RESEARCH

EVALUATION OF A NON-DESTRUCTIVE IMPACT SENSOR TO DETERMINE ON-LINE FRUIT FIRMNESS

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ABSTRACT

A non-destructive impact sensor to measure on-line fruit firmness was evaluated. This sensor is an adaptation of a static model used in the laboratory to measure fruit quality and was installed in an experimental fruit packing line with a commercial sizer chain. The firmness index is related to the acceleration-time curve supplied by an accelerometer attached to an impacting arm. The main objective of this study was to evaluate sensor performance and sources of variation. We made classification trials on three fruits: peaches (*Prunus persica* (L.) Batsch), apples (*Malus domestica* Borkh.), and pears (*Pyrus communis* L.), as well as working trials, such as placing the fruit, orientation, and others. The sensor works correctly at a speed of 7 fruits s^{-1} (0.63 m s^{-1}) and allows fruit classification at three levels of firmness using specific software. Good discrimination was obtained only for soft peaches. There were variations in results between different fruits and different parts of the same fruit mainly due to the non-uniformity of fruit shape and lack of ripeness homogeneity of each one.

Key words: packing line, fruit quality, peach, low-energy impact, sorting.

INTRODUCTION

Increasing demand of quality fruit by consumers is promoting an advance in the development and application of sensors capable of measuring different quality parameters (sugar, acids, firmness, etc.) in a non-destructive way.

Firmness can be measured by impacts based on Hertz's contact theory. Initially, this methodology was used to decrease fruit bruising and calculate fruit rebound in crop systems. Afterwards, it was adapted to study fruit firmness. Different authors have shown that this impact technique can be successfully used to evaluate fruit firmness (García and Ruiz-Altisent, 1988; Jarén *et al*., 1992; Chen and Ruiz-Altisent, 1993). Furthermore, García-Ramos *et al*. (2005) describe many ways of using impact sensors, such as hitting the fruit with some element that includes the sensor, putting the fruit over a load cell and letting a weight fall on it, or placing the fruit on a flat plate with a load cell located beneath it. Moreover, some of them reached a commercial use, as is the case of iFD (Intelligent Firmness Detector, Greffa, Netherlands), Aweta (Netherlands), and Sinclair iQ Firmness Tester.

This contact theory considers fruit as an elastic body, thus enabling the calculation of the maximum compression tensions and effort in the impact area. García (1988) mentioned that firm fruits are better adapted to Hertz's theory than soft ones because fruit becomes more visco-elastic when it matures.

Based on the study by Timoshenko and Goodier (1951) on the theoretical analysis of the elastic impact between two spheres, Chen (2001) described the magnitude of the peak impact force F acting on each body, considering an impacting sphere and a fruit, and which can be expressed as:

$$F=\left(\frac{5}{4}\nu_0^2\right)^{\frac{3}{5}}\left(\frac{m_1m_2}{m_1+m_2}\right)^{\frac{3}{5}}\left(\frac{\frac{4}{3}E_1E_2}{E_2\,(1\text{-}\mu_1^2)+E_1\,(1\text{-}\mu_2^2)}\right)^{\frac{2}{5}}\left(\frac{R_1R_2}{R_1+R_2}\right)^{\frac{1}{5}} \quad [1]$$

where F = impact force acting on each body; ν_0 = relative velocity of approach of both bodies; m_1 = mass of impacting sphere; m_2 = fruit mass; μ_1 = Poisson's ratio of impact sphere; μ_2 = Poisson's ratio of fruit; E_1 = modulus of elasticity of impacting sphere; E_2 = modulus of fruit elasticity; R_1 = radius of curvature at contact point of

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impacting sphere; R_2 = radius of curvature at contact point of fruit; $\nu_0 = \nu_1$ at a static impact ($V_2 = 0$).

The effects of changes in m_2 and R_2 also diminish when the impacting sphere spreads are smaller than the fruit (Chen, 2001).

Based on this theory, Chen and Ruiz-Altisent (1996) developed a static, non-destructive impact sensor to measure fruit firmness. The sensor consisted of a semi-spherical impacting head which impacted the fruit (Figure 1). Fruit firmness was obtained by the signal supplied by an accelerometer located on the impacting head. Characteristics of the semi-spherical impacting head according to Equation [1] were as follows:

Rigid: $E_1 = \infty$

$$\text{Low mass } (m_1) = \frac{m_1 m_2}{m_1 + m_2} \approx m_1$$

$$\text{Small size } (R1 << R2) = \frac{R_1 R_2}{R_1 + R_2} \approx R_1$$

In this way, F is:

$$F = \left(\frac{5}{4}\,\nu_0^2\right)^{\frac{3}{5}} \left(\frac{m_1 m_2}{m_1 + m_2}\right)^{\frac{3}{5}} \left(\frac{\frac{4}{3} E_2}{1 - \mu_2^2}\right)^{\frac{2}{5}} \left(\frac{R_1 R_2}{R_1 + R_2}\right)^{\frac{1}{5}} \quad [2]$$

Maximum acceleration (A_{max}), during the impact is:

$$A = F / m_1 \quad [3]$$

Acceleration can be expressed as:

$$A = \left(\frac{5}{4}\,\nu_0^2\right)^{0.6} \frac{1}{m_1} \left(\frac{m_1 m_2}{m_1 + m_2}\right)^{0.6} \left(\frac{4}{3}\,\frac{E_2}{(1-\mu_2^2)}\right)^{0.4} \left(\frac{R_1 R_2}{R_1 + R_2}\right)^{0.2} \quad [4]$$

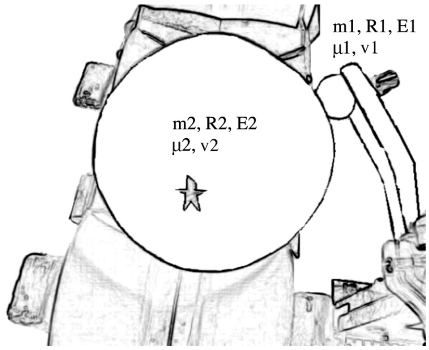
The relationship of A/t, also used as an index of firmness, is expressed as:

$$A / t = 0.68 F \nu_0 / D m_1 \quad [5]$$

Or:

$$A/t = 0.8954\ \nu_0^{1.4}\ \frac{1}{m_1} \left(\frac{m_1 m_2}{m_1 + m_2}\right)^{0.2} \left(\frac{E_2}{(1-\mu_2^2)}\right)^{0.8} \left(\frac{R_1 R_2}{R_1 + R_2}\right)^{0.4} \quad [6]$$

The sensor initially developed by Chen and Ruiz-Altisent (Chen and Ruiz-Altisent, 1996) was used in a static position in the laboratory and was also successfully tested on a 3 m length conveyor belt at California University, Davis (Chen and Tjan, 1998). A manual prototype has recently been developed (Chen *et al*., 2000). García-Ramos (2001) modified Chen and Ruiz-Altisent's impact sensor by enhancing the mechanical part, and by also creating a new electronic control and software, thus generating the LPF 2.0 prototype. The sensor was installed in the sizer of an experimental fruit packing line at the Physical Properties Laboratory (Universidad Politécnica de Madrid).



m_1 = mass of impacting sphere; m_2 = fruit mass; μ_1 = Poisson's ratio of impact sphere; μ_2 = Poisson's ratio of fruit; E_1 = modulus of elasticity of impacting sphere; E_2 = modulus of fruit elasticity; R_1 = radius of curvature at contact point of impacting sphere; R_2 = radius of curvature at contact point of fruit.

Figure 1. Impact between impacting head and fruit.

The objective of this study was to evaluate the performance and sources of variation of this sensor which can affect the obtained signal.

MATERIALS AND METHODS

The firmness measuring system, mounted on an experimental line, consisted of a conveyor, impact sensor, control software, and ejection system. A more detailed description of the system and its components was described by García-Ramos *et al*. (2003).

The experimental fruit packing line had variable speed, a commercial sizer chain with plastic trays with a 9 cm separation between trays, and three fruit outlets.

The impact sensor (Figure 2) consisted of an optical sensor (a photoelectric switch based on the reflection technique with response time ≤ 0.5 ms and detection length of 20 cm) to detect the presence fruit, a 10 g spherical low-mass with a piezoelectric accelerometer (sensitivity of 1 mV m^{-1} s^{-2} and range±4900 m s^{-2}) which impacts the fruit to sense its firmness, a spring to release the impacting mass, and an electromagnet to hold the impacting mass.

The firmness index was obtained from the acceleration-time curve supplied by the accelerometer with a specific software (F.A.S.T. 1.1) developed at the Physical Properties Laboratory of the Universidad Politécnica de Madrid, Spain. The software allowed classifying fruit at three levels of firmness, one for each outlet. Simultaneously, acceleration-time curve data were recorded for later analysis in the search for an appropriate

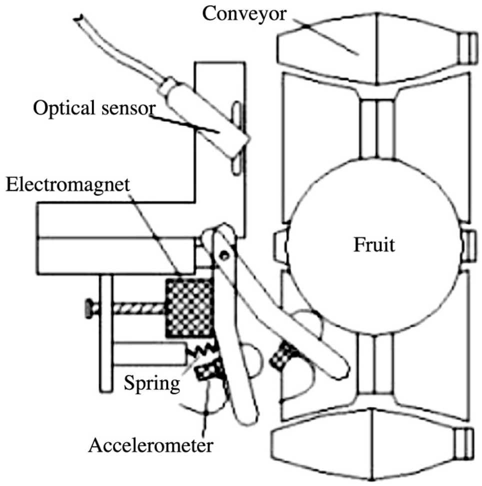


Figure 2. Impact sensor.

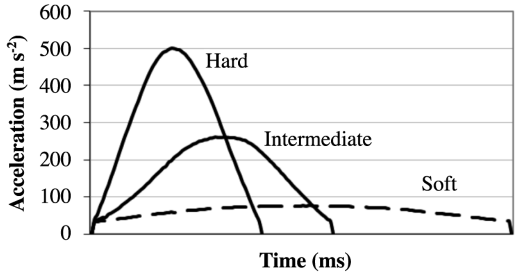


Figure 4. Different curves obtained by accelerometer at three firmness levels.

firmness index (for example, maximum acceleration (A_{max}), maximum slope, mean slope, impact ratio of maximum acceleration/time (A_{max}/t), etc.).

Figure 3 shows the impact system and how it operates: a) the optical sensor detects the fruit, and then the electronic control circuit de-energizes the electromagnet holding the impacting mass; b) a spring releases the impacting mass, and a signal is sent at the same time to the PC to begin digitalising the data supplied by the accelerometer with a CIO-DAS08 acquisition card (Measurement Computing, Norton, Massachusetts, USA); and c) the electromagnet retracts the impacting mass after a brief period and the system waits for a new fruit. A signal is sent to the micro-controller of the ejection system once the fruit is classified.

There are clear differences among impact curves (Figure 4) according to material hardness. The curve of a hard fruit has a maximum acceleration and minimum impact duration, whereas a soft fruit shows opposite results. The acceleration-time curve supplied by the accelerometer allows calculating a fruit firmness index.

After adapting the non-destructive impact sensor to the experimental packing line, several preliminary tests were carried out using different types of balls (tennis, cork, and rubber) with 100 impacts of each and velocities of seven fruits per second to determine the sources of signal variation: photoelectric cell position, fruit position, impact area, and impact velocity. The purpose of these tests was to find the best possible measurement technique, with the objective of studying sensor characteristics and determining the correct firmness index to separate fruit into different classes.

Once the best regulation of the sensor was set, two tests were developed along with two goals:

Test 1. To analyze the effect of the distance and impact arm swinging time variables on the sensor signal. Distance refers to the distance between fruit and impact sensor. Impact arm swinging time refers to the time passed between when the arm begins to move until initial contact with the fruit (logically, this variable varies with distance).

The effect of impact distance was evaluated in a static way. For this goal, a reference rubber ball was impacted in a series of 10 impacts considering different distances

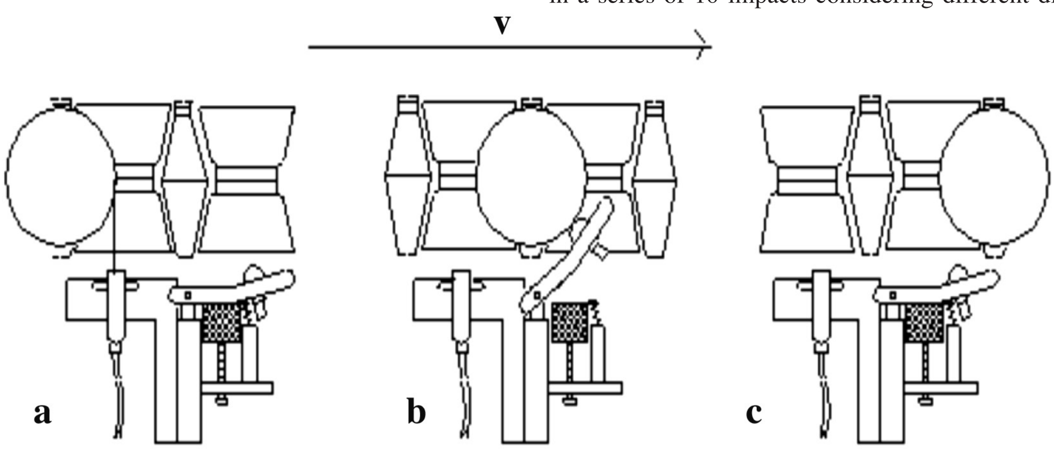


Figure 3. Phases of impact sensor operation: a) fruit detection; b) impact; c) collection by the arm.

between impact arm and ball: 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, and 2 cm.

Once the best distance was established (1.5 cm), a new trial was developed on-line by regulating the mean distance between sensor and fruit at 1.5 cm. A test was carried out with an apple at a velocity of seven fruits per second. The apple was located in three positions: centred on the chain, moved slightly to the right, and moved slightly to the left. Ten measurements were taken with the sensor for each position.

Test 2. The applicability of the sensor to measure firmness on different fruits was analyzed with 'Queencrest' peaches, 'Golden' apples, and 'Comice' pears. Peaches were picked directly from the field and immediately tested. Apples and pears were acquired from wholesalers. Fruits were measured by positioning the fruit axis in the same direction as the sizer chain. Test characteristics are shown in Table 1.

Once tested on-line, each fruit was tested in the laboratory with a Texture Analyzer XT2 (Stable Micro Systems, Godalming, Surrey, UK). For each test, three measurements were taken in the area where the fruit was impacted on the line.

Different indexes of fruit firmness were obtained with tests in laboratory trials that is, Magness-Taylor (MT) with its characteristic indication and non-destructive compression test through a sphere with a 3 N force (CD3N). In this case, the fruit was compressed with a small sphere until reaching a firmness of 3 N, and we calculated the deformation and force/deformation relationship (Homer, 2003).

Data obtained in test 2 were analyzed by discriminant analysis for impact sensor indexes capable of correctly discriminating firmness levels which were established either by laboratory static trials or by commercial considerations. Each model was created with 2/3 of the number of fruits and validated with the remaining 1/3.

Sensor indexes or variables obtained from the acceleration-time curve also used to develop statistical models were: A_{max} (maximum acceleration), t_{Amax} (time until maximum acceleration), t_{inic} (time from arm releasing until contact), t_{imp} (time from impact until maximum acceleration), $Pend_{max}$ (maximum slope), $Pend_m$ (slope to mean point of the curve), and $A_{m/t}$ (acceleration in the middle point of the curve in relation to the time needed to reach this point).

RESULTS AND DISCUSSION

Test 1

The effect of impact distance on maximum acceleration (deceleration) is shown in Figure 5. A significant variation was detected as impact distance to the ball increased. When the distance was greater, an initial and abrupt acceleration increase was registered, followed by a decrease. A good impact distance was around 1.5 cm because acceleration was not affected by small variations in distance (Figure 5).

Results were less variable when using the impact sensor statically in the laboratory than on-line because of the absence of fruit motion. Working on-line, a small variation of sensor regulations varied the moment of impact, and therefore, the observed values. For that reason, values obtained were very sensitive to variations in the shape, impact angle, and curvature radius of the fruit. These variations implied that the photoelectric cell could prompt or delay fruit detection (that would anticipate or delay impact), thus varying the point where the fruit was impacted.

As a consequence of working on-line, it was necessary to adjust the arm for an impact distance of approximately 1.5 cm (Figure 5). Although the sensor was calibrated with an average fruit at this distance, not all the fruits were at the same distance and correctly located where they should have been. Figure 6 shows the

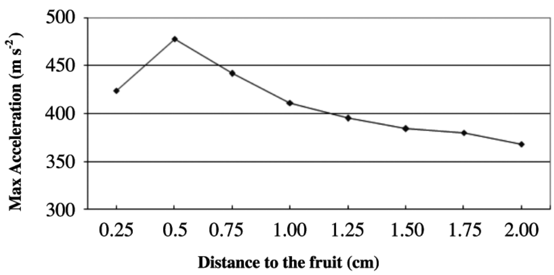
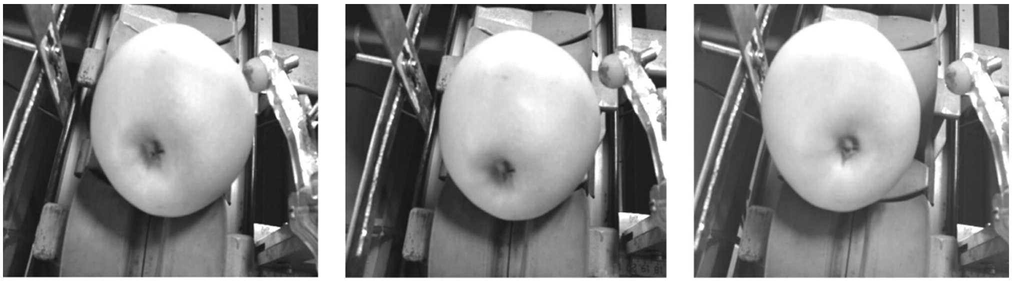


Figure 5. Deceleration variation according to impact distance.

Table 1. Characteristics of Test 2 measurements.

Fruit	Variety	Number of fruits	Number of measurements per fruit (line/laboratory)	Laboratory measurements
Peaches	Queencrest	160	3/3	MT/CD3N
Apples	Golden	110	3/3	MT/CD3N
Pears	Comice	118	3/3	MT/CD3N

MT/CD3N relationship between results of Magness-Taylor (MT) and compression tests through a sphere with a 3 N force (CD3N).



	Mean	SD	Mean	SD	Mean	SD
A_{max}, m s^{-2}	1300.58	16.48	929.41	50.55	713.90	116.35
T_{inic}, ms	59.69	4.26	67.62	2.72	79.87	9.95

SD: standard deviation.

Figure 6. Effect of impact distance on firmness indexes. Mean values for 10 impacts on the same fruit in three chain positions: right, center, and left (A_{max}: maximum acceleration; t_{inic}: impact arm swinging time before contact with the fruit).

effect of positioning the same fruit on the tray during the on-line measurements. For the same fruit, different fruit positioning showed different values of A_{max} associated to different values of t_{inic}.

Figure 7 shows variations of acceleration with regard to time of impact. The curve is smoothed in higher acceleration values (over 1000 m s^{-2}) due to the saturation of the accelerometer signal. Under normal conditions, variations of impact swinging time (time lapse between the start of the arm movement and initial contact with the fruit) varied from 2 to 20 ms when comparing three impacts on each fruit.

It was found that one of the most important parameters affecting the sensor signal was impact arm swing time. Lower accelerations were usually associated to longer times, and by contrast, higher accelerations were usually associated to shorter times. This variation was usually associated to the orientation and positioning of the fruit on the tray. Since standard trays were used, fruits were not located every time at a similar distance from the impact.

We must remember that the test was made on a conveyor consisting of a chain, commonly used in commercial packing lines. In order to correct this fruit positioning problem, some modifications, such as using a guide or redesigning the trays, should be made so that the fruit surface will always be located at the same position on the tray at the time of impact, thus obtaining a similar t_{inic}.

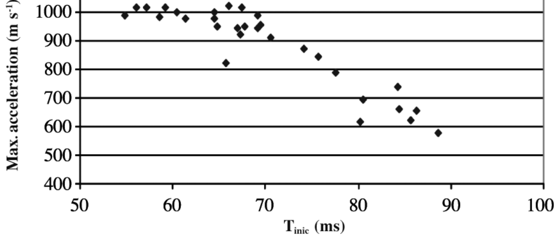


Figure 7. Variations of acceleration and time from arm release until contact (T_{inic}).

Test 2

The Magness Taylor firmness ranges for the different fruits analyzed were the following: peaches from 0.9 to 33 N, apples from 10 to 30 N, and pears from 24 to 46 N.

For this firmness measurement technique, it must be considered that variations in the results between different fruits and different parts of the same fruit can be produced mainly by the non-uniformity of the shape among fruits and the lack of ripeness homogeneity. This implies: variability of force/deformation properties in different areas of the same fruit; variability in the lateral position of fruits which affects the distance of impact; and variations in the time of impact in different detection of the photoelectric cell.

These problems could be solved by making some changes in the line and finding an improved method to position each fruit at the same distance to the impacting head.

The results of an application of an impact sensor are shown in Figure 8 for a group of 45 peaches. When there was a wide range of firmness, a graph showed the relationship between maximum MT Forces (laboratory measurement) and maximum acceleration values (mean values of three impacts on each fruit on-line). Good discrimination was observed in these cases in low ranges of firmness (discrimination of soft fruit < 10 N), but there was a flat tendency in firm fruits, hindering fruit separation in the 20 and 40 N ranges, separation that

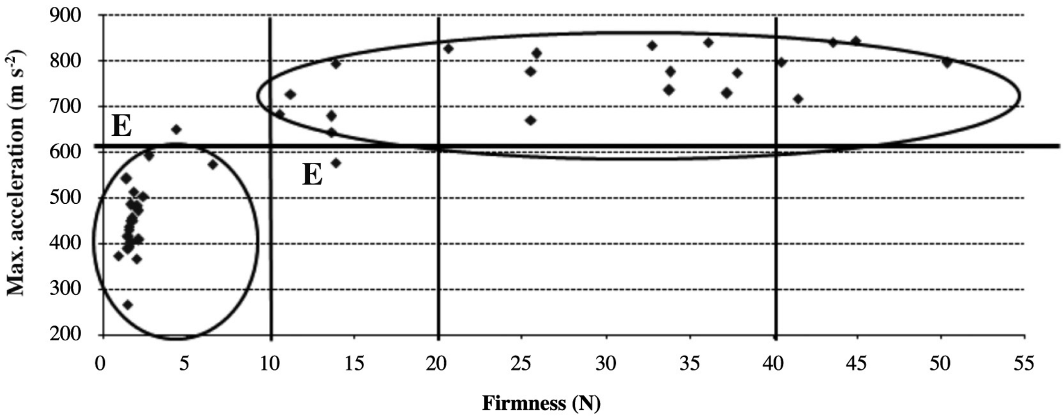


Figure 8. Example test with 45 'Queencrest' peaches showing separation of two firmness groups and two erroneous cases (E).

is a multiple of 10 N defined for soft fruit. There was a good separation between soft fruit and the others (firm), in this case 95% of the fruits were correctly classified (43 correct and 2 erroneous). Vertical lines were theoretical separations at 10, 20, and 40 N. These separations were pre-established by commercial criteria approaches and were not natural sample separations. The thick horizontal line was the chosen acceleration value which enabled the sample to be separated into two groups: below and above 10 N. Encircled data reflect those correctly classified fruits included in each group, whereas those two fruit labeled with an "E" were errors.

It was also observed that, in the case of fruit with similar firmness, between 20 and 40 N for example, correlations decreased and it was not possible to ensure an adequate fruit separation mainly due to saturation of the acceleration signal.

For discriminant analysis, groups were in accordance with the MT instrumental variable, but whenever a good classification was not possible, they were classified according to the slope of the curve of CD3N (PendCD3N) grouping variable. The results analyzed here were focused on the classification of the fruits in two groups of firmness using only one of the three impacts measured online.

The number of impact variables needed to obtain the classification increased when a higher level of correctly classified fruit was required, when the number of impacts could be reduced, and when the instrumental variable was not considered adequate.

For trials carried out with peaches, the best results obtained allowed an adequate classification in two groups of firmness (Table 2) with 88% of correctly classified fruit (133 correct and 17 erroneous). Variables used to classify were A_{max} and t_{inic}.

It was necessary to form groups using the PendCD3N variable for 'Golden' apples (Table 3) due to the low level of correlation between impact variables and MT firmness. A percentage of 84% of correctly classified fruits was obtained.

A threshold value should be defined if this latter variable was considered for classification purposes. For this purpose, the value which divided the PendCD histogram in two halves (same as MT previously) was the threshold value considered.

Variables considered to classify two groups of apples were: A_{max}, t_{inic}, t_{imp}, and $Pend_m$. Results similar (80% of correctly classified) to those with apples were observed with pears (Table 4). Variables considered to classify two groups of apples were: A_{max}, t_{imp}, $Pend_m$, and $A_m/_t$.

Regarding sensor performance, no damage in fruits after sensor impact was observed, nor any influence in the presence or absence of "fluff" in peaches.

In general, the prototype contains a series of variation sources that can be easily amended in a new version. In spite of the variation sources, the impact sensor showed a high potential to carry out a classification of firmness in two or three groups, or to only eliminate some kinds of fruits (e.g. soft fruits).

Table 2. Discriminant analysis of firmness for two groups of 'Queencrest' peaches using force Magness Taylor (MT) as separation parameter for soft fruits.

Rows: Observed classifications
Columns: Predicted classifications

	Percent Correct %	G1 p=0.41	G2 p=0.59	Nº of fruits	MT firmness
G1	92	53	5	58	< 10 N
G2	85	12	80	92	> 10 N
Total	88	75	85	150	

Variables A_{max}, t_{inic}.
Variables: maximum acceleration (A_{max}) and time from arm release until contact (t_{inic}).

Table 3. Discriminant analysis of firmness for two groups of 'Golden' apples using PendCD3N (slope of the curve of force/deformation by applying 3 N compression force with a sphere [CD3N]) as separation parameter.

Rows: Observed classifications
Columns: Predicted classifications

	Percent correct %	G1 p=0.52	G2 p=0.48	Nº of fruits	PendCD (3N) N mm^{-1}
G1	80	45	11	56	< 7.5
G2	87	7	47	64	> 7.5
Total	84	52	58	110	

Variables A_{max}, t_{inic}. t_{imp}, and $Pend_m$.
Variables: maximum acceleration (A_{max}); time from arm release until contact (t_{inic}); time from impact until maximum acceleration (t_{imp}); slope to mean point of the curve ($Pend_m$).

Table 4. Discriminant analysis of firmness for two groups of 'Comice' pears using PendCD3N (slope of curve force/deformation by applying 3 N compression force with a sphere [CD3N]) as separation parameter.

Rows: Observed classifications
Columns: Predicted classifications

	Percent correct %	G1 p=0.50	G2 p=0.50	Nº of fruits	PendCD (3N) N mm^{-1}
G1	76	44	14	58	< 4
G2	83	10	50	60	> 4
Total	80	54	64	118	

Variables $A_{máx}$, t_{imp}, $Pend_m$, and A_m/t.
Variables: maximum acceleration (A_{max}); time from arm release until contact (t_{inic}); time from impact until maximum acceleration (t_{imp}); slope to mean point of the curve ($Pend_m$); acceleration in the middle point of the curve in relation to the time needed to reach this point ($A_{m/t}$).

CONCLUSIONS

The impact distance between fruit and the impacting arm must be set at 1.5 cm to decrease the effect of changes in fruit diameter and orientation.

One of the most important parameters affecting the sensor signal is impact arm swing time (time lapse between the start of the arm movement and initial contact with the fruit). The lowest accelerations are associated to the longest times to impact.

Good discrimination of peaches in two firmness categories was obtained using the Magness Taylor value (MT < 10 N) with 88% of correctly classified fruits.

Using the variable of compression with a sphere and a 3 N fixed force (CD3N), apples and pears can be classified in two groups of firmness with 84 and 80% correctly classified fruit, respectively.

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RESUMEN

Evaluación de un sensor de impacto no-destructivo para la determinación de la firmeza de frutos en líneas de manipulación. Se evaluó un sensor de impacto no destructivo para medir firmeza de frutas en líneas de manipulación. Este sensor es una adaptación de la versión estática utilizada en algunos laboratorios de calidad de frutas, el cual fue modificado e instalado en una línea experimental de manipulación de fruta que contaba con un calibrador comercial. La firmeza de los frutos está relacionada con la curva de aceleración-tiempo que suministra un acelerómetro unido a un brazo que impacta la fruta. El objetivo del presente trabajo fue evaluar funcionamiento y fuentes de variación del sensor. Para ello se realizaron ensayos de clasificación con duraznos (*Prunus persica* (L.) Batsch), manzanas (*Malus domestica* Borkh.), y peras (*Pyrus communis* L.), y ensayos de funcionamiento como pruebas de posicionamiento del fruto, orientación, entre otras. El sensor funciona correctamente a una velocidad de siete frutos por segundo (0,63 m s^{-1}). Este sistema permite la clasificación de la fruta en tres niveles de firmeza, mediante un software específico. Se obtuvo buena discriminación sólo de duraznos blandos con respecto al resto. Se encontraron variaciones entre diferentes frutos y diferentes partes del mismo fruto, debido mayormente a la diferencia de forma y a la poca uniformidad de la madurez en cada uno de los frutos.

Palabras clave: líneas de packing, calidad de fruta, durazno, impacto de baja energía, clasificación.

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