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Non-Destructive Impact Device for Measuring the Flesh Firmness of Peaches

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A low-mass non-destructive impact device was tested and compared with destructive tests to evaluate the firmness of peach [*Prunus persica* (L.) Batsch var. persica]. The tests were carried out on four peach varieties, namely, Royal Glory, Caterina, Tirrenia and Suidring. In the measurements, impact acceleration and contact time were sensed by an accelerometer attached on impact head, and the primitive impact parameters such as maximum acceleration (A_{max}), time required to reach peak acceleration (t_{max}) and contact time during impact ($t_{contact}$) were determined by using impact acceleration-contact time curves. Other parameters were derived by using the theory of elasticity. These non-destructive impact parameters were compared with the destructive reference parameter (Magness-Taylor force). The levels of firmness of the four peach varieties were classified with discriminant analyses based on the primitive impact parameters and their derivatives.

The accuracy of classification was improved with linear discriminant analysis, and the number of parameters being processed was reduced with stepwise regression analysis. The correlations between destructive reference and non-destructive impact parameter test results were statistically significant. Discriminant analysis results showed that the accuracy of classification was 65.40% by the primary impact parameters and 76.50% by all 10 impact parameters.

Results of the four most dominant parameters [$t_{contact}$, $A_{max}^{2.5}$, $A_{max}/(t_{max})^2$, $A_{max}/(t_{contact})^2$] extracted with stepwise regression analysis showed that overall accuracy of classification was improved to 77.90%. Because the four most dominant parameters gave better classification accuracy than the 10 impact parameters, they could be practical in static application using a low-mass lateral impactor. To improve the accuracy of classification, the four impact parameters approach may be adopted for extracting the soft peaches (81.6%) and the primary impact parameters approach for the hard peaches (83.3%).

Key Words: discriminant analysis, impact parameters, Magness-Taylor force, non-destructive, peach

INTRODUCTION

Quality is an increasingly important factor in the production and marketing of fruits and vegetables. Fruits and vegetables, especially those for export, must be of high quality standards in today's modern market (Shmulevich et al. 2003). Firmness, one of the most important quality properties of fruits, can be an indicator of postharvest treatment, storage conditions and shelf-life (Yurtlu 2012).

Different parameters are used to quantify the ripeness of fruits at or near harvest. Flesh firmness is a critical handling parameter for fruits such as peaches, nectarines, kiwis and pears (Garcia-Ramos et al. 2003). From a practical standpoint, peaches and nectarines should be packed at the stage of development which insures acceptable ripening at the terminal market, but they should also be firm enough so as to minimize mechanical damage during packing, storing and shipping (Delwiche et al. 1987). This stage of development is called horticultural maturity in horticultural terminology.

According to Delwiche and Sarig (1991), Rood (1957) evaluated a number of fruit properties as indicators of peach maturity. His study revealed that flesh firmness, as indicated by a Magness-Taylor firmness test, was the best single index of peach maturity, followed by the color of the skin. In a study of clingstone peaches, Slaughter et al. (2006) found that skin color was not a good predictor of flesh firmness. As a result, it can be said that the ability to predict flesh firmness using flesh color is poor. The Magness-Taylor test, a penetration test of destructive nature, represents mechanical properties at the point of measurement only, and is time-consuming. Therefore, this technique is not practical for real-time monitoring when fruits are sorted (Lien et al. 2009).

At present, researchers have tried various non-destructive techniques for sensing fruit firmness such as acoustic, vibration, sonic transmission, ultrasonic

transmission, near-infrared, micro-deformation and impact (Chen 2001). Researchers have shown interest in using impact techniques for predicting firmness of fruits. Previous studies have shown that impact techniques such as impacting of fruits on a load-cell (Delwiche et al. 1987; Delwiche et al. 1989; Gutierrez et al. 2007; Lien et al. 2009; Ragni et al. 2010) and impacting the fruit with a small spherical impactor (Delwiche and Sarig 1991; Delwiche et al. 1996; Chen et al. 2000; Jaren and Garcia-Pardo 2002; Garcia-Ramos et al. 2003; Shmulevich et al. 2003; Diezma-Iglesias et al. 2006; Garcia-Ramos et al. 2005; Homer et al. 2010; Yurtlu 2012) can be used to evaluate the firmness of fruits successfully.

Chen and Ruiz-Altisent (1996) developed a prototype impact system with a low-mass spherical impactor for nondestructive firmness sorting of fruits. Garcia-Ramos (2001) improved this system and used it on an experimental fruit packing line at the Polytechnic University of Madrid. Furthermore, Ortiz-Canavate et al. (2001) adapted a modified version of the low-mass impact method for an experimental fruit packing line with an operation speed of 5–7 fruit s^{-1}. Recently, Homer et al. (2010) used this non-destructive impact sensor to measure on-line fruit firmness by classification trials on three types of fruits (peaches, apples and pears). None of the researchers, however, worked with a low-mass non-destructive impact system that used detailed discriminant analysis method for firmness classification of peaches.

The objectives of the present study were to determine the relationship between the destructive reference parameter (Magness-Taylor force: FMT) and the non-destructive impact parameters [maximum acceleration A_{max}, impact duration until maximum acceleration t_{max}, impact duration during contact $t_{contact}$, A_{max}/t_{max}, $1/t_{max}$, $(1/t_{max})^{2.5}$, $(A_{max}/t_{max})^{1.25}$, $A_{max}^{2.5}$, $A_{max}/(t_{max})^2$, $A_{max}/(t_{contact})^2$], and to investigate an optimum linear combination of the impact variables for firmness classification of four peach varieties (Royal Glory, Caterina, Tirrenia and Suidring) with classification procedure using linear discriminant analysis.

MATERIALS AND METHODS

For non-destructive measurement, a low-mass lateral impact device (LPF-Lateral Impact Sensor 2.0) developed by the Madrid Polytechnic University Physical Properties Laboratory was used. The impact device (Fig. 1) consists of a spherical low-mass of 10 g, which impacts the sample, with a piezoelectric accelerometer with a sensitivity of 1 mV/m s^{-2} and a range of ±4900 m s^{-2} (ENDEVCO model 256-10 USA), which impacts the fruits to sense their firmness; a spring to release the impacting mass; and an electromagnet to hold the impacting mass. A conditioning circuit supplies power to the accelerometer and also amplifies the acceleration signal. Response of the accelerometer is sampled at 40 kHz sampling rate with 12 bit precision DAQ card. A Windows® based software was designed to control all the process which stores data and provides the users with an interface to manage the data and control the measurement process (Diezma-Iglesias et al. 2006).

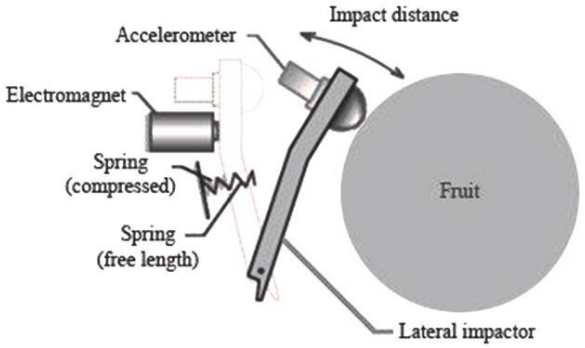


Fig. 1. Schematic drawing of the impact device showing all the main components.

Several variables of the impact sensor signal characterizing the impact such as acceleration versus time, velocity, deformation, energy, force versus deformation, etc. can be obtained by the software. The impactor was held by an electromagnet. It saved potential energy and after releasing, its saved potential energy was modified to kinetic energy during the release and impacted the fruit at a velocity of about 0.265 m s^{-1}. Because the impactor was designed also considering fruit elasticity threshold, low impact forces were composed (about 2–4 N) during the impact on fruit surface, therefore, mechanical damage did not occur on the fruit surface. For this reason, measurements by means of the impactor were named as "nondestructive measurement".

The distance between lateral impactor and peach was fixed at 2 cm as suggested by Diezma-Iglesias et al. (2006). By means of an accelerometer mounted on the impact head, main impact parameters such as maximum acceleration (C_1), measured in m s^{-2}, impact duration until maximum acceleration (C_2) in ms and impact duration (C_3) in ms were extracted from the deceleration data registered by the accelerometer. These parameters are commonly used as fruit firmness index (Chen and Tjan 1998).

Four peach varieties, namely, Royal Glory, Caterina, Tirrenia and Suidring were used during the 2011 summer season. The varieties were supplied from the market in Madrid and were kept under laboratory conditions of about 20 °C during the test period. A total of 136 peach fruits (33 each for Royal Glory and Caterina, 43 for Tirrenia and 27 for Suidring) were considered and selected from the boxes for each variety. One variety was tested every week and tests were done for a total of 4 wk.

The peaches were tested every day for about 5 d during storage at 20 °C room conditions. The tests were done to get a wide range of firmness stage depending on the properties of the varieties for destructive and nondestructive measurements. The samples were tested nondestructively and destructively. For the measurements, two sides of the peaches, considered to be divided by the suture of the fruit, were differentiated into the most

colored side (blush), and the least colored side (non-blush). In all, six measurements for each fruit were taken from three points within the longitudinal axis for two sides of the peach in each test. The non-destructive test points on a peach sample are shown in Figure 2.

The reference destructive tests were conducted to define the ripeness stage of the test samples. The machine used for the reference destructive tests was a Texture analyzer TA-XT2 (Stable Micro Systems Ltd., Godalming, U.K.), a universal machine with a texture analyzer microprocessor, connected to a computer and controlled by specific software. The load-cell admits a maximum force of 250 N (resolution 0.0098 N) and an error range of 0.025%. The texture analyzer was used for the mechanical test to determine the firmness group of the test samples and for comparison with the non-destructive technique. Magness-Taylor tests were performed by using an 8-mm diameter probe, at a deformation rate of 18 mm min^{-1} on both sides of each fruit at six different points (Fig. 2).

Destructive firmness measurements were taken after non-destructive measurements on exactly the same positions as the other measurements. For destructive measurements, on each labeled place, a piece of skin was removed and the Magness-Taylor probe was used to penetrate at least 8 mm into the flesh of the peaches. The force at the maximum point was selected from the force-deformation curve and was expressed as Magness-Taylor force (FMT). Symbols and units belonging to the destructive and non-destructive impact parameters are shown in Table 1.

Based on a study by Timoshenko and Goodier (1951) on the theoretical analysis of the impact, the impact of a low-mass spherically tipped impactor on a fruit can be modeled by the impact of a rigid sphere on an elastic sphere. The magnitude of the peak impact force, F, acting on each body can be expressed as follows:

$$F = \left(\frac{5}{4}\frac{V^2}{n_1}\right)^{3/5} n^{2/5} \quad (1)$$

where V is the relative velocity of approach of both spheres.

$$n_1 = \frac{m_1 + m_2}{m_1 m_2}$$

$$n = \frac{4}{3}\frac{E}{(1-\mu^2)}[r]^{1/2}$$

$$r = \frac{R_1 R_2}{R_1 + R_2}$$

m_1 = mass of the impactor, m_2 = mass of the fruit, R_1 = radius of the impactor's spherical tip, R_2 = radius of curvature of the elastic sphere, μ = Poisson's ratio, and E = modulus of elasticity of the elastic sphere.

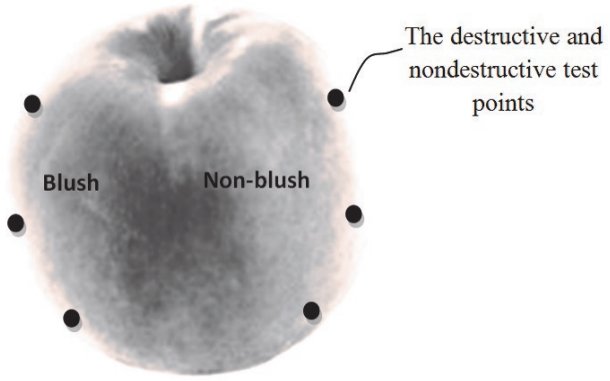


Fig. 2. The destructive and non-destructive test points on a peach sample.

Table 1. Non-destructive impact and destructive reference parameters in the measurement of flesh firmness of peach.

Measurement	Impact Parameter	Symbol	Measurement Unit
Non-destructive	A_{max}	C_1	m/s^2
	t_{max}	C_2	ms
	$t_{contact}$	C_3	ms
	A_{max}/t_{max}	C_4	m/s^3
	$1/t_{max}$	C_5	1/s
	$(1/t_{max})^{2.5}$	C_6	$(1/s)^{2.5}$
	$(A_{max}/t_{max})^{1.25}$	C_7	$(m/s^3)^{1.25}$
	$A_{max}^{2.5}$	C_8	$(m/s^2)^{2.5}$
	$A_{max}/(t_{max})^2$	C_9	$(m/s^2)/s^2$
	$A_{max}/(t_{contact})^2$	C_{10}	$(m/s^2)/s^2$
Destructive		FMT	N

A_{max}: maximum acceleration
FMT: Magness-Taylor force
$t_{contact}$: contact time during impact
t_{max}: time required to reach peak acceleration

In a sample, the impact acceleration-contact time curves for a low-mass impact of a rigid sphere on soft, intermediate and hard peaches are shown in Figure 3. There are clear differences among impact curves (Fig. 3) according to the hardness of the material. The curve of a hard peach has a maximum acceleration and a minimum impact duration, whereas a soft peach shows opposite results. The peak acceleration (C_1) and the ratio of the peak acceleration to the time required to reach the peak acceleration (C_4) have been used as fruit firmness index for impact measurement of fruits by researchers earlier (Delwiche 1987; Chen and Tjan 1998).

The time required to reach peak force can be expressed as follows (Chen et al. 1996):

$$t_{max} = 1.47 D_m / V \quad (2)$$

where D_m, the maximum deformation during contact, is expressed in the equation:

$$D_m = \left(\frac{5}{4}\frac{V^2}{n n_1}\right)^{2/5} \quad (3)$$

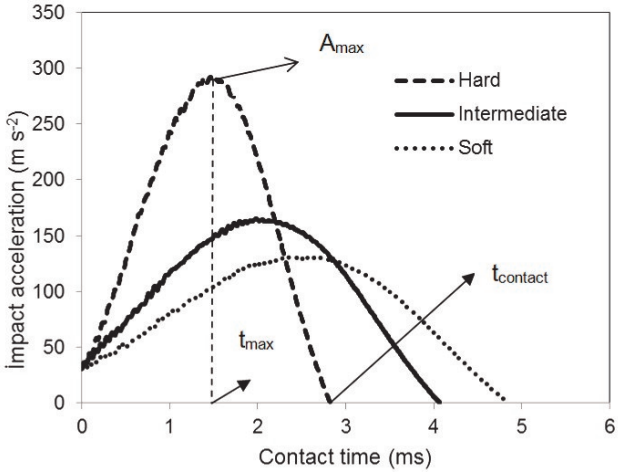


Fig. 3. Different curves obtained by accelerometer attached on impact head at three firmness levels of peach.

The gravitational effect during impact of a low-mass lateral impactor can be neglected, and the relationship between peak acceleration (C_1) of the impactor and the modulus of elasticity (E) of the fruit is given as follows (Slaughter et al. 2009):

$$E = \frac{0.54 m_1 n_1}{V^3} \frac{(1-\mu^2)}{r^{0.5}} A_{max}^{2.5} \quad (4)$$

The modulus of elasticity given in Equation (4) can also be written as functions of time (C_2) required to reach peak acceleration (C_1) as in Equation (5), and the ratio of the peak acceleration to the time required to reach the peak acceleration (C_4) as in Equation (6).

$$E = \frac{2.46}{n_1 V^3} \frac{(1-\mu^2)}{r^{0.5}} \left(\frac{1}{t_{max}} \right)^{2.5} \quad (5)$$

$$E = \frac{1.15 m_1^{1.25} n_1^{0.25}}{V^{1.75}} \frac{(1-\mu^2)}{r^{0.5}} \left(\frac{A_{max}}{t_{max}} \right)^{1.25} \quad (6)$$

where A_{max} is maximum acceleration, and t_{max} is impact duration until maximum acceleration.

The non-destructive impact parameters (Table 1) were derived by using the main impact parameters such as C_1, C_2 and C_3, and the others such as C_6, C_7 and C_8 were taken from equations 4 to 6.

Correlation coefficients between destructive measurement and non-destructive impact parameters for each variety and four varieties together were determined by Pearson Correlation Matrix method.

For the classification procedure, linear discriminant analysis was used to find an optimum linear combination of the independent variables, C_1, C_2, … C_{10}, that minimizes the probability of misclassifying fruits into their respective groups. In this technique, the dependent variable used in the discriminant functions was selected from the stepwise manner, both forward and backward procedures. At each step, the variable that adds most to the separation of the classes is entered into (forward) or the variable that adds least is removed from (backward) the discriminant function. All pooled data (four varieties together) were taken into consideration for the discriminant analysis. SPSS 16.0 for Windows was used for all data analysis.

The test to evaluate potential bruising of the peaches due to the impact device was conducted. Four peach varieties were checked visually at the impact point after 1 d of storage at 20 °C. Furthermore, to validate the non-destructiveness of the low-mass impact system, deformation-contact time curves obtained for each of the firmness levels were used to find permanent deformations that occurred at the impact point of the peaches. To obtain the deformation values, a Windows-based software and interface was used. After the impact process, the software gave direct information about acceleration, velocity, deformation, impact energy, impact force and contact time values. Deformation-contact time data were taken from the files directly by using Microsoft Excel and the deformation-contact time curves were created to find permanent deformation.

RESULTS AND DISCUSSION

The correlation coefficients of the non-destructive impact parameters and the Magness-Taylor force were significant at the 1% and 5% levels, respectively (Table 2). Using all pooled data as an example, the Magness-Taylor force of the peach was closely related to C_8, but less associated with C_2. Further, the best non-destructive impact parameters to estimate the Magness-Taylor force of the peach varieties were found to be C_8 and C_{10} for Royal Glory, C_8 for Caterina, C_{10} for Tirrenia and C_8 for Suidring. Based on the results obtained in Table 2, the model based on equation 4 using C_8 gave the best performance for peach varieties Royal Glory, Caterina, Tirrenia and Suidring with correlation coefficients of r = 0.67, 0.86, 0.69 and 0.87, respectively.

Shmulevich et al. (2003) reported that the impact parameters C_4 and C_9 failed to predict the Magness-Taylor force in the apple cultivars Starking Delicious and Granny Smith because of their non-uniform shape and the sensitivity of these empirical parameters to test conditions. In their report, both impact parameters C_4 and C_9 did not correlate well (0.12 and 0.27 for Starking Delicious, 0.26 and 0.32 for Granny Smith). These reported findings might indicate that the Magness-Taylor force is not an appropriate measure of apple firmness during shelf-life. In our study, better correlations were found between the Magness-Taylor force (FMT) and the non-destructive impact parameters C_4 (r = 0.66) and C_9 (r = 0.68) for all pooled data. Furthermore, C_1, C_7 and C_{10} also correlated well with the Magness-Taylor force for the four peach varieties.

For the analysis, the peaches were segregated into three classes using previously established firmness

Table 2. Correlation coefficients (r) between Magness-Taylor force (FMT) and non-destructive impact parameters in the measurement of flesh firmness of peach.

Variety	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
All pooled data	0.69**	-0.43**	-0.51**	0.66**	0.49**	0.53**	0.68**	0.75**	0.68**	0.73**
Royal Glory	0.64**	-0.37*	-0.54**	0.57**	0.38*	0.38*	0.58**	0.67**	0.64**	0.67**
Caterina	0.82**	-0.65**	-0.73**	0.82**	0.71**	0.75**	0.83**	0.86**	0.82**	0.85**
Tirrenia	0.69**	-0.60**	-0.63**	0.67**	0.60**	0.59**	0.67**	0.69**	0.69**	0.70**
Suidring	0.86**	-0.69**	-0.77**	0.83**	0.71**	0.72**	0.83**	0.87**	0.86**	0.86**

C_1: maximum acceleration, m s^{-2}; C_2: impact duration until maximum acceleration, ms; C_3: impact duration, ms; C_4: ratio of the peak acceleration to the time required to reach the peak acceleration; C_5: $1/t_{max}$; C_6: $(1/t_{max})^{2.5}$; C_7: $(A_{max}/t_{max})^{1.25}$; C_8: $A_{max}^{2.5}$; C_9: $A_{max}/(t_{max})^2$; C_{10}: $A_{max}/(t_{contact})^2$
A_{max}: maximum acceleration, $t_{contact}$: contact time during impact, t_{max}: time required to reach peak acceleration
**Correlation is significant at the 0.01 level. *Correlation is significant at the 0.05 level.

criteria, prior to classification analysis. The firmness threshold defining these classes was chosen based on previous work that described bruising threshold. For the four peach varieties, a three-group firmness classification was created by using 18–35 N Magness-Taylor force threshold. Therefore, peach between 18–35 N was considered "intermediate". The peach below 18 N and above 35 N was defined to be "soft" and "hard", respectively. These firmness thresholds were selected because of critical changes in peaches during postharvest ripening and their susceptibility to bruising damage (Crisosto et al. 2001; 2004; Valero et al. 2007).

Table 3 gives the mean Magness-Taylor forces, quantity and standard deviation values in three firmness groups of the four peach varieties. The sample size tested was 136 peaches. Mean destructive reference FMT values were 6.13, 22.83 and 50.67 N with a standard deviation of 4.61, 4.67 and 8.31 N for soft, intermediate and hard firmness groups, respectively. The numbers of fruits tested in our study for soft, intermediate and hard firmness groups were 103, 21 and 12, respectively. It is important to consider that the big difference in the numbers of samples among the three firmness groups and the small numbers of intermediate and hard peaches will impair the overall accuracy and reliability of firmness classification in the discriminant analysis.

The impact parameters C_1, C_2 and C_3 gave direct information about the firmness of peach. The measurements of the impact responses to three firmness groups for four peach varieties are summarized in Table 4. The difference among the three firmness groups on an impact parameter was analyzed by using the Scheffê test with a significant difference of $P<0.05$. The C_1 impact parameter had a significant difference among the three firmness groups. The C_2 impact parameter did not have a significant difference between the soft and the intermediate firmness groups, but it signified the hard group among the peach samples. This result means that the C_2 impact parameter failed to distinguish these two groups. Total contact time C_3 signified the difference between any two groups as in the C_1 impact parameter. Therefore, C_3 can be used as an effective indicator of firmness because the soft peach is less firm than the intermediate and the hard peaches, resulting in prolonged total contact time in the soft peaches.

Results of the discriminant analysis of the primitive impact parameters are given in Table 5. The C_1 impact parameter performed well in identifying the levels of firmness obtained for the soft and the hard peaches, but not in identifying the intermediate firmness level. The C_2 impact parameter was poor for the soft and the intermediate firmness groups but quite promising for the hard peaches. Same trend was also observed for the C_3 impact parameter, but it had poorer peach classification in the intermediate firmness level than in the hard firmness level. The best result was found for hard peach classification at 83.30%. Though the C_3 impact parameter had significantly different mean values between any two firmness levels, its accuracy was not better compared with use of the C_1 impact parameter. This performance using the primitive impact parameters gave the best accuracy of 60%, which is less than 75%, and is therefore considered too poor to be applicable (Gutierrez et al. 2007; Lien et al. 2009).

The levels of accuracy of using the three primitive impact measurement parameters through discriminant analysis are given in Table 6. The result is improved (65.40% well classified) compared with Table 5 (60% well classified) but because it is still less than 75%, and it may be considered too poor to be applicable.

To improve the accuracy obtained for the three primitive impact parameters, linear discriminant analysis (LDA) was applied to all impact parameters including the primitive and the derived. The results showed that accuracy was improved from 65.40% to 76.50% (Table 7). The worst performance occurred by incorrectly identifying 28.60% of the intermediate peaches as soft.

The use of the 10 impact measurement parameters can be complicated in real-time application in relation to numerical and logical processing. Therefore, to reduce the number of impact parameters, stepwise regression analysis was used to find out the most significant parameters in classification. The results of stepwise regression analysis showed that C_3, C_8, C_9 and C_{10} were the four most dominant parameters with analytical results given in Table 8.

Table 9 shows the levels of accuracy of classification using discriminant analysis of impact parameters C_3, C_8, C_9 and C_{10}. It gave a whole accuracy of 77.90%. In this case, it can be said that the use of the four impact parameters extracted by the stepwise analysis is practical in real-time application because of higher overall accuracy. To improve the overall accuracy of classification, the four impact parameters approach can be adopted for extracting the soft peaches and the primary impact parameters approach C_1, C_2 and C_3 (as given in Table 6) for the hard peach groups.

Table 3. Magness-Taylor forces (FMT) in three firmness groups of four peach varieties.

Firmness Group	Quantity	Magness-Taylor Force (N)	
		Mean	SD ±
FMT<18 N (Soft)	103	6.13	4.61
18N<FMT<35N (Intermediate)	21	22.83	4.67
FMT>35N (Hard)	12	50.67	8.31

Table 4. Measurements of impact responses to various firmness groups for four peach varieties.

Parameters	Class of Origin		
	Soft (103 pcs)	Intermediate (21 pcs)	Hard (12 pcs)
C_1	202.86 ± 35.71[a]	226.19 ± 48.27[b]	287.56 ± 67[c]
C_2	1.68 ± 0.19[a]	1.63 ± 0.22[a]	1.46 ± 0.31[b]
C_3	3.48 ± 0.36[a]	3.36 ± 0.45[b]	2.98 ± 0.6[c]

C_1: maximum acceleration, m s^{-2}; C_2: impact duration until maximum acceleration, ms; C_3: impact duration, ms
Values are mean ± SD. In the same row, values with different superscripts are significantly different (P<0.05) by Scheffé test.

Table 5. Accuracy of peach classification based on primitive impact parameters.

Parameters	Class of Test Response			Total	Accuracy (%)
	Soft (103)	Intermediate (21)	Hard (12)		
C_1	64 (62.1)[b]	7 (33.3)	10 (83.3)	81	60%[a]
C_2	50 (48.5)	2 (9.5)	10 (83.3)	62	46%
C_3	55 (53.4)	4 (19.0)	10 (83.3)	69	51%

C_1: maximum acceleration, m s^{-2}; C_2: impact duration until maximum acceleration, ms; C_3: impact duration, ms
[a]Best accuracy is 60% = (64 + 7 + 10)/136 × 100, i.e., 60% well classified.
[b]Value in parentheses presents the best response as a quantity percentage of the original class.

Table 6. Accuracy of peach classification using discriminant analysis of primary impact parameters A_{max}, t_{max} and $t_{contact}$.

Class of Origin	Class of Test Response			Total
	Soft	Intermediate	Hard	
Soft	67[a] (65.00)[b]	33 (32.00)	3 (2.90)	103
Intermediate	7 (33.30)	12[a] (57.10)	2 (9.50)	21
Hard	1 (8.30)	1 (8.30)	10[a] (83.30)	12

A_{max}: maximum acceleration, $t_{contact}$: contact time during impact, t_{max}: time required to reach peak acceleration
[a]Overall accuracy is 65.4% = (67 + 12 + 10)/136 × 100, i.e., 65.4% well classified.
[b]Value in parentheses presents the test response as a quantity percentage of the original class.

Table 7. Accuracy of peach classification using discriminant analysis of all impact indices C_1, C_2, C_3, C_4, C_5, C_6, C_7, C_8, C_9 and C_{10}.

Class of Origin	Class of Test Response			Total
	Soft	Intermediate	Hard	
Soft	82[a] (79.6)[b]	19 (18.4)	2 (1.9)	103
Intermediate	6 (28.6)	13[a] (61.9)	2[a] (9.5)	21
Hard	1 (8.3)	2 (16.7)	9 (75.0)	12

C_1: maximum acceleration, m s^{-2}; C_2: impact duration until maximum acceleration, ms; C_3: impact duration, ms; C_4: ratio of the peak acceleration to the time required to reach the peak acceleration; C_5: $1/t_{max}$; C_6: $(1/t_{max})^{2.5}$; C_7: $(A_{max}/t_{max})^{1.25}$; C_8: $A_{max}^{2.5}$; C_9: $A_{max}/(t_{max})^2$; C_{10}: $A_{max}/(t_{contact})^2$
A_{max}: maximum acceleration, $t_{contact}$: contact time during impact, t_{max}: time required to reach peak acceleration
[a]Overall accuracy is 76.5% = (82 + 13 + 9)/136 × 100, i.e., 76.5% well classified.
[b]Value in parentheses presents the test response as a quantity percentage of the original class.

Table 8. Statistics of the most significant impact parameters by stepwise regression analysis.

Parameters	Partial R-square	F Value	Pro.>F
C_3	-0.895	20.287	<0.0000
C_8	1	35.099	0.0000
C_9	0.980	25.885	0.0000
C_{10}	0.991	18.700	0.0000

C_3: impact duration, ms; C_8: $A_{max}^{2.5}$; C_9: $A_{max}/(t_{max})^2$; C_{10}: $A_{max}/(t_{contact})^2$
A_{max}: maximum acceleration, $t_{contact}$: contact time during impact, t_{max}: time required to reach peak acceleration

Table 9. Accuracy of peach classification using discriminant analysis of impact parameters C_3, C_8, C_9 and C_{10}.

Class of Origin	Class of Test Response			Total
	Soft	Intermediate	Hard	
Soft	84[a] (81.6)[b]	17 (16.5)	2 (1,9)	103
Intermediate	6 (28.6)	13[a] (61,9)	2 (9,5)	21
Hard	1 (8.3)	2 (16,7)	9[a] (75,0)	12

C_3: impact duration, ms; C_8: $A_{max}^{2.5}$; C_9: $A_{max}/(t_{max})^2$; C_{10}: $A_{max}/(t_{contact})^2$
A_{max}: maximum acceleration, $t_{contact}$: contact time during impact, t_{max}: time required to reach peak acceleration
[a]Overall accuracy is 77.9% = (84 +13 + 9)/136 × 100, i.e., 77.9% well classified.
[b]Value in parentheses presents the test response as a quantity percentage of the original class.

Occurrence of potential bruising in the peaches due to impact device was evaluated by visual inspection and mechanical analysis. After impact, the impact region of the peach samples was checked visually. In addition, deformation-contact time curves obtained for each firmness level were evaluated by investigating the permanent deformation points.

Figure 4 shows the deformation-contact time curves of various firmness levels of peaches. Mean values of four peach varieties for each firmness level were used in the curve. The permanent deformation values of soft, intermediate and hard peaches are 0.51, 0.22 and 0.02 mm, respectively. Even though all the peaches exhibited inelastic deformation at the time of impact, they did not develop bruising except in some soft peaches. It can be due to elastic recovery potential of peach impact surfaces with time. This situation was also supported by our visual inspection. Hence, using the non-destructive impact device for firmness classification could be a risk especially for the occurrence of potential bruising in soft peaches.

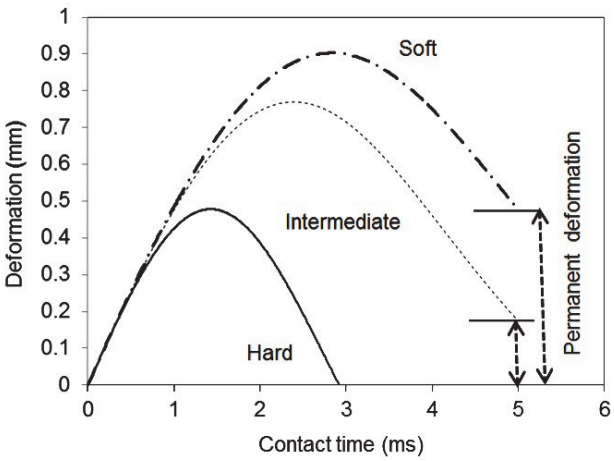


Fig. 4. Deformation-contact time curves at three firmness levels of peach.

CONCLUSION

Four peach varieties, namely, Royal Glory, Caterina, Tirrenia and Suidring were tested under laboratory conditions by using a low-mass impact response method to evaluate non-destructively the firmness of peach tissue. The low-mass impact method is practicable in firmness measurement, and therefore, in the classification of the level of firmness into hard, intermediate and soft. This technique does not damage the peaches except in some soft samples. This non-destructiveness was revealed by using the permanent deformation values that do not exceed the elastic limit of peaches. The conventional impact parameters C_1, C_2 and C_3 did not give substantial information about the classification of peach firmness. The classification accuracy was improved by the 10 impact parameters instead of the three primitive impact measurements using discriminant analysis.

The accuracy was improved from 65.40% to 76.50%. Stepwise regression analysis of the 10 impact parameters gave only four most dominant parameters, i.e., C_3, C_8, C_9 and C_{10}. This simplification reduced the complexity of numerical analysis and increased the overall accuracy from 76.50% to 77.90%. Because an accuracy of classification better than 75% is good enough for practical application, this technique encourages the use of a low-mass impact technique in the on-line firmness sorter of peaches.

To improve the overall accuracy of classification, the 10 impact parameters approach can be used for extracting the soft peaches (79.60%) and the primary impact parameters approach for the hard peach groups (83.30%). Furthermore, the four impact parameters approach obtained using stepwise regression analysis can be used for extracting the soft peaches (81.60%) and the hard peach groups (75.00%). Although this study focuses on the classification of peach firmness, similar studies should also be performed for other fruits by using the same approach of linear discriminant analysis and stepwise regression analysis.

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