASUREMENTS PER TOMATO SLICE (A) AND NUMBER OF SLICES (B) USING THE 2.5-mm PROBE IN THE RADIAL DIRECTION

TABLE 2.
NUMBER OF TOMATOES AND MEASUREMENTS PER FRESH-CUT TOMATO SLICE

# Tomatoes	6	7	8	9	10	11
# Measurements per slice	8	5	3	3	2	2

When accepting a 5% probability of having outliers in the experimental results with an SD that is 30% larger than the SD present in the entire population, it is possible to use one of the combinations of tomatoes and measurements per slice shown in Table 2.

From these results, it was chosen to carry out the fresh-cut sliced tomato storage experiments with eight tomatoes and three measurements per slice. The number of measurements per slice is limited by the size of the fruit and the puncture method used, which avoids measurements in the area where the outer pericarp and the radial arms meet.

Experiment 2 – Changes in Storage of Fresh-cut Sliced Tomatoes Evaluated Using Optimized Firmness Measurement

ANOVA. The firmness of fresh-cut sliced tomatoes during storage at 5C for up to 15 days is expressed as maximum force and deformation at break in Figs. 5 and 6, respectively. The measured firmness, expressed as maximum force to deform 3 mm, was dependent on the probe used ($\Pr > F = 0.0001$), direction of force applied ($\Pr > F = 0.0001$) and storage time ($\Pr > F = 0.0001$). Although the three main effects were significant at the 0.001 level, the R^2 was 67% for probe size and less than 1% for direction and time, indicating that the effect of probe size was by far the most important factor. Although all the interactions were statistically significant at the <0.0001 level, together they explained less than 1% of the variation in firmness and, for that reason, were not further explored.

In relation to the pattern of firmness change with storage time, the effect of direction of puncture force applied was more striking. When the force was applied in the radial direction, a drop in firmness was observed during the first 2 days of fresh-cut sliced tomato storage. In the axial direction, this decrease was only observed in the 3.5-mm probe, but at a smaller magnitude. This difference, with respect to the direction of force applied, was observed mainly in the first 2 days after processing. After the first 2 days of storage, the pattern of change in firmness with storage time was about the same for both axial and radial directions within each probe size.

Firmness was also expressed as deformation at breaking force (Fig. 6). In this case, firmness was affected by the probe size used ($\Pr > F = 0.0001$),

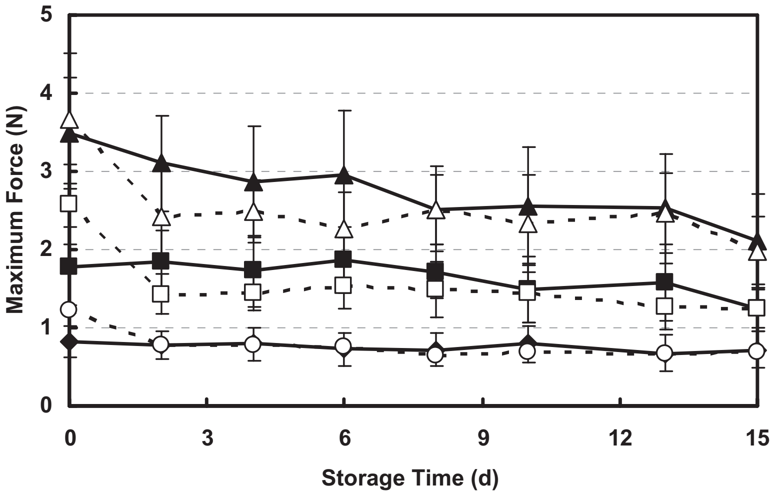

FIG. 5. FIRMNESS OF FRESH-CUT SLICED TOMATOES STORED AT 5C, EXPRESSED AS MAXIMUM FORCE TO CAUSE A DEFORMATION OF 3 mm (N), MEASURED USING A STAINLESS STEEL FLAT-TIPPED PROBE OF 1.5- (○●), 2.5- (■□) OR 3.5-mm (△▲) DIAMETER, WITH FORCE APPLIED IN AXIAL (BLACK SYMBOLS, SOLID LINE) AND IN RADIAL (WHITE SYMBOLS, DOTTED LINE) DIRECTIONS
Mean ± SE, $N = 24$.

direction of force applied ($\Pr > F = 0.0001$) and storage time ($\Pr > F = 0.0001$). Again, the probe size explained most of the variation in the data set (R^2=36%), while the direction of force explained 11%. The effect of probe size was dependent on the direction (probe × direction, $\Pr > F = 0.0001$) and storage time (probe × time, $\Pr > F = 0.0001$), but as observed for F_{max}, the variation accounted for by these interactions was very low and was not further investigated.

Modeling. Nonlinear regression analysis using Eqs. (2) and (3) was conducted for all probe sizes and the two directions of force applied simultaneously on firmness values (F_{max}), as described in the Modeling section of the Materials and Methods. The correction factor cannot be applied in advance because the factor f_{cs} has to be estimated. The estimated values of the parameters are shown in Table 3.

The proposed ratio factor for compression and shear (F_{cs}) seems to be valid for all probe sizes and measurement directions because it accounts for the major part of the variance present in the data (R^2_{adj} 94% for the mean data). This means that the same model may be applied to all combinations with the same correction for shear and compression (Fig. 7). The fact that the same

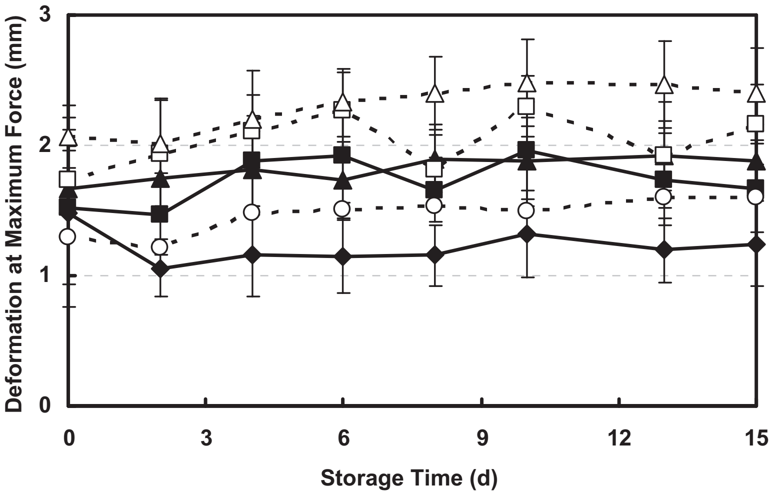

FIG. 6. FIRMNESS OF FRESH-CUT SLICED TOMATOES STORED AT 5C, EXPRESSED AS THE DEFORMATION AT BREAKING FORCE (mm), MEASURED USING A STAINLESS STEEL FLAT-TIPPED PROBE OF 1.5- (○●), 2.5- (■□) OR 3.5-mm (△▲) DIAMETER, WITH FORCE APPLIED IN AXIAL (BLACK SYMBOLS, SOLID LINE) AND IN RADIAL (WHITE SYMBOLS, DOTTED LINE) DIRECTIONS
Mean ± SE, $N = 24$.

TABLE 3.
RESULTS OF THE STATISTICAL NONLINEAR REGRESSION BASED ON EQ. (2) FOR FIRMNESS OF FRESH-CUT SLICED TOMATOES

Parameter	Individual values		Mean values	
	Estimate	SE	Estimate	SE
F_0	2.8152	0.0446	2.1178	0.0773
F_{fix}	1.891	0.0287	1.4176	0.0509
k	0.3572	0.0474	0.3449	0.0968
f_{cs}	0.8016	0.0306	0.5299	0.0705
$Ø_{ref}$	2.5		2.5	
N_{obs}	1,152		48	
R^2_{adj}	74.6		94.1	

F_0 = initial firmness at harvest (in Newton); F_{fix} = invariable part of firmness (in Newton); k = reaction rate constant at temperature t; f_{cs} = relative influence of shear force (f_{cs}) and compression force ($1 - f_{cs}$) on the observed force; $Ø_{ref}$ = diameter of reference; N_{obs} = number of observations; R^2_{adj} = coefficient of determination.

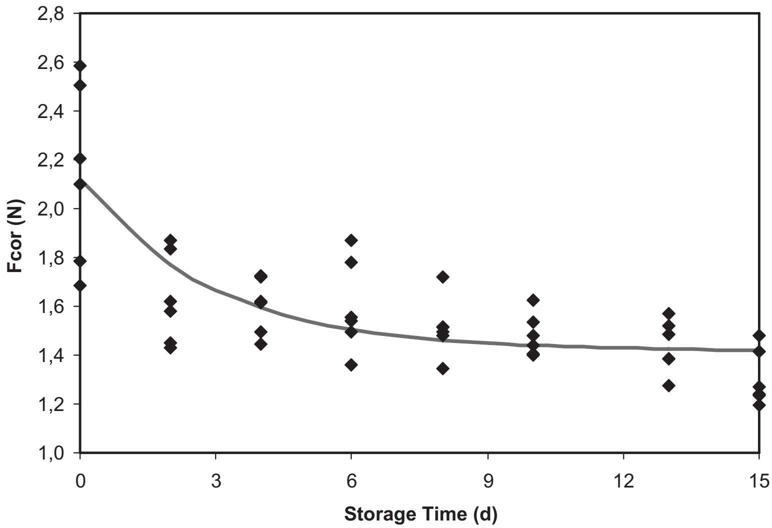

FIG. 7. FIRMNESS OF FRESH-CUT SLICED TOMATOES AT 5C, EXPRESSED AS MAXIMUM FORCE TO CAUSE A DEFORMATION OF 3 mm (N), MEASURED USING A STAINLESS STEEL FLAT-TIPPED PROBE OF 1.5-, 2.5- OR 3.5-mm DIAMETER, WITH FORCE APPLIED IN AXIAL AND IN RADIAL DIRECTIONS

Points are measured data (means of eight replicates), and the solid line shows the simulated values according to Eqs. (2) and (3).

correction factor holds true for all combinations of probe size and measurement direction indicates in the first place that the correction factor for shear and compression seems to be valid, and that the same underlying textural properties are being measured by each set of conditions. This also suggests that shear and compression forces decay with storage time according to the same mechanism, irrespective of the measurement direction.

However, during the first 2 days of storage, the firmness measurement in the axial versus radial direction seems to be measuring a slightly different aspect of the textural properties of the fresh-cut sliced tomatoes. The exponential decay is steeper when firmness is measured in the radial direction. This difference is not present in the model probably because of the long time interval considered (15 days) for the entire storage study. The differences present in the first 2 days are diluted in the total storage period because the firmness practically does not change from 3–4 to 15 days, irrespective of the direction of force applied in the measurement. This is in accordance with the ANOVA results that indicated that although the effect of direction of force applied is highly significant, it accounts for less than 1% of the variation in firmness. It explains why it was possible to estimate a common decay rate constant for firmness measurements in both the axial and radial direction. To determine the parameter values more accurately, and to determine whether the texture loss mechanism, as well as the rate constants for loss, is the same, additional experiments focusing on a shorter time interval, in particular during the first 2 days of storage, are required. The correction factor does not compensate for the direction of force-applied effect. It is merely that in this data set, this effect is too small to be estimated, and too small compared to the probe size effect.

Softening of Tomato Slices during Refrigerated Storage. Results of the present study confirm those reported previously by Lana *et al.* (2005), e.g., that the decay in the firmness of fresh-cut sliced tomatoes obtained from ripened fruits and stored at low temperature is very small. When the firmness was measured in the axial direction, the development of translucency was not associated with a decrease in firmness, different from what has been observed for other fresh-cut fruits. As discussed previously, although it was not possible to estimate a difference between the two directions of force applied, an indication is given that in the first 2 days after processing, the firmness measured in the radial direction decreases faster. This is the same time span for the development of translucency, which starts at the side of the pericarp closest to the locular gel. Further investigations of changes in firmness, carried out in a shorter time interval, preferably associated with anatomical studies, are necessary to elucidate the reasons for this apparent difference.

Considerations about the Probe Size. Although the effect of probe size was the most significant one determined in the ANOVA, the same model with the same parameter values was obtained when the correction for probe sizes was applied. This means that to study the changes in firmness during storage time, all probe diameters used in this study would be appropriate. Wu and Abbott (2002) found more consistent results (lower coefficient of variation) when using a 4-mm cylindrical probe compared with a 6.4-mm spherical probe. In the present work, only flat probes were used, and the coefficient of variation was about the same for probes of different sizes (from 27.7% to 33.2%).

Based on the results presented and on the observations made when conducting the assays, it was decided to use the 2.5-mm probe in the following experiments. The 3.5-mm probe had almost the same range as the pericarp in fruits with narrower pericarp, which can lead to inaccurate results. Because of its small size, the 1.5-mm probe requires special care when placing the sample in the texture analyzer, to assure that the same tissues are being measured in successive slices. With the 2.5-mm probe, it is relatively easy to place the sample in a way that the probe punctures the central part of the sample, and consequently evaluates the same plant tissue.

CONCLUSION

Using Monte Carlo simulation to study the variation in firmness within and between slices (from different fruits), it was concluded that adding more slices and more measurements per slice reduces the SD, but in general, the efficiency of adding more slices is higher. The combination of eight slices and three measurements per slice was chosen from a number of possible combinations because the number of measurements per slice is limited by the size of the fruit and by the puncture method used, which should avoid measurements in the area where the outer pericarp and the radial arms meet.

The firmness of fresh-cut sliced tomatoes did not change significantly during storage when the tomatoes were sliced at the red stage and were stored at low temperatures after processing. When the firmness was measured in the radial direction, a sharper decrease in firmness was observed in the first 2 days of storage, compared with the firmness measured in the axial direction. After 4 days of storage, there were no significant differences in the measurement of firmness, whether the force applied was in the axial or radial direction, and a common rate constant for firmness decay could be estimated using the model presented here.

The reasons for the initial difference in firmness decay, as related to the direction of force application, are not clear at the moment but deserve further investigation. One important aspect is the relationship between this initial decrease in firmness and the development of water soaking or translucency. Both phenomena happen during the same interval of time, and the translucency starts at the pericarp border where it is in contact with the locular gel. In Lana *et al.* (2006), a detailed discussion about the evidences for a predominantly physical process in the development of translucency are presented. However, the results are not conclusive, and further studies using electron microscopy and other indicators of cellular integrity may elucidate the phenomenon that results in development of translucency.

Using the technology of measuring firmness with a range of probe diameters in a nondestructive fashion offers in the long run the opportunity to separate the compression force underneath the surface of the probe from the shear force exerted at the perimeter of the probe. Considering that a long-lasting difference exists between texture as perceived sensorially and instrumentally, this technique could provide valuable information on the type and importance of firmness in the perspective of consumers.

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