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Measurement of tomato firmness by using a non-destructive mechanical sensor

Patrick Lesage, Marie-France Destain *

Faculté des Sciences Agronomiques, Laboratoire de Mécanique Agricole, Passage des Déportes 2, 5030 Gembloux, Belgium

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Abstract

A non-destructive mechanical sensor (*Cantifruit*) was designed to measure the firmness of tomatoes. It consists of a small plunger constrained to penetrate slightly into the fruits, by using an accurate lever mechanism. A highly significant correlation exists between firmness measurements performed with this device and the Stable Micro System (SMS), fitted with the same plunger diameter. Using the *Cantifruit*, data related to firmness variability and changes are easily obtained. The firmness of a tomato varies about 12% around its circumference. In a single lot of tomatoes picked at the same time, the variability may exceed 25%. If the tomatoes are stored at 4–5°C and 92–99% relative humidity (RH), their firmness decreases by about 20% over ten days.

Keywords: Tomatoes; Firmness; Non-destructive measurement method

1. Introduction

Firmness is a criterium often used to evaluate fruit quality as it is directly related to fruit development, ripening after maturity and storage potential. It is also related to the likelihood of bruising when fruit are subjected to impacts during handling.

However, firmness is a loosely defined concept, evaluated by techniques that are mainly subjective. The common ways used to estimate firmness include manual touch or use of penetration tests which indicate the load required to cause skin collapse or tissue break (in the case where the peel has been removed). Amongst these tests, the EFFEGI penetrometer (designed by the firm Facchini in cooperation with the Istituto di Coltivazioni Arboree of the University of Milan) is well known. It utilizes either an 8- or 11.1-mm diameter plunger and is manually operated.

* Corresponding author. Fax: +32 (81) 614-544.

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In fact, "firmness" in food materials corresponds to "stiffness" in engineering materials and is more conveniently described by the force–deformation relationship. This can be investigated by applying a load on the fruit; by using flat plates, spherical indenters or cylindrical dies. Based on this principle, several non-destructive laboratory instruments for measuring firmness have been used for tomatoes.

For example, the automatic firmness meter in use at the Glasshouse Crops Research Institute consists essentially of two plates compressing the fruit (Hobson and Ambler, 1986). When testing tomato fruits, the calyx is removed and each specimen is placed blossom-end up on the first plate which is fixed, while the pressure is applied on the second plate by lowering a known weight onto the tomato. The distance by which the fruit is compressed due to that load is measured and a "firmness index" is computed. Although non-destructive, this test may cause some permanent change in the fruit shape.

The DUROFEL spring dynamometer instrument (CTIFL Station de Conservation, Saint-Rémy de Provence) is used for firmness measurements and different diameters and shapes of probes are fitted. For tomatoes, the instrument is equipped with a 0.25-cm^2 probe which does not penetrate the tomato skin but measures the superficial retraction under the strain of a force (Planton, 1990).

The INSTRON Universal Testing Machine (Holt, 1970) is a laboratory system which provides the linear displacement of probes at controlled speed. They are fitted with load and displacement sensors, ensuring the ability of textural characteristics computation. Using this device, experiments were carried out by Batu and Thompson (1993) to evaluate the differences in epicarp strength, deformation, firmness, ... of green and red tomatoes by applying a constant weight of 50 N. It was shown that using a diameter of 4 mm and a cross-head speed of 20 mm min^{-1}, for example, the distance travelled by the probe from first contact with the tomato skin to the bioyield point was 6.4 mm for red tomatoes and 4.4 mm for green ones. It was shown that the probe size and the cross-head speed significantly affected this distance.

Other methods have been designed for conducting non-destructive tests that are particularly suited for fruit testing. They may be accompanied by sorting devices. For example, a firmness sorting system was developed which conveyed fruit horizontally at constant speed and caused them to impact on a rigid surface. Impact force characteristics were used to sort fruit into hard, firm and soft categories (Delwiche et al., 1989). In another system, a 3-mm diameter pin was used as a mechanical thumb to sense firmness of oranges and tomatoes and was included in devices to differentiate between firm and soft oranges, or hard-green, firm-red and soft-red tomatoes (Mizrach et al., 1992). Firmness has also been investigated by methods using sonic transmission. The measurements are conducted by exciting the fruit with an impact and measuring the acoustic response by means of a small microphone. The responses are analysed according to their resonant frequencies which are mathematically related to firmness (De Baerdemaeker et al., 1982; Affeldt and Abbott, 1989).

The objective of this research was to develop a non-destructive, low-cost and accurate mechanical sensor of firmness. The principle of the sensor is based on the slight progressive penetration of a plunger into the fruit peel which enables measurement of the force–deformation curve of fruits and computation of the firmness K_{fr}. In the present work, the device was manually operated and emphasis was laid on the ability of the device to evaluate inherent variability both within the fruit and among fruit in a population. The results were compared with those obtained with a reference laboratory testing machine, SMS TA.XT2/25 manufactured by the firm Stable Micro System in England.

2. Materials and methods

Sensor design

The main requirements of the sensor for conducting non-destructive tests are:

- the sensor must be sensitive enough to give easily readable output signals (describing the skin deformation) while the input signals (applied force) are low;
- the accuracy of the measurements must be high, as the measured values (forces and displacements) are very small;
- the design of the plunger and its displacement have to be adapted in order to minimize the stresses in and around the contact area.

The principle of the device (*Cantifruit*) is a lever (L) which rotates accurately around an axle (C) (Fig. 1a). One of its extremities is attached to an extension spring AB while the other bears a small plunger (P) of 3 mm diameter. This latter is constrained to penetrate into the fruit, in a progressive way, thanks to a screw (S) attached to its lower part. The screw rotation ensures a vertical motion of the plunger relative to the lever. As the fruit is fixed to the device frame by means of a wide elastic band (E) and resists the plunger penetration, the lever rotates around point C (Fig. 1b).

To avoid any undesirable change of direction of the plunger, the lever is again positioned horizontally (Fig. 1c) by acting on the extremity B of the spring with a second screw (not represented in the figure). At this stage, the lever is in equilibrium under the action of the forces F_1 and F_2 coming from the resistance of the fruit and the spring, respectively, according to the following equation:

$$F_1 \times a = F_2 \times b \tag{1}$$

where: F_1 = resistance force of the fruit; F_2 = force of the spring; a = distance between the centre of the plunger and the lever axle; and b = distance between the spring and the lever axle.

Assuming that the plunger displacement into the fruit is very small and that the fruit behaviour is elastic, Eq. 1 can be replaced by:

$$\Delta x_{fr} \times K_{fr} \times a = \Delta x_s \times K_s \times b \tag{2}$$

where: Δx_{fr} = displacement of the plunger in the fruit (mm); K_{fr} = fruit firmness (N mm^{-1}); K_s = spring stiffness (N mm^{-1}); Δx_s = displacement of the extremity A of the lever.

A gauge indicates the vertical displacement of the lever with an accuracy of 0.01 mm, giving the displacement values Δx_s and Δx_{fr}. Fruit firmness can thus be

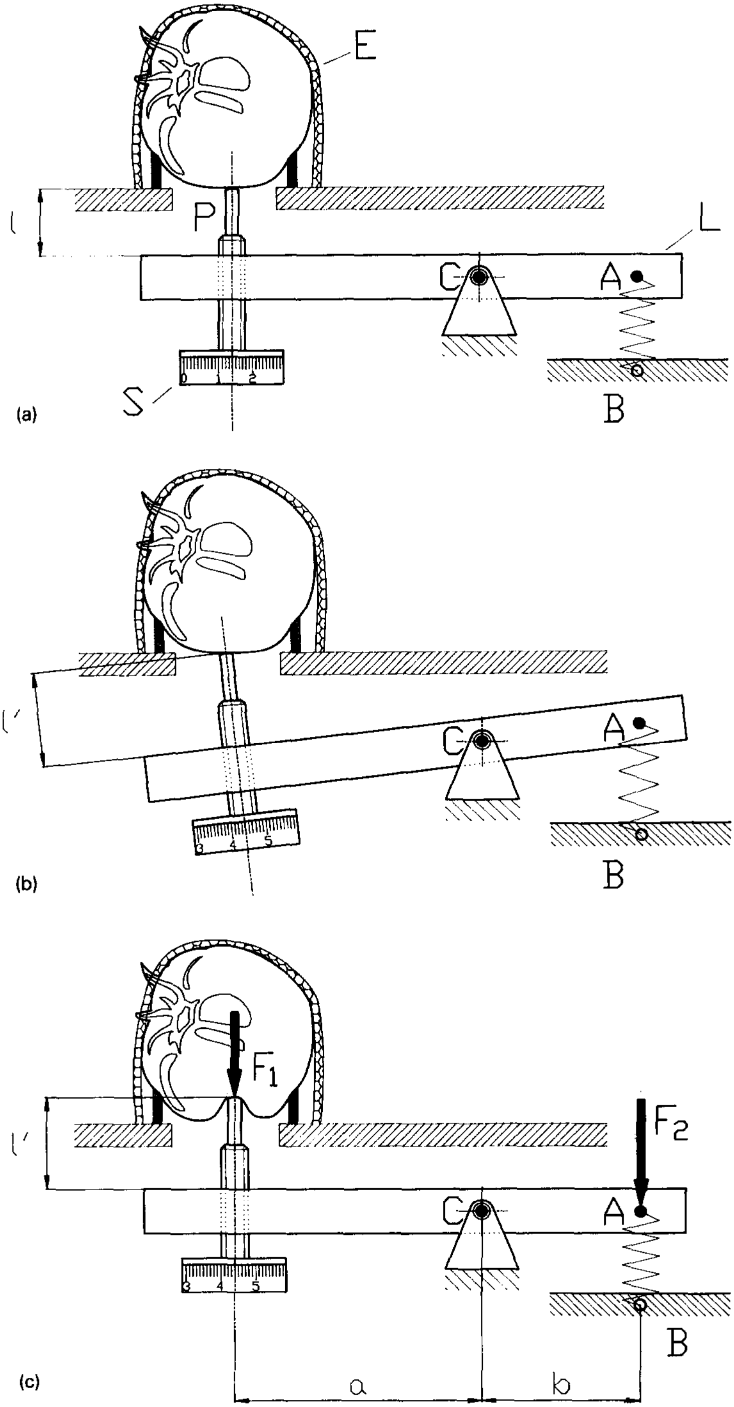

Fig. 1. Device principle.

computed, provided that the other parameters a, b and K_s have been previously determined.

The force–displacement relationship is obtained progressively, as the screw moving the plunger is rotated by steps of one tenth of a turn, corresponding to a plunger vertical motion of 0.1 mm. This operation is repeated until the plunger penetration into the fruit attains the desired value, in our case 1.5 mm. This value is chosen on the basis of trials performed by Mizrach et al. (1992) on tomatoes. The firmness will be computed as the slope of the straight line that best fits the couples of points force F_l versus displacements Δx_{fr} for values zero to 1.5 mm displacement.

In the *Cantifruit* design, several constraints are taken into account.

- The fruit is placed on a transparent annular support with edges chamfered to mould to the fruit's convex shape and to keep the contact surface constant during compression. Moreover, the fruit is maintained by means of a soft elastic band attached to the frame to eliminate the influence of the weight of the fruit on the measurements.
- The contact with the small plunger might create internal stresses and strains and bruising could be initiated slightly below the skin. If the deformation exceeds the biological yield limit in these locations, the tissue will be damaged and infections caused by various fungi may occur. To avoid any problems, the end of the plunger is round in shape and its displacement is always kept smaller than 1.5 mm. Up to this value, the peel deformation remains elastic (this will be shown later) and no damage (mould, bruising marks, ...) is observed several days after the tests.
- The friction and the clearances in the mechanism are kept as low as possible to avoid any error in the measurement of forces and displacements. For instance, the lever axle is mounted on small bearings to avoid any friction.
- As biological materials generally affect viscoelastic properties (the relationships between stresses and deformation are time dependent), and due to the sensor principle, the measurements are made slowly enough to be considered as static.

Experimental design

The measurements were performed on greenhouse tomatoes (cv. Recento) grown in Belgium. The tomatoes were manually harvested at three different times: mid-May, end of May 1993 and mid-July 1995. They were sized between 57 and 67 mm of girth diameter, with a mean weight of 150 g and a colour varying from green to pale orange. These fruits were placed in refrigerated storage chambers at 4–5°C and 92–99% relative humidity (RH).

At each harvest date, three lots in the same stage of development were picked.

The two first lots were repeatedly tested as the fruits ripened. They each contained 30 fruits. This was found sufficient on the basis of Hobson and Ambler's (1986) observations who estimated that a population of about 20 fruit is the minimum number on which firmness readings for a particular treatment should be based. Firmness measurements were repeated 1, 3, 7, 12 and 25 days after picking with the *Cantifruit*. Two measurements were taken on each fruit, opposite one another, at the equator at random, except for the tomatoes issued from lot 2,

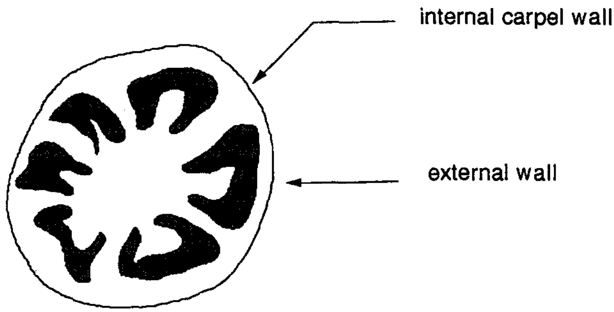

Fig. 2. Tomato cross section and measurement locations.

three days after picking. In this case, the test was designed to take into account the non-homogeneity of the internal structure of the fruit and four measurements were performed, two on the external wall and two on the internal carpel wall (Fig. 2).

The third lot containing 90 tomatoes was divided into three equal groups. For the first group, the *Cantifruit* K_{fr} measurements were coupled with reference tests three days after picking. For the two other groups, the comparisons were performed 12 and 25 days after picking, respectively. In these reference tests, two systematic measurements were performed on the internal carpel wall of each tomato. The reference device was a Stable Micro System (SMS) TA-XT2/25 universal testing machine especially equipped with pins of 3 mm diameter. The skin was not removed, as is usually the case when testing tomatoes (Kader et al., 1978). The force was increased until the deformation reached 10 mm and the cross head speed was 100 mm min^{-1}. An example of result is shown in Fig. 3. Firmness was computed as the average slope of the force–deformation curve up to the yield point.

The measurement scheme is indicated in Table 1. The data from each experiment were subjected to analysis of variance. Means and standard errors were computed and Duncan's range test was used to determine significant differences between means.

3. Results and discussion

Behaviour of tomatoes during loading

Fig. 3 gives a typical force–deformation curve obtained during penetration of an individual tomato measured with the SMS device. The cross-head speed was equal to 100 mm min^{-1} and the chosen probe diameter was 3 mm. The first section of the curve is nearly straight and the biological yield limit corresponding to the skin failure appears clearly.

The same linear behaviour is obtained with the *Cantifruit*, but the curve is restricted to the deformation limit imposed by the device. Fig. 4 shows the force–deformation relationship for two tomatoes chosen at random and belonging to lots 1 and 2, one day after picking.

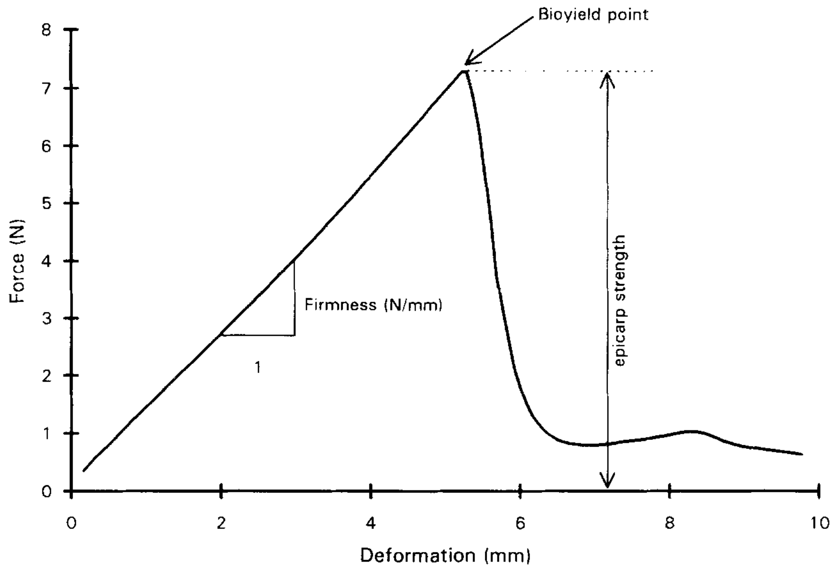

Fig. 3. Typical force–deformation curve obtained with the SMS universal testing machine during penetration of individual tomato.

Table 1
Experimental design (N.D.F. measurement = non-destructive firmness measurement)

Number of days after picking	Lot 1	Lot 2	Lot 3
1	N.D.F. measurement (random)	N.D.F. measurement (random)	
3	N.D.F. measurement (random)	N.D.F. measurement (systematic)	N.D.F. measurement (systematic) Reference tests (systematic)
7	N.D.F. measurement (random)	N.D.F. measurement (random)	
12	N.D.F. measurement (random)	N.D.F. measurement (random)	N.D.F. measurement (systematic) Reference tests (systematic)
25	N.D.F. measurement (random)	N.D.F. measurement (random)	N.D.F. measurement (systematic) Reference tests (systematic)

At these low deformations, the force–deformation relationships fit to a linear regression ($r^2 > 0.99$) and the firmness was estimated to be 3.09 and 4.73 N mm^{-1}, respectively. For the maximum penetration distance (1.5 mm), the forces applied to

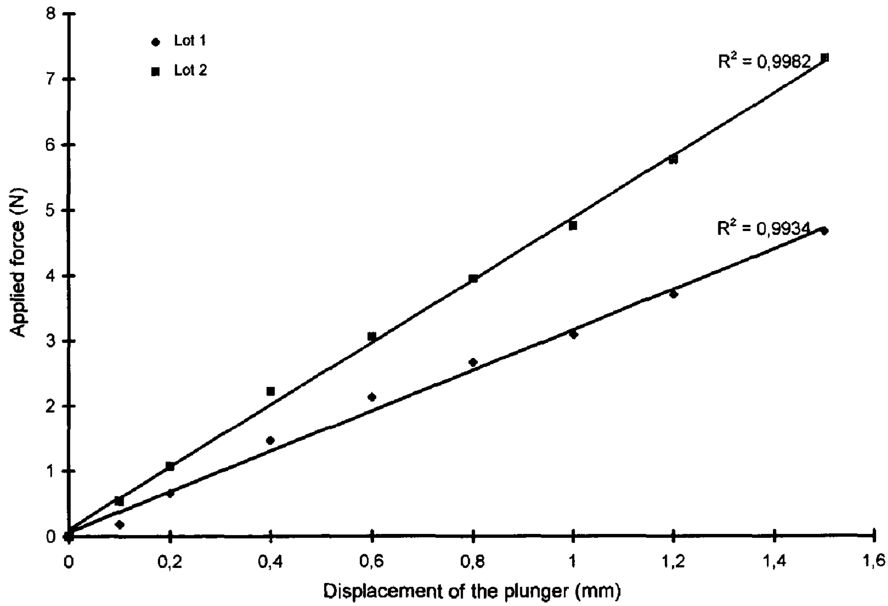

Fig. 4. Force–deformation relationship for two tomatoes, one day after picking.

the fruits were equal to 4.64 and 7.10 N. A similar linear regression can be adapted for fruits after several days of storage, the correlation coefficient was always greater than 0.99.

Taking into account the good linear behaviour of the fruits, the measurements accuracy would not be greatly affected if the firmness was computed by directly dividing the maximum authorized force by the plunger displacement of 1.5 mm, instead of using statistical fitting.

Firmness distribution

The picked tomatoes were estimated by the producer to be at the same development state. Table 2 gives the mean firmness and coefficients of variation (CV) for

Table 2
Mean firmness and CV

Number of days after picking	Lot 1		Lot 2	
	Mean K_{fr} (N mm^{-1})	CV (%)	Mean K_{fr} (N mm^{-1})	CV (%)
1	2.78	16.9	2.67	27.1
3	2.46	24.2	–	–
7	2.12	24.5	2.38	24.0
12	1.98	27.3	2.06	21.9
25	1.34	26.4	1.35	28.3

lots 1 and 2. The CV indicate a variability within the groups ranging between 16.9 and 28.3%. This means, for example, that one day after picking, in lot 1, the mean value is 2.78 N mm^{-1} and may attain low values such as 1.87 N mm^{-1} and high values such as 3.51 N mm^{-1}. This variability has two origins:

- The tomato is a non-homogeneous fruit and it may so happen that the measurements performed on a random way coincide with an internal carpel wall or not.
- When the tomatoes are picked, there is only a visual judgment of their ripeness and this involves a degree of tolerance.

At this stage, it is impossible to decide which of the above factors is responsible for the quite high values of firmness CV. To clarify this point, the results of the systematic tests should be analysed.

In the systematic tests (three days after picking, lot 2), statistical analysis indicates that firmness varied according to the measurement location. On the external wall, the mean value is 2.39 N mm^{-1} while it is 2.94 N mm^{-1} on the internal carpel wall. It is clear that carpel walls, because of their cellular structure, contribute to the firmness, even minimally, and hence enhance the total strength of the fruit. Between the internal carpel walls, where the tomato medium consists of a viscous liquid, the mechanical resistance of the fruit is lower. The CV indicating the variability resulting from the measurement location is 12.1%. On the other hand, the variability between the tomatoes, whatever the measurement location, is somewhat higher and attains 17.1%.

We conclude that the variability due to the non-homogeneous structure of the tomato is less than the total variability of the fruits. However, random measurements are thought to produce acceptable results, even if their variability is somewhat higher than that of the systematic measurements.

Changes in maturity with time

Table 2 and Fig. 5 show that, in the chosen storage conditions, firmness decreases with time. One day after picking, the mean value for lots 1 and 2 was 2.73 N mm^{-1} while it decreased to 2.25 N mm^{-1} after seven days and attained 1.35 N mm^{-1} after 25 days. Water loss was found very small (0.5% of the mean tomato weight) and a regression was performed to express the changes of the firmness versus time. For lot 1 it may be written as:

$$\ln K_{fr} = \ln 2.731 - 0.029t \quad (r = 0.990)$$

where t is the time after picking in days. According to this equation, the firmness of tomatoes stored at 4–5°C and 92–99% RH decreased by about 20% in ten days.

When considering the same period after picking, there is no significant difference between the means of lots 1 and 2 where the harvest periods are separated by 15 days.

Comparison with reference device

Comparison of firmness obtained with the *Cantifruit* and the SMS were performed on the third lot, 3, 12 and 25 days after picking.

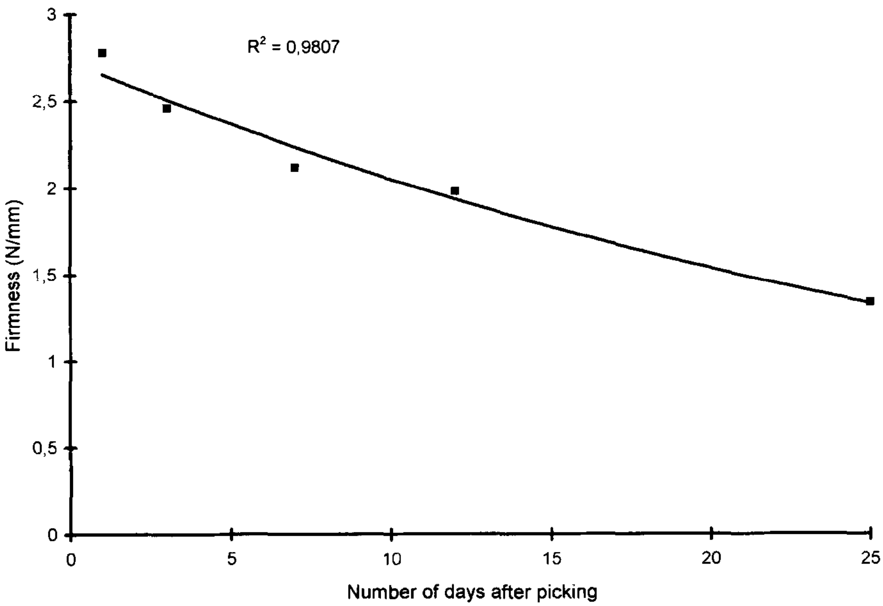

Fig. 5. Changes in tomato firmness over 25 days.

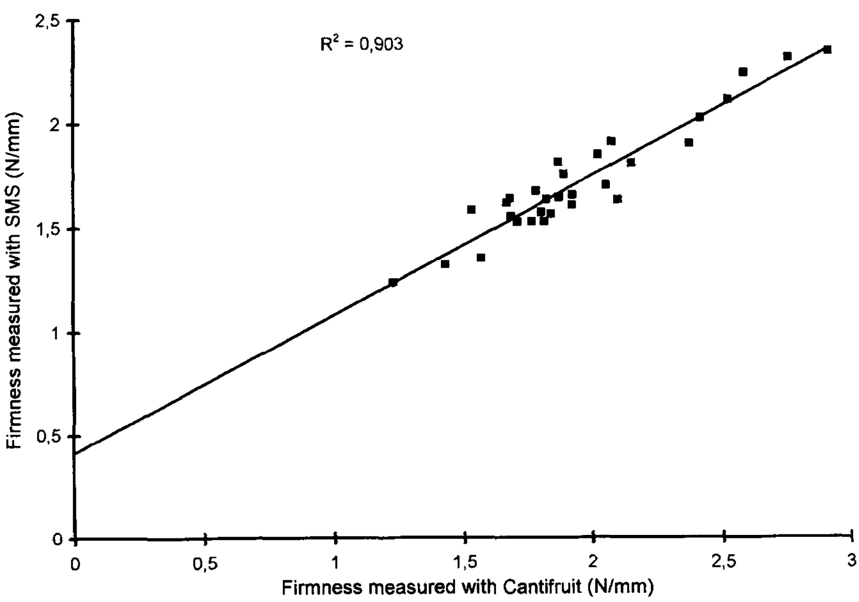

Fig. 6. Comparison of firmness measured with the *Cantifruit* and the SMS, 12 days after picking.

In all three cases, a good correlation exists between the measurements (Fig. 6). SMS firmness K_{SMS} versus *Cantifruit* firmness K_{fr} was: $K_{SMS} = 0.734K_{fr} + 0.100$, $K_{SMS} = 0.669K_{fr} + 0.411$, and $K_{SMS} = 0.805K_{fr} + 0.152$, respectively. According to the coefficient of determination r^2, 91.2% (three days), 90.3% (12 days) and 74.2% (25 days) of the K_{fr} values were linearly correlated with the K_{SMS} values.

Due to the non-destructive character of the proposed device in conjunction with its high degree of reliability, we conclude that it might be used successfully instead of the SMS machine.

4. Conclusion

A reliable, non-destructive mechanical plunger was designed to measure fruit firmness in batches of tomatoes. With this tool, called the *Cantifruit*, we have shown that in a single lot of tomatoes picked at the same time, the variability may exceed 25%. Firmness decreases quickly during time from its initial picking value and hence it would be interesting to sort the fruit directly at the site of production into different categories according to their firmness level. A simple non-destructive device like the *Cantifruit* has the potential for the development of a sensor which could be incorporated into such a sorting machine.

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