Non-destructive fruit firmness sensors: a review

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Abstract

The development of sensors to measure fruit internal quality variables is one of the challenges of post-harvest technology. Several variables can currently be measured, including sugar content, acid content, firmness and internal disorders. This article reviews the state of the art of non-destructive fruit firmness sensors. These include static and on-line sensors that use different technologies for determining force-deformation relationships, impact forces, the acoustic response to vibrations or impacts, and optical properties. The rebound technique and nuclear magnetic resonance is also used. Although many techniques are under development, some companies already market instruments that determine the internal quality of fruit.

Additional key words: impact, NMR, physical properties, post-harvest, quality.

Resumen

Revisión. Sensores para la medida no destructiva de firmeza en fruta. Estado de la técnica

Uno de los principales desafíos de la tecnología de poscosecha en el sector de la fruta es el desarrollo de sensores capaces de medir parámetros de calidad interna entre los que se pueden citar: contenido en azúcares, contenido en ácidos, firmeza, defectos internos, etc. En este artículo se realiza una revisión de los diferentes sensores y técnicas existentes para la medida de firmeza de la fruta de forma no destructiva. Para ello se analizan sensores estáticos y dinámicos (en línea) basados en diferentes tecnologías y técnicas: análisis de la relación fuerza-deformación, análisis de la fuerza de impacto, técnica de rebote, respuesta acústica a vibraciones o impactos, propiedades ópticas y resonancia magnética nuclear. Aunque todavía muchas de estas técnicas se encuentran en fase experimental, ya existen en el mercado equipos comerciales capaces de medir diferentes parámetros de calidad interna en fruta. En este caso concreto se realiza un breve análisis de dichos equipos para el caso de la medida de firmeza.

Palabras clave adicionales: calidad, impacto, poscosecha, propiedades físicas, RMN.

Introduction

Fruit quality is related to both internal variables (firmness, sugar content, acid content and internal defects) and external variables (shape, size, external defects and damage). Increasing consumer demand for high-quality fruit has led to the development of optical, acoustic and mechanical sensors that determine this quality. Fruit packing companies need to measure these quality variables, but they need to do so in a non-destructive manner. Manufacturers and research groups have understood this and are currently developing sensors with this aim.

Fruit firmness is one of the most important quality variables; it is an indirect measurement of ripeness and its accurate assessment allows appropriate storage periods and optimum transport conditions to be established. The texture of an edible material is defined by the British Standards Institution as *the attribute of a substance resulting from a combination of physical properties perceived by the senses of touch (including kinaesthesis and mouthfeel), sight and hearing* (Anonymous, 1975). These physical properties may include size, shape, number and the conformation of constituent structural elements (Anonymous, 1975). Texture is defined as a sensory attribute, and can only be measured directly by sensory means (Brennan, 1984). Firmness, which is also a qualitative concept, is only a small part of the sensation of texture in the mouth. Szczesniak (1963) proposed a classification of food texture based on rheological principles which could be monitored by both instrumental and sensory methods of

characterization. This author classified the textural characteristics of food into mechanical, geometrical and «other» properties. The mechanical properties were subdivided into five primary variables (hardness, cohesiveness, viscosity, elasticity and adhesiveness) and three secondary variables (brittleness, chewiness and gumminess). The geometrical characteristics were divided into two general groups - those related to the size and shape of particles, and those related to shape and orientation. The «other» characteristics included moisture content, oiliness and greasiness.

Fruit texture is described by sensorial terms such as crispness, juiciness, grittiness and flouriness. Instrumental measurements, however, define the mechanical properties of fruit tissues in terms of force, pressure and energy. Different mechanical properties can be measured instrumentally, each of them related to firmness and texture in a particular way. Usually, devices designed to measure firmness are sensitive to one mechanical property in particular (e.g., the force needed to produce a deformation) or to the propagation of an excitation (light, acoustic, magnetic resonance etc.) inside the fruit, which varies according to its texture.

Traditionally, fruit firmness has been estimated in a destructive manner by means of the Magness Taylor test. This can be performed in the laboratory or with portable equipment, and is based on the introduction of a cylindrical head into the flesh of a peeled fruit to measure the maximum penetration force. Depending on the equipment used, other variables can be measured such as maximum force, deformation, and the values for different relationships between force and deformation. However, the Magness Taylor test has three main drawbacks: it is destructive, measurements are highly variable (by up to 30%; Barreiro 1994) and it cannot be used in on-line situations. Nevertheless, this technique is well accepted and used for classifying fruit by many packing companies and quality laboratories.

Technical advances over the last few decades have led to the development of non-destructive devices capable of measuring fruit internal variables. Originally, these were developed for use in the laboratory, but have been adapted for on-line use (as have weight or diameter-measuring devices). This article describes the characteristics of the non-destructive fruit firmness sensors currently available to fruit producers for use in their laboratories or packing lines.

Principles of non-destructive firmness sensors

Fruit firmness can be estimated by different techniques including the measurement of variables extracted form force-deformation curves, the analysis of impact forces, the rebound technique, the measurement of acoustic responses to vibrations and impacts, the measurement of optical properties, and nuclear magnetic resonance.

Measuring the variables of force-deformation curves

The basic principle underlying the measurement of force-deformation lies in Hertz's theory: the compressive stress between two bodies in contact is proportional to their elastic modulus and inversely proportional to their radius. In this case, one of the bodies is the fruit and the other a metallic plunger (either a small sphere or flat-ended probe). By applying a small deformation force to the fruit in such a way that it causes no damage, the non-destructive force-deformation curve can be recorded using an analogue (spring) or a piezoelectric sensor positioned at the back of the compression plunger. The curve is produced by applying a small load for a fixed period of time (Macnish *et al.*, 1997) or by calculating the force necessary to reach a pre-set deformation (Fekete and Felföldi, 2000).

This non-destructive technique (also known as micro-deformation) has led to the production of a number of devices. Figure 1 shows a micro-deformation
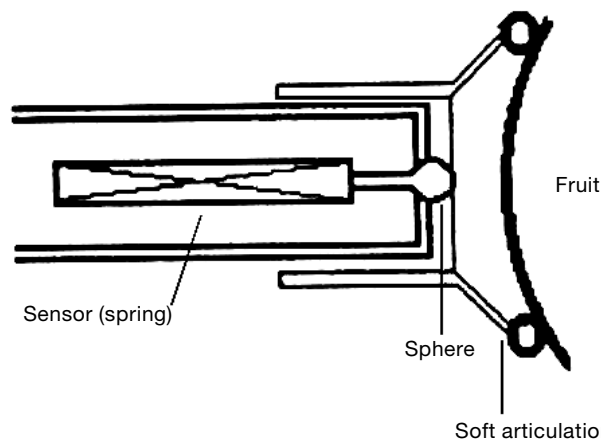

Figure 1. Micro-deformation firmness measurement device (Steinmetz *et al.,* 1996).

sensor developed by CEMAGREF (French acronym for *Centre National du Machinisme Agricole, du Génie Rural, des Eaux et Forêts*) (Steinmetz *et al.*, 1996) in collaboration with the also French enterprise Caustier. A flexible positioning cup (a «soft articulation») with a contact plunger (a probe with a sphere at the end) in the centre helps the operator to slightly deform the fruit surface (maximum 2 mm approx.). A spring then shows the firmness index on a scale.

Other companies have also developed micro-deformation devices, such as Copa Technology (now Agro Technology) in collaboration with CTIFL (*Centre Techniques Interprofessionnel des Fruits et Légumes)*. Their «Durofel» instrument has a metallic, flat-ended probe with three possible contact areas (10, 25, 50 cm^2, depending on the fruit to be analysed), and is based on the Shore A durometer. The «hardness» value is determined by the penetration of the probe into the sample. The result is expressed as an index ranging between 0 and 100. Both the analogue (equipped with a spring and a gauge) and digital version (electronic sensor, display and computer interface) have been widely used with apricots (Jay *et al.*, 2000), tomatoes (Planton, 1991), cherries (Clayton *et al.*, 1998) and other soft fruits.

Macnish *et al.* (1997) describe two non-destructive devices for measuring firmness developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO): the Analogue CSIRO Firmness Meter (AFM) and the Digital CSIRO Firmness Meter (DFM). These devices have been used with tomatoes and mangos. The fruit is placed in a v-shaped structure, and then a 40 mm diameter disc is applied to it. The disc is joined by an arm to an analogue displacement gauge. A 500 g weight is then placed on the disc, and the displacement information (compression) recorded after 30 s. The second apparatus (DFM) is similar, but has a digital gauge and slightly different supports.

A texturometer equipped with specific arms for different fruits has also been successfully used (Studman, 1999).

A non-spectroscopic method of measuring mechanical deformation with a laser was developed by HortResearch. Known as the «laser air-puff», this device measures the deformation of fruits subjected to a short but strong current of air (69 kPa in 100 ms). According to its designers, this apparatus has a high potential for on-line use (10 fruits per second can be tested), but the prototype has not been developed commercially since the firmness sensor market is not big enough (Hung *et al.*, 1998; HortResearch, 2002). McGlone *et al.* (1999) used a similar system to test kiwis, but only very soft fruit could be accurately distinguished.

Sensors based on force *vs.* time measurements (impacts)

Many of the theories on the measurement of firmness by impact testing are based on Hertz's theory and the elastic impact theory (Timoshenko and Goodier, 1951). Following a low energy elastic impact involving the fruit, the mechanics of that impact are studied.

Chen and Ruiz-Altisent (1996) indicate that the impact of a fruit on a hard surface, or the impact of a sphere on a fruit, can be studied as an impact between two elastic bodies. These authors report that impact force and impact duration are directly related to fruit firmness. Originally, this methodology was used to study the susceptibility of onions to mechanical damage (Edgerly, 1951, cited by Jarén, 1994), but since the 1970s impacts have also been used in firmness studies. Mohsenin (1970) described a technique for measuring firmness that involved impacting fruit with a pendulum (Fig. 2). This system, with several modifications, is still used to measure damage in tomatoes (Desmet *et al.,* 2002).

There are many ways of using impact sensors, such as: a) hitting the fruit with some element that includes the sensor; b) putting the fruit over a load cell and
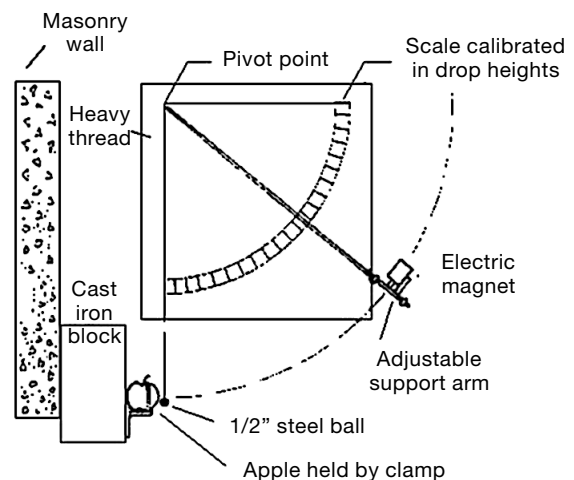

Figure 2. Measuring firmness by the pendulum technique (Mohsenin, 1970).

letting a weight fall on it; c) placing the fruit on a flat plate with a load cell located beneath it.

Chen *et al.* (1985) developed an instrument to measure the response of fruit to impacts. The sensor consisted of a small, semi-spherical mass with an accelerometer, which was dropped from different heights onto the fruit (Fig. 3). The results obtained with this technique are better when the impact mass is smaller (Jarén 1994; Chen and Ruiz-Altisent, 1996; Chen *et al.*, 1996). Later, García *et al.* (1988) developed a new vertical impact sensor based on this system. This was used to measure the firmness of apples and pears in a non-destructive manner (Jarén *et al.,* 1992; Jarén and García-Pardo, 2002). Ortiz (1999) used this technique to distinguish woolly peaches by combining it with infrared spectroscopy, a methodology used in a number of studies to determine mealiness in apples (Salvadores *et al.*, 2000) and woolliness in peaches (Ortiz, 1999; Ortiz *et al.*, 1999, 2001) and nectarines (Arana, 2001). The vertical impact sensor has also been used to test and classify different padding materials in fruit packing lines (García-Ramos *et al.*, 2002).

Chen and Ruiz-Altisent (1996) developed a new «lateral impact sensor» consisting of a small arm with lateral movement that impacts the fruit with a semi-spherical head. A piezoelectric accelerometer located on this head estimates fruit firmness. In agreement with work performed by Timoshenko and Goodier (1951), lateral-sensor measurements are based on the theoretical analysis of the elastic impact between two spheres. According to this theory, Chen (2001) described the magnitude of the peak impact force F to depend on characteristics of both fruit and impacting sphere, including approach velocity, mass, the Poisson ratio, the modulus of elasticity, and the radius of curvature of the contact point.
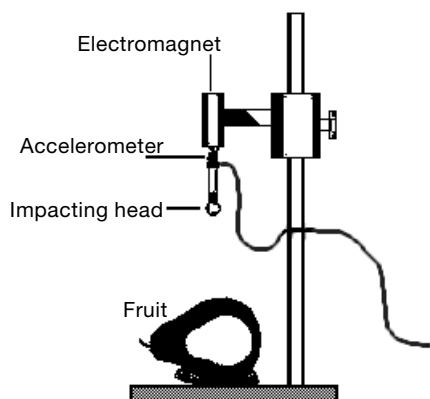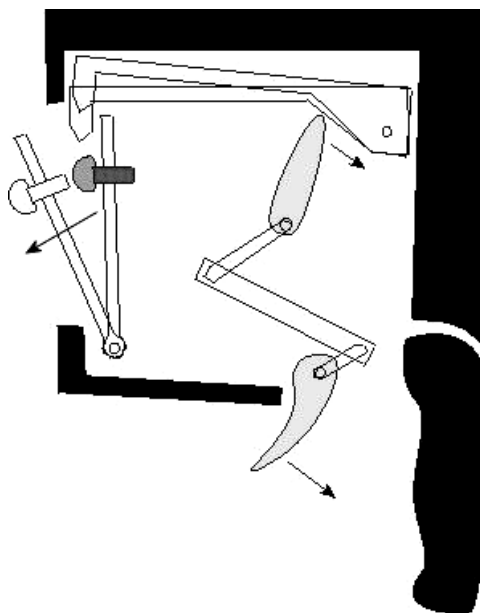

Figure 4. Manual impact sensor developed by Chen *et al.* (2000).

A step forward in this technique was the development of a manual impact sensor shaped like pistol (Fig. 4). This can be used in orchards to determine the optimum harvest date (Chen and Thompson, 2000; Chen *et al.*, 2000). Caution must be taken with this type of sensor to make measurements in the correct position —vertical— and in similar conditions of humidity (Chen and Thompson, 2000).

Moltó *et al.* (1996) developed a sensor based on a load cell. The test fruit is placed on this and struck by a mass of 128 g which falls from a height of 1 cm onto the fruit. The signal supplied by the load cell measures the fruit firmness.

The impact technique has been used on-line in different ways. Lateral impact sensors were adapted for use with a conveyor belt at the University of California (Davis) (Chen and Ruiz-Altisent, 1996). Peach and apple firmness could be measured at a maximum speed of 6 fruits per second. Firmness values were related to the Magness Taylor maximum force. The coefficients of determination were $r^2 = 0.84$ for peaches and $r^2 = 0.40$ for apples (Tjan, 1997; Chen and Tjan, 1998). Later, the system was modified to introduce a second sensor (thus requiring two impacts per fruit); the average value was used for classification purposes (Chen and Thompson, 2000).

García-Ramos *et al.* (2003) modified Chen's lateral impact sensor by changing its structure, release system, electronics, software and control system for use in
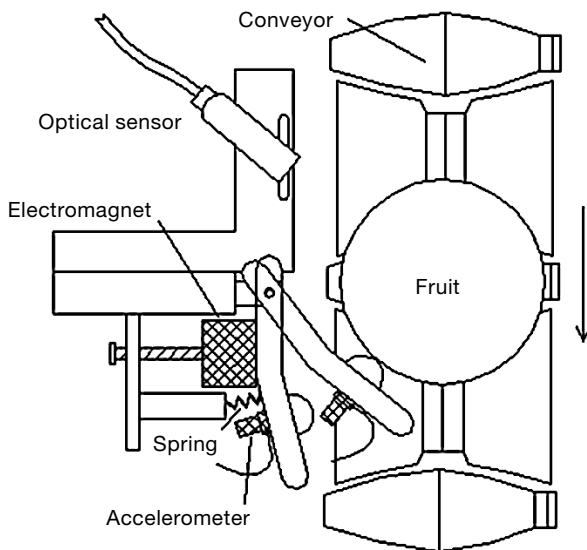

Figure 3. Vertical impact sensor (Chen *et al.,* 1996).

Figure 5. On-line, lateral impact sensor (García-Ramos *et al.,* 2003).

commercial packing lines (Fig. 5). Initial tests showed this prototype to discriminate in a manner similar to the bench top version, validating the extensive work previously performed. Tests carried out with this sensor (Homer *et al.*, 2002) on peaches and nectarines showed it to be 88% successful in classifying fruits into two groups (below and above 10 N) and 82% successful in classifying them into three groups (between 10 and 30 N).

Delwiche *et al.* (1996) developed a sensor, based on the impact technique, that acts horizontally and consists of a cylindrical head with an attached accelerometer, all moved by a pneumatic cylinder. The sensor was installed successfully in an experimental packing line.

Impact techniques can also involve dropping the test fruit onto a load cell. Moltó *et al.* (1996) and Gutiérrez *et al.* (1999) described a sensor based on this idea, the load cell recording the impact when the fruit falls on it. The sensor, patented in Spain by IVIA (the Valencian Institute for Agricultural Research) and the FOMESA company, has been used to detect puffed clementines on-line at a speed of 5 fruits per second and with an effectiveness of over 90%. Later, this sensor was used in an experimental production line together with near infrared (NIR) sensors to sort apples, nectarines and peaches (IVIA, 2004; Gutiérrez *et al.*, 2003). With respect to the maximum force/maximum penetration obtained with a texturometer (using the Magness Taylor test configuration) in peaches, this same sensor

provided final values of $r^2 = 0.32$ and $r^2 = 0.68$ according to variety. These low values are due to the lack of roundness and the irregularities of the fruit, although the authors concluded that, with the algorithms created, it can be successfully used to classify fruits (Burgos *et al.*, 2002). Nahir *et al.* (1986) used this technique in a conveyor system, and separated tomatoes into three categories after dropping them from 7 cm above the plate. The system showed good correlation between stiffness (force signal divided by the duration of impact) and the results obtained in a standard parallel plate compression test. Based on this previous technique, Delwiche *et al.* (1987) determined peach firmness using two variables as indices: F/t^2 (F = maximum force and t = time to reach this force) and the 295 Hz spectrum magnitude of the impact.

Chen and Ruiz-Altisent (1996) mention several studies undertaken with this methodology but report the technique to be sensitive to the mass and radius of curvature of the fruit as well as its free-fall speed. The control of the impact zone is therefore difficult.

To minimize the effect of variations in the impact angle, weight and the radius of curvature, a multiple impact system was proposed (for use with melons), which, via the calculation of the mean, meant no reorientation of the fruit was necessary (Ozer *et al.,* 1998). It was also proposed that F/t be used to minimise this same effect since a 10% change in the mass of the fruit can induce a change of 5.88% in F and 4.44% in F/t. A 10% change in the velocity at the moment of impact also causes appreciable changes in F and F/t (Chen, 2001).

All the equipment described above has been developed by research groups and is currently being used in the form of prototypes. However, some companies are marketing a number of impact apparatuses for on-line use (although few technical details are available, the sensors used are usually piezoelectric, providing a voltage signal proportional to the impact force in a manner similar to an accelerometer). For example:

— The iFD (intelligent firmness detector, manufactured by GREEFA). This is a large wheel equipped with multiple sensor heads that rotates over the packing line, and which impacts the top of the fruits. The number of measurements per fruit made by this wheel of sensors ranges from 9 to 20, according to a working velocity of 7 fruits per second (Greefa, 2004).

— The Sinclair iQ firmness tester. The sensor head (with groups of four sensors per fruit line) consists of

a piezoelectric sensor surrounded by a rubber bellow activated by compressed air. This moves the sensor vertically over the fruit. The system can take readings from 10 fruits per second (Sinclair, 2004). The sensor has been tested with avocados, citrus fruits, kiwis, plums, nectarines and peaches (Howarth and Ioannides, 2002). A bench-top version can be used in static form in the laboratory (Shmulevich *et al.*, 2002).

Rebound technique

Impact theory shows that firmness can be quantified according to the rebound of the fruit after impact against a surface. This technique was first used commercially in potato harvesters to separate out clods of soil. The idea was that, after impacting against a revolving cylinder, potatoes and clods would fall at different distances from the impact point according to the difference in their restitution coefficients. However, the restitution coefficients of potatoes and clods are similar (Feller *et al.*, 1984, cited by Gan-Mor *et al.*, 1985 and by Jarén, 1994). Later, separation of clods and potatoes was performed by impacting them against an elastic platform. This allowed the energy of the clods to be adsorbed, thereby reducing their restitution coefficient. Although the final difference in restitution coefficient between the clods and the potatoes remained very small, it was sufficient to separate them (Gan-Mor *et al.*, 1985; Gan-Mor and Galili, 2000).

Building on this concept, an on-line system was designed to separate out soft from good olives (Barreiro *et al.*, 2002). The system consists of a transporting belt that transfers the olives to a horizontal cylinder covered by a padding material. The cylinder rotates in the opposite direction to the belt. Soft olives rebound less and fall closer to the impact point than do those in good condition, thus separating them. With this methodology, Bryan *et al.* (1978) also managed to separate puffed clementines from good fruit at a rate of 36-90 fruits per second.

Acoustic response to vibration

The response of fruit and vegetables to vibrations depends on their modulus of elasticity, their mass and their shape. Different types of vibrations can be used, the most common being acoustic and mechanical (which in some cases are very similar). Using a micro-

phone or a piezoelectric sensor, acoustic methods measure the signal (audible range: about 0-20,000 Hz) issued by the fruit after making it vibrate by means of a small impact. The acoustic signal captured is Fourier transformed and the main frequency calculated. The range varies from 5 MPa for green fruit to 0.5 MPa for overripe fruit (Studman, 1999).

Cooke and Rang (1973), cited by Studman (1999 and 2001), proposed a mathematical model for the modulus of elasticity:

$$E = C \cdot f^2 \cdot m^{2/3} \cdot \rho^{1/3}$$

where E is the coefficient of elasticity (Pa), C is a constant, f is the frequency for the highest amplitude (Hz), m the mass (kg) and ρ the density (kg m^{-3}).

The acoustic response is used to estimate the overall texture of the fruit (Clark and Mikelson, 1942; cited by Studman, 1999). Vibration theory assumes that the object is spherical and approximately elastic for small deformations. According to Abbot and Masie (1998), most fruits are viscoelastic but generally have been assumed to be elastic when the induced deformations are very small. This technique has been used in several studies (Yamamoto *et al.*, 1980; Armstrong *et al.,* 1990; cited by Diezma *et al.*, 2002). Other studies have opted to use piezoelectric films instead of microphones to gather the signal coming from the impact (Shmulevich *et al.*, 1996). Muramatsu *et al.* (1997), who worked with kiwi fruit, generated the acoustic impulse with a small loudspeaker, and the response was received with a small microphone on the other side of the fruit.

Different equations based on the modulus of elasticity have been developed in order to obtain a «firmness index» as a function of f (Hz) and m (kg). The index is commonly referred to as S because of its relation with the stiffness of the tissue. Different authors quote different m exponents depending on the importance given to the fruit mass. Abbott *et al.* (1998) and Fekete and Felföldi (2000) propose the following equation to estimate the firmness index: $S = f^2 m$.

De Belie *et al.* (2000) used this methodology to measure pear firmness while the fruits were still on the tree. These authors impacted each fruit near the stem and read the frequency at the opposite side using an accelerometer. A manual prototype was developed which used the stiffness factor $S = f^2 m^{2/3}$ to estimate on-tree apple firmness (m was estimated from the fruit diameter) (Landahl *et al.*, 2002). Currently, several companies offer devices based on this technique. AWETA markets the «AFS» (acoustic firmness sensor)

for laboratory use. This equipment detects the vibration modules of the acoustic wave travelling across the fruit. The excitation impact is generated mechanically at the top of the fruit. Based on studies performed by De Baerdemaeker *et al.* (cited by De Belie *et al.*, 2000), the system is appropriate for measuring the firmness of apples and tomatoes.

Another commercial device is the «Firmalon». This is based on work performed by Shmulevich *et al.* (1996), and is manufactured by Eshet Eilon Ltd. (Kibbutz Eilon, Israel). The instrument consists of three piezoelectric sensors and three electro-mechanical impulse hammers. A force transducer measures the fruit mass and compensates the signal. Firmness is estimated by using the average of the two closest first resonant frequencies supplied by the sensors.

Ultrasonic response to vibration

Ultrasound ($> 20,000$ Hz) is difficult to use in fruit and vegetable quality determination since it is strongly attenuated when travelling through plant tissues. In addition, these waves cannot penetrate deeply into the fruit (Chen, 1996). The response of whole avocados and other fresh products to ultrasound stimulation was studied by Galili *et al.* (1993). Mizrach *et al.* (2001) used ultrasound to measure firmness in two varieties of apples. Good results were obtained with the Jonagold variety, but not with the Cox variety.

Mechanical vibration

Firmness can also be measured by analysing the response of fruit to mechanical vibration. In this case, the fruit is placed on a surface that vibrates at pre-selected frequencies, and the response measured by an accelerometer. Abbott and Massie (1988) recommend placing the fruit on a platform that vibrates in the range of 0 to 200 Hz. A sonic stiffness coefficient is then calculated that relates the mass of the fruit to the frequency of a selected sonic resonance. This allows kiwi fruits to be classified into two or three levels of firmness.

Peleg (1993) developed a firmness sensor based on the relationship between the vibration produced by an electro-mechanic vibrator located on a fruit support, and the response signal measured by an accelerometer attached to a «finger» that comes into contact with the upper part of the fruit. Soft fruits attenuate the vibration

whereas firm fruits supply a strong signal. This system was successfully used on-line by using a sensor wheel with either 8 (1.3 to 2 fruits per second) or 24 sensors (4 to 6 fruits per second). The estimated errors for tests on peaches and apples were around 10% and 20% respectively.

Optical techniques

The interaction between light and fruit tissues can be used to measure fruit internal quality. An optical sensor consists of a light source and a receiver which records the optical signal. The optical signal has different wavelengths. According to the light pathway inside the sample, there are two main optical techniques: reflectance (incident light penetrates the external tissues and exits towards the sensor near the entering point) and transmittance (incident light goes through the tissues and hits the sensor on the opposite side of the fruit - or at least 90 degrees away from entrance point).

Optical sensors also can be used to estimate fruit firmness, since light (both in the visual [VIS] and near infra-red [NIR] ranges) is scattered when it travels through plant tissues. Several techniques have been developed:

Near infrared reflectance spectroscopy

This technique, which measures the reflected spectrum of a sample lit with halogen light is closely related to that employed by optical equipment (e.g., cameras etc.). Much research effort is currently being made in this area. Lu (2001) used the spectrum between 800 and 1,700 nm to estimate the firmness and sugar content of two cultivars of sweet cherries. These were classified into three firmness categories, < 3.5 N, 3.5-6.0 N and > 6.0 N. Correlations with the Magness-Taylor test (6 mm diameter probe) were r = 0.8 (for 800 nm) and r = 0.65 (for 1,700 nm) respectively. The standard prediction error was 0.55 and 0.44 N respectively. Choi *et al.* (1997) studied VIS and NIR spectra to estimate sugar content and firmness in apples. After partial least squares analysis, the results were deemed to satisfactorily estimate the ºBrix (r = 0.94), but not the maximum force obtained in the Magness-Taylor test.

Woolly peaches have been detected using the transmission NIR spectra, by combining information on

their juiciness and softness (Ortiz, 1999; Ortiz *et al.,* 1999, 2001). Lammertyn *et al.* (1998) estimated the soluble solid content, acidity and firmness of Jonagold apples using NIR spectroscopy. The light spectra were compared with the stiffness factor (acoustic response) and the force/deformation ratio (Magness-Taylor test): the correlation with the former was found to be better (r = 0.9 compared to r = 0.75). McGlone *et al.* (1997) also worked on determining fruit sugar content, acidity and firmness, but with kiwifruit. NIR wavelengths grouped by multivariate regression showed a poor correlation (r^2 = 0.7) with standard firmness tests (McGlone and Kawano, 1998). In other work, samples of kiwi were illuminated with a 864 nm laser by McGlone *et al.* (1997), and the scattered light (reflectance spectra) recorded at output angles of between 20º and 55º. A scattering constant («S») depending on light intensity and geometric factors was strongly correlated (r > 0.88) with the results of the Magness-Taylor test.

Image analysis with laser light

Duprat *et al.* (1995) constructed an optical system combining a stereomicroscope and a camera to record the scattering area of an apple illuminated with a 670 nm laser. A correlation coefficient of 0.84 was obtained between the size of the area and Young's modulus.

Tu *et al.* (1995) illuminated tomatoes and apples with a He-Ne laser and acquired an image of the scattered light using a RGB (red-green-blue) camera. The total number of pixels above a certain intensity threshold was measured and compared with different ripeness levels and with the firmness estimated by acoustic response tests. A later study using the same technique found no clear relationship between light scattering, turgidity and loss of weight under different storage conditions (De Belie *et al.*, 1999). Han and Lambert (1998) used 632, 685 and 678 nm laser diodes for sorting apples into four firmness classes. Certain features of the laser images were used to estimate fruit firmness in multiple regression analysis. The reference test for firmness was again the Magness-Taylor test; by this standard the system only classified 41-61% of fruits well.

Laser photon counting spectroscopy

Cubeddu *et al.* (2001a) describe a system to non-destructively measure internal fruit quality using time-resolved diffuse reflectance spectroscopy (TRS). The theory of light diffusion in matter underlies this technique which consists of producing a short pulse of laser light that becomes broader when it passes through fruit tissues. The photons recovered after travelling through the sample are recorded as well as the time elapsed (Fig. 6) (Cubeddu *et al.*, 2001b). The scattering coefficient (μ'_s) is associated with the structure of the fruit, and therefore its firmness, while the absorption coefficient (μ_a) is associated with its chemical components (sugar content, acidity). Tests carried out using the TRS coefficients of absorption and dispersion in the VIS and NIR ranges were used to create different internal quality estimation models. In the estimation of firmness (three categories), the system correctly classified 76% of apples, 77% of peaches, 81% of tomatoes, 75% of kiwis and 60% of melons (Valero, 2001). The system can also be used to detect mealiness in apples (Valero *et al.*, 2001).

Commercial, on-line, optical devices based on NIR spectroscopy and the use of either halogen lamps or laser sources are available. Some were developed for use with melons but have been successfully used with pears, apples, peaches and Sharon fruit. These sensors can handle 2-5 fruits per second depending on the species. The internal variables measured are sugar content plus an indirect measurement of firmness («ripeness»). The only device that currently gives an indication of firmness is the «SACMI F5» system developed initially by Fantec (Japan) and now by SACMI (Italy). Its silica sensor analyses spectra between 650 and 1050 nm to obtain information on sugar content, acidity, maturity, watercore and brown core. If the fruits are previously orientated in a line, five fruits per second can be tested (Sacmi, 2002). Other instruments such as the «Tastemark» device
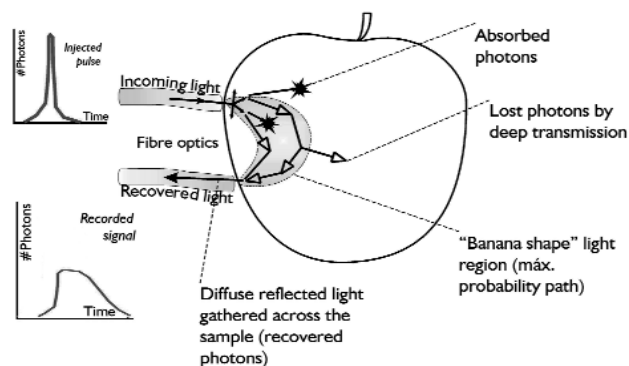

Figure 6. Laser light diffusion using time-resolved diffuse reflectance spectroscopy.

manufactured by Taste Technologies Ltd. of New Zealand, the «internal quality analyser (IQA)» produced by Aweta (The Netherlands) or the «intelligent flavour analyser (iFA)» by Greefa (The Netherlands) are designed to sense taste and internal variables related to ripeness in on-line situations (Aweta, 2002; Taste Technologies, 2002; Greefa, 2004).

Nuclear magnetic resonance (NMR)

This technique measures internal features based on the magnetic properties of the nuclei of atoms making up a material. Although it does not measure firmness directly, it does measure properties related to maturity and internal defects (Bellon *et al.*, 1992). The features extracted from a NMR signal can be related to a sample's chemical content (e.g., moisture distribution) and internal structure (McCarthy, 1994), which affect the firmness and rheological properties.

NMR induces transitions between proton energy levels to establish a state of imbalance and then observes the return equilibrium. The frequency of the energy needed to excite the system is given by Larmor's equation, $v = \gamma B/2\pi$, where v is the precession frequency, γ is the magnetic proportion, and B the external magnetic force. A radio frequency (RF) pulse at the Larmor frequency excites the nuclear spin system, and a radio signal is then emitted by the sample when it returns to equilibrium. Signal intensity is recorded over time, and by Fourier transformation is converted to yield intensity *versus* frequency. This signal provides information about the environment of the nucleus (Chen *et al.*, 1993).

Normally, the nuclei excited are H^+ and, therefore, the information related to firmness extracted from a NMR signal is linked to the water content of the sample, the water mobility, and the hydrogen bonds present in the structural constituents of the tissues. The variables T1 and T2 (longitudinal and transversal relaxation times) provide information about the different chemical components and their mobility states respectively.

As in VIS and NIR optical techniques, NMR can also be used to obtain images. In this case, a graded magnetic field is applied to the sample and double Fourier transformation used to calculate a two-dimensional signal.

There are few mentions of direct relationships between NMR signals and firmness measurements (determined either by destructive or non-destructive methods) in the literature, and those that have been reported are often relatively poor. For example, Krutz *et al.* (1993) report a correlation between the NMR result and the Magness-Taylor force of only r = 0.48. The estimation of firmness by NMR is usually achieved by quantification of the maturity state or water mobility. Chen *et al.* (1993, 1996) used NMR with avocados (both statically and on-line) and obtained T2 and T1-enriched spectra and images to quantify the water state. A similar methodology (used with static fruit) was found useful for detecting internal breakdown in apples (Wang *et al.*, 1988), soft tissues caused by bruising in apples (Zion *et al.*, 1993), internal softening in heated papayas (Suzuki *et al.*, 1994), internal decay in melons (Zion, 1994), and softening induced by *Botrytis cinerea* in strawberries (Goodman *et al.*, 1996). Mealiness (or wooliness), a combination of softening with a reduction in water mobility, can be detected in apples, peaches (Barreiro *et al.*, 1998; 2002) and nectarines (Sonego *et al.*, 1995) by NMR.

The use of NMR for the on-line, non-destructive estimation of firmness is restricted by the high cost of these devices and the need to resolve problems associated with capturing signals from moving samples.

Future tendencies

The implementation of fruit firmness sensors in commercial packing lines is one of the challenges for fruit producers in the short term. The main requirement is the marketing of reliable sensors that can accurately measure fruit firmness.

Currently, producers incorporate into their fruit packing lines sensors that can measure external variables such as weight, size and colour at maximum speeds of 10 fruits per second. The future lies in the fusion of different sensors to provide systems that give more global information on each fruit (i.e., on external and internal variables). The integration of such sensors should ensure consumers purchase quality products; combinations of sensors should give better results than individual sensor acting alone. Sensors might also be developed that measure more than one variable (Steinmetz *et al.*, 1996; 1999). The concept of sensor fusion is very recent, and arises from the need to improve the efficiency of fruit classification systems. Not only should this reduce the margin of error, it

should also rationalise the number of commercial categories recognised. However, choosing the method of fusion is difficult (Steinmetz *et al.*, 1999).

In an attempt to simulate the sorting process carried out by human experts, Ozer *et al*. (1995) combined complimentary sensors (colour, firmness, shape and weight) to classify melons into four classes, and achieved a success rate of 85.1%.

Three European research laboratories performed a study to measure peach firmness with three different non-destructive techniques: acoustic, impact and micro-deformation. The fusion of the information supplied by the three sensors was undertaken using Bayesian classifiers associated with a heuristic integration method. Fruits were classified into three groups: soft, half-firm and firm. When fruits were measured independently, the error rate varied between 19% and 28% compared to the algorithms obtained with the Magness-Taylor test. However, by the fusion method, this error was reduced to 14% (Steinmetz *et al.*, 1996).

In conclusion, optical techniques and NMR have the advantage that they can estimate several internal variables, such as sugar content, acid content, internal disorders and firmness with a single sensor. However, the impact technique appears to be more reliable for measuring fruit firmness, and the sensors and electronics needed to produce a working device are cheaper.

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