Reliability of vibration measurements and impact response characteristics for the quality assessment of tomatoes

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Abstract The applicability of the acoustic impulse-response and the impact response devices for the measurement of fresh table tomato firmness was analysed and compared in a collaborative test. Tomato fruits were measured at different firmness states with both instruments. A high positive correlation was found between the maximal acceleration, measured with the impact response device, and the stiffness measured with the acoustic tester. For the impact tester, the ratio between the maximal acceleration and the impact duration was the most segregating parameter when classifying tomatoes into different firmness classes. For the acoustic tester, the repeatability of the measurements was significantly higher at the equator than at the bottom of the tomato. This was not the case for the impact tester, which gave similar results at both positions. The overall discriminant power of both methods was found to be very similar. For the acoustic tester, discrimination between different firmness states was much better when measuring at the bottom. For the impact tester, it makes not too much difference in discriminant power where to measure.

Introduction

Firmness is a very important quality property for grading tomatoes. It is the main sensory parameter to define quality, as it relates to ripeness, and soft tomatoes are strongly rejected by consumers, as they have an image of 'not fresh and maybe rotten'. As long ago as 1960, Garrett *et al.* made a comparative study on different instruments to measure firmness of tomatoes. Later, Shafshak and Winsor (1964) used a simple compressibility tester, with a balance and flat-plate compression. This is the principle of some instruments used today in the market practice. Holt (1970) used 'plunger' punching to detect ripening and firmness differences between cultivars. These procedures are still used in laboratories.

Two new instruments, based on: 1) acoustic impulse-response and 2) impact response have been developed during the last twenty years. The first was developed at the University of Leuven (De Baerdemaeker *et al.* 1982, Chen and De Baerdemaeker 1990, De Ketelaere and De Baerdemaeker 2001) and the second in the UPMadrid (Chen and Ruiz-Altisent 1996, Chen *et al.* 1996,

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Ortiz-Cañavate *et al.* 2000). These instruments have been tested on various types of fruits. Both are being developed into on-line sensors.

The objective of this paper is to analyse and compare the applicability of the acoustic impulse-response and the impact response devices to the measurement of fresh table tomato firmness by measuring the same tomato fruits at different firmness states with both instruments, in a collaborative test.

Materials and methods

A total of 46 'firm' and 46 'less firm' fruits were measured on 2 testers. Tomatoes were picked directly from a Belgian auction. The total measurement span, including both types of measurements as well as the reference measurements was less than 24 hours.

Acoustic response tester

The vibration behaviour of the tomatoes was studied on a lab-scale test bench. The main parts of the test bench are shown in Figure 1. The tomato is placed on a cushioning material and is impacted by a small plastic rod that is driven by an electromagnet. At the end of the rod a small steel ball is glued. The vibration of the tomato is captured by a small microphone (type ECM-2005, Monacor®) and is fed to the 16-bit soundcard of a portable PC. The parameter of interest is the stiffness factor S defined as $S = f^2m^{2/3}$ where f denotes the resonant frequency of the elliptical mode (Hz) and m is the mass of the object (g) (Abbott *et al.* 1968).

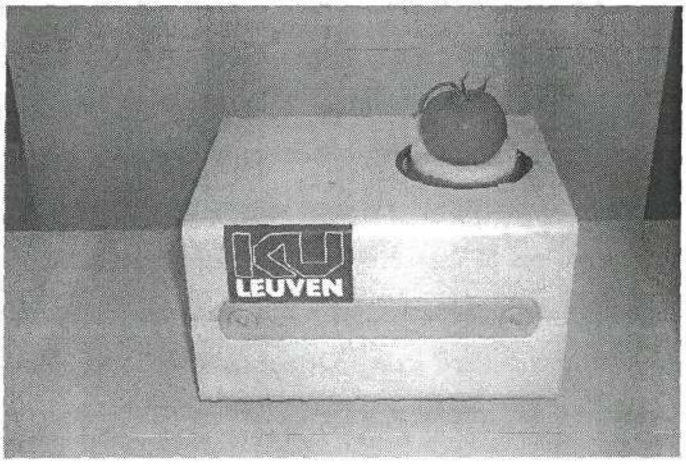

Fig. 1. The acoustic response tester

Impact tester

The LPF-Lateral 2.0 was used. It consists of an impacting mass pivoting in an arm, instrumented with an accelerometer and controlled from the computer (Fig. 2). The position of contact to the fruit can be selected, and the distance to the fruit was fixed at 2 cm. Each tomato was tested at eight different points in two positions: four at the equator and four at the flower end or bottom.

Reference measurements

carried out were (i) firmness determined using an automatic testing machine (Texture analyser, TA-XT2), and (ii) force/deformation in a contact test with a similar spherical tip as used in the impact tester. The applied deformation was 1 mm and 2 mm at 0.3 mm s^{-1}. Maximum force (N) and deformation energy under the force-deformation curve (Nmm) that is equivalent to the recovered elastic energy were analysed. Six randomly selected fruits were tested, at two positions.

Fig. 2. The impulse response tester

Results and discussion

Reference firmness

Both groups of tomatoes ('firm' and 'less firm') were clearly separated by the static contact test described above, with an average difference of 5 N (n = 6) and the stress-strain properties. No overlap was present between both samples of fruits for these parameters. The deformation to up to 1 mm, according to its highest F-value in an ANOVA, was the best static reference test.

Data overview and overall relationships

A positive correlation (r = 0.84) was found between the stiffness measured with the acoustic tester, and the maximal force measured with the impact tester. Both parameters are highly negatively correlated with the maximal deformation (r = 0.76, 0.90, respectively). This was to be expected, since stiffer tomatoes will deform less than softer ones under a pre-defined impact. There is a relative independence between the absorbed energy and the impact duration.

Repeatability

Repeatability is quantified by the standard error divided by the average $\frac{SE}{X}$, and has to be analysed, in particular applications, with respect to the range of the data, $\frac{SE}{Range}$. Both statistics were calculated for data averages of 4 repetitions in each point (equator and bottom), and this for both devices. The SE/range is very good for both devices, with a slightly better performance for the acoustic tester (Table 1). A similar analysis was performed separating the measurements at the equator of the tomatoes and those taken at the bottom (Tables 2 and 3). It can be concluded that much more reliable results are obtained when measuring the tomatoes at their bottom in case of the acoustic tester. This difference is not clearly visible in case of the impact tester: results are even slightly more repeatable at the equator (Tables 2 and 3).

Table 1. Repeatability of the acoustic tester and the impulse response tester; All data used

PARAMETER	$\overline{X}$	*SE*	*Range*	$\frac{SE}{\overline{X}}$	$\frac{SE}{Range}$
A_{max} / Time	63.15	6.29	117.07	**0.10**	**0.05**
Stiffness ($\times10^6$)	9.44	0.64	17.98	**0.07**	**0.04**

Table 2. Repeatability of the acoustic tester and the impulse response tester; Equator data

PARAMETER	$\overline{X}$	*SE*	*Range*	$\frac{SE}{\overline{X}}$	$\frac{SE}{Range}$
A_{max} / Time	71.2	6.59	102.2	**0.09**	**0.064**
Stiffness ($\times10^6$)	8.68	0.84	16.08	**0.10**	**0.05**

Table 3. Repeatability of the acoustic tester and the impulse response tester; Bottom data

PARAMETER	$\overline{X}$	*SE*	*Range*	$\frac{SE}{\overline{X}}$	$\frac{SE}{Range}$
A_{max} / Time	55.1	*5.98*	102.4	**0.11**	**0.058**
Stiffness ($\times10^6$)	10.20	0.44	15.03	**0.04**	**0.03**

Discriminant power

The discriminant power of both devices, indicating the ability to distinguish between both tomato classes was calculated as $\frac{SE}{(\overline{X}_1)-(\overline{X}_2)}$. This statistic can be used to compare different instruments for the same quality parameter, in this case firmness, and also those used as reference. Following results were obtained when all data were collapsed in one analysis (Table 4). Again, very similar results are obtained with both devices, with slightly more discriminant power for the impact tester. As above, the data were also analysed for equator and bottom data separately (Tables 5 and 6). The discriminant power of the acoustic tester is much better when measurements are taken at the bottom of the tomato. This result, together with the result shown in Tables 2 and 3, clearly favours taking measurements at the bottom of the tomato for the acoustic tester. For the impulse response tester, the choice between the two measuring locations is not that clear.

Table 4. Discriminant power of the acoustic tester and the impulse response tester; All data used

PARAMETER	$\overline{X}_1$	$\overline{X}_2$	*SE*	Discriminant power
A_{max} / Time	39.10	87.19	6.29	**0.131**
Stiffness (x10^6)	7.10	11.57	0.64	**0.144**

Table 5. Discriminant power of the acoustic tester and the impulse response tester; Equator data

PARAMETER	$\overline{X}_1$	$\overline{X}_2$	*SE*	Discriminant power
A_{max} / Time	46.6	95.9	6.59	**0.133**
Stiffness (x10^6)	6.58	10.60	0.84	**0.209**

Table 6. Discriminant power of the acoustic tester and the impulse response tester; Bottom data

PARAMETER	$\overline{X}_1$	$\overline{X}_2$	*SE*	Discriminant power
A_{max} / Time	31.6	78.5	*5.98*	**0.127**
Stiffness (x10^6)	7.67	12.55	0.44	**0.090**

Conclusions

The results show that the acoustic response tester and the impact tester are sufficiently accurate to classify non-destructively tomatoes into firmness classes. Repeatability, standard error/range and discriminant power are very high for the tomatoes tested for both devices. The repeatability of both devices was very comparable when collapsing all data (both at the equator and the bottom) into one global analysis. For the acoustic tester, repeatability improves drastically when measuring at the bottom of the tomato. Furthermore, the bottom measurements prove to have a far better discriminant power when compared to the equator measurements. For the impact tester, it makes not too much difference in discriminant power where to take the measurements.

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