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Modeling of impact parameters for nondestructive evaluation of firmness of greenhouse tomatoes

K.K. Vursavus[1,*] and Z. Kesilmis[2]

[1]University of Çukurova, Faculty of Agriculture, Department of Agricultural Machinery and Technologies Engineering, 01330 Adana, Turkey
[2]University of Osmaniye Korkut Ata, Faculty of Engineering, Department of Electrical and Electronics Engineering, Karacaoglan Campus, Fakiusagi, Osmaniye-Turkey
[*]Correspondence: kuvursa@cu.edu.tr

Abstract. In this research, the potential of a nondestructive method for predicting firmness using impact parameters taken by a low-mass lateral impact device was explored. The tests were carried out on *Bandita F1* greenhouse tomato variety at different maturity stages. In the nondestructive impact measurements, impact acceleration and contact time were sensed by an accelerometer attached on impact head, and main impact parameters such as maximum impact acceleration (A), time required to reach maximum acceleration (t) and contact time (t_c) were extracted from the impact acceleration-contact time curves. Other impact parameters were derived through the theory of elasticity. These nondestructive impact parameters were compared with destructive reference parameters for predicting firmness of tomatoes. Force-deformation ratio at rupture point was used in the measurements of destructive reference parameter and this was expressed to be tomato firmness. A total of 10 (A, t, t_c, A/t, A/t_c, A/t^2, A/t_c^2, $(1/t)^{2.5}$, $(A/t)^{1.25}$, $A^{2.5}$) measured and derived impact parameters were analyzed with the destructive reference test. A correlation matrix, stepwise regression and multiple linear regression were used for statistically evaluation. The effect of maturity stages on firmness and impact parameters was investigated by ANOVA test. Statistical analysis showed that the correlations between destructive reference and nondestructive impact parameter test results were significant at 1% level except t and $(1/t)^{2.5}$. The number of parameters being processed was reduced with stepwise regression analysis. The best model using MLR on variables A/t, A/t_c^2, and $A^{2.5}$ was selected for predicting tomato firmness. As a result, low-mass impact device tested in the laboratory conditions gave high prediction of firmness for greenhouse tomato.

Key words: greenhouse tomato, nondestructive low-mass impact device, tomato firmness, impact parameters, multiple linear regression.

INTRODUCTION

For fresh tomatoes, the two quality attributes that are most important to buyers and consumers are texture and skin color (Batu, 2004). Texture is influenced by flesh firmness and skin strength. Softening during storage, distribution and ripening of tomatoes can be a major problem because of the susceptibility to bruise damage. The loss of fruit firmness is a physiological process that occurs during fruit maturation/ripening on the tree, during cold storage and retail handling (Valero et al., 2007). The firmness of a fruit is an index of the mechanical, chemical and rheological properties of the fruit. It is negatively proportional to the maturity of the fruit, and can therefore be used as an alternative indicator to maturity in fruit grading and sorting (Lien et al., 2009).

Magness-Taylor test, which is called as destructive measurement is a classical method and commonly used for measuring the fruit flesh firmness. This test is conducted by handheld penetrometer or a PC controlled material test device that records the force required to puncture the flesh with a cylindrical probe of fixed diameter and tip geometry. Destructive reference test measures the mechanical attitudes of fruits under the static loading.

At present, some nondestructive techniques such as acoustic, ultrasonic, vibration, micro-deformation, impact and near infrared (NIR) were applied to many fruits and vegetables to evaluate the texture quality (Sirisomboon, 2012). According to these nondestructive detection methods, some commercial firmness sorting device (bench top) or systems (in-line) have been using in practice (Garcia-Ramos et al., 2003).

The firmness of fruits and vegetables is usually managed by the workers in the field through a destructive sampling on several lots: during the conferring of goods, the pre-stocking, the post-stocking, the packaging and before delivery. All these stages need a rather long time and a large waste of fruits; moreover they are not always homogenous. Instead of destructive firmness measurement, nondestructive techniques can satisfy easy and quick use of the system, customers can test bigger sampling within the same lot. This system also avoids the variability that can be caused by manual labor of workers. The nondestructive systems make use of the sensor technology and they can be assembled on existing packing lines. Plocharski & Konopacka (2003) was developed a method based on the measurement of the plums, using a cylindrical probe and a force of 1 N. This method was extremely sensitive and was fully non-destructive. Although this method was non-destructive it was not adopted to a firmness sorting systems because of using the Universal Testing Machine. Previous studies carried out by different researchers show that the nondestructive impact techniques can be used to evaluate firmness of fruits and vegetables successfully (Nahir et al., 1986; Delwiche et al., 1987; Garcia-Ramos et al., 1988; Chen & Ruiz-Altisent, 1993; Diezma-Iglesias et al., 2006; Lien et al., 2009; Ragni et al., 2010).

Two different methods based on theory of elasticity have been used to measure fruit firmness using the nondestructive impact technique. The first one is the force response of an elastic sphere impacting on a rigid surface. A problem inherent to the technique of dropping the fruit on a force sensor is that the impact force is also a function of the mass and radius of curvature of the fruit. Therefore, a large variation in these two parameters will affect the accuracy in firmness measurement (Chen et al., 1996). The second one is to impact the fruit with a small spherical impactor of known mass and radius of curvature and measure the acceleration of the impactor. The advantage of this method is that the measured impact acceleration response is independent of the fruit mass and is less sensitive to the variation of the radius of curvature of the fruit. Many researchers have studied on the impact of fruit nondestructively on a force sensor. Nahir et al. (1986) reported that impact force magnitude substantially is related with fruit mass and fruit firmness in the case of dropping tomato from a 70 mm height on a rigid surface. Delwiche et al. (1987) analyzed impact force response of peach samples striking a rigid surface and found that impact force parameters were closely related with the fruit's modulus of elasticity and fruit flesh firmness. Lien et al. (2009) used nondestructive impact technique to determine tomato ripeness. They reported that maximum impact force, impact time and fruit mass was related highly with Magness-Taylor force of tomato dropped on a force sensor with a classification precision of 82.30%. Ragni et al. (2010) for kiwi and Gutierrez et al. (2007) for peach also reported successfully nondestructive firmness sorting based on the analysis of fruit impact on a load cell in pre-commercial sorting line.

Chen et al. (1985) first described the impact technique with a small spherical impactor to the fruit, and this technique was used by researchers in Spain for sensing fruit firmness. Further versions have been developed at the Physical Properties Laboratory (LPF) to obtain systems with better data resolution, signal-noise ratio and precision (Diezma et al., 2000). Thereafter, Garcia-Ramos et al. (2003) modified and adapted this lateral impact sensor to a prototype impact system for evaluating on-line firmness sorting of fruits. Dieazma-Iglesias et al. (2006) estimated peach firmness by using nondestructive impact and acoustic tests. For impact and acoustic tests, low-mass lateral impactor developed by researchers was used in their laboratory. As well as using these techniques for determining fruit firmness, some researchers used this technique as a reference test for monitoring fruit ripeness with different methods. For instance, Ruiz-Altisent et al. (2006) studied the feasibility of using nondestructive information such as optical reflectance combined with contact firmness to estimate ripeness and consumers acceptability of peaches at harvest site. Also, Herrero-Langreo et al. (2011) studied spectral machine vision for peach ripeness assessment at harvest and post-harvest, and used Magness-Taylor penetrometry firmness and low-mass impact firmness as a reference measurement.

The objectives of the present research were to determine the relationship between tomato firmness and nondestructive impact parameters, to develop the calibration equation with multiple linear regression using impact parameters and, to explore the potential of prediction of the tomato firmness nondestructively using low-mass impact device.

MATERIALS AND METHODS

Fresh greenhouse tomatoes (*Bandita F1*) that were sorted by color and size, free from disease and injury, and uniform in shape were harvested by hand from a commercial greenhouse in 2014 season.

Color measurements were performed using Minolta CR-400 colorimeter; four replicates in the equatorial region were taken on each intact tomato. The L*, a* and b* values were obtained directly, and were used to calculate the a*/b* ratio. Average readings at four pre-determined points on the circumference of the fruits were recorded. The instrument was calibrated against a standard white color Plate (Y = 93.5, x = 0.3114, y = 0.3190). In a Minolta chromometer, the a* value corresponds to the degree of redness whereas the b* value represents yellowness. In this research, redness values of tomatoes were recorded as a*/b* values due to the convention of recording tomatoes redness values as a*/b* in the Hunter system for many years (Batu, 2004). Table 1 shows the relationship between the a*/b* ratio and maturity stages of tomatoes.

Table 1. a*/b* values used for maturity classification of tomatoes (Batu, 2004)

Maturity stage	a*/b*
Mature green	-0.59<a*/b*≤-0.47
Breaking	-0.47< a*/b*≤-0.27
Turning	-0.27< a*/b*≤0.08
Pink	0.08< a*/b*≤0.60
Light red	0.60< a*/b*≤0.95
Red	a*/b*>0.95

Tomatoes were classified at six different maturity stages (mature green, breaking, turning, pink, light red and red) according to the a*/b* ratio recommended by Batu (2004).Tomatoes at six maturity stages were used for getting a wide range of firmness stage depending on the maturity properties for destructive and nondestructive measurements. Three major dimensions of tomato fruits were illustrated in Fig. 1.

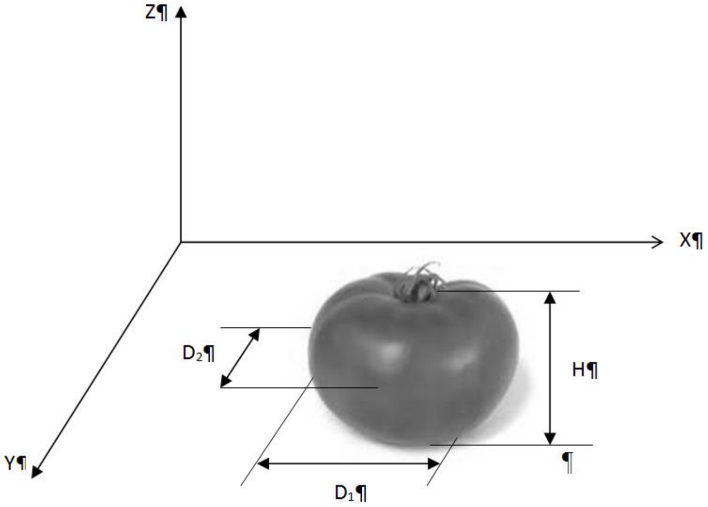

Figure 1. Three major dimensions of tomato: D1, Equatorial diameter; D2, Thickness; H, Height.

A nondestructive low-mass lateral impact device, which is similar to test device developed by Chen & Ruiz-Altisent (1996) have been manufactured and used in the experiment. the nondestructive lateral low-mass impact device showing all the main components was given in Fig. 2. It consists of a spherical low-mass of 26 g, which impacts the sample, with a piezoelectric accelerometer of a mass of 1.5g, sensitivity of 1.063 mV m^{-1} s^{2} and a range of ± 4,900 m s^{-2} (DeltaTron® Accelerometer Type 4516 manufactured by Bruel&Kjaer), which impacts the fruits to sense its firmness; a spring to release the impacting mass; and an electromagnet to hold the impacting mass. Radius of curvature of the semi-spherical impacting mass was designed to be 25 mm as suggested by Van Linden et al. (2006).

At the impactor was held by an electromagnet, it saved potential energy and after releasing, its saved potential energy modified to kinetic energy during the releasing and impacted to tomato samples with a velocity of about 0.28 m s^{-1}. Furthermore, impact energy of the lateral impactor during the impact process was calculated to be 1.02 mJ. Due to impactor was designed also considering fruit elasticity threshold, low impact forces were composed (about 2–4 N) during the impact on fruit surface and thus mechanical damage did not occur on the tomato surface. For this reason, measurements by means of impactor were named as ‘nondestructive measurement’. The distance between lateral impactor and peach was fixed at 2 cm as suggested by Vursavus et al. (2015). A conditioning circuit (Model 4102C, DYTRAN) supplies power to the accelerometer and also amplifies the acceleration signal. Response of the accelerometer was sampled at 100 kHz sampling rate with 16 bit precision NI 6221PCI DAQ card. A MATLAB 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. Impact acceleration, impact velocity and deformation–contact time curves could be monitored graphically in MATLAB software interface. By means of an accelerometer mounted on impact head, main impact parameters such as maximum acceleration (A), measured in m s^{-2}, impact duration until maximum acceleration (t) in ms and impact duration (t_c) in ms were extracted from the deceleration data registered by the accelerometer. These parameters are commonly used as fruit firmness index (Chen & Tjan, 1998). Totally, ten nondestructive impact parameters (A, t, t_c, A/t, A/t_c, A/t^2, A/t_c^2, $(1/t)^{2.5}$, $(A/t)^{1.25}$, $A^{2.5}$) were used and, $A^{2.5}$, $(A/t)^{1.25}$ and $(1/t)^{2.5}$ were derived by using the theory of elasticity as suggested by Slaughter et al. (2009) and Vursavus et al. (2015) from the main impact parameters such as A, t and t_c for modeling of these impact parameters for nondestructive evaluation of firmness of tomatoes. In this study, four replicates in the equatorial region were taken on each intact tomato for nondestructive impact measurements at the same points of the color measurements.

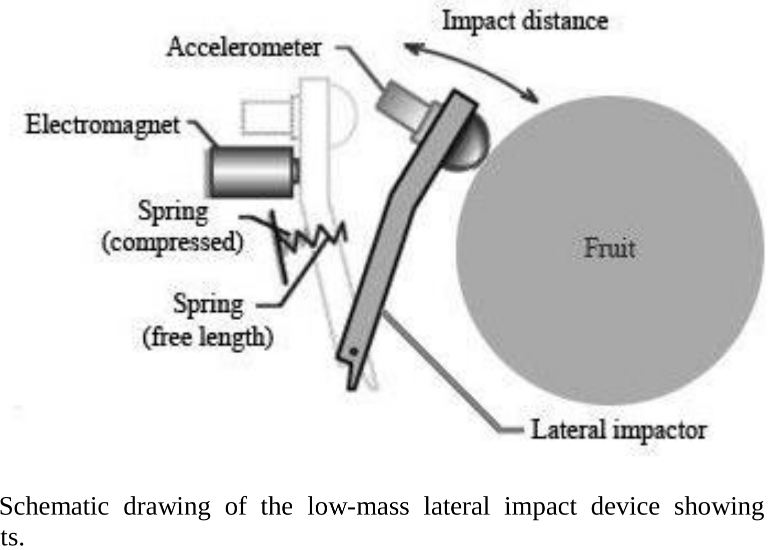

Figure 2. Schematic drawing of the low-mass lateral impact device showing all the main components.

The reference destructive tests were conducted to define the firmness stage of tomato samples. Lloyd Testing Machine (Model LRX Plus Series) was used for the mechanical test to determine the firmness group of the test samples and, to compare with the nondestructive impact parameters. Puncture test was performed by using a flat ended probe with 4 mm diameter, at a deformation rate of 10 mm min^{-1} at four equatorial region of each tomato fruit. The load-cell admits a maximum force of 5,000 N (resolution 0.005 N) and an error range of 0.03%. Destructive firmness measurements were taken after nondestructive measurements on exactly the same points as the other measurements. For destructive measurements, on each labeled place, puncture probe penetrated at least 11 mm into the flesh. Force-deformation ratio at maximum point was selected from the force-deformation curve and expressed to be tomato firmness in N mm^{-1} (F_T).

A correlation matrix, which gives the correlations between pairs of these ten variables was obtained. Stepwise regression analysis was made on all the impact parameters in order to identity those variables (independent variables) which could be used to predict tomato firmness (dependent variable). After the independent variables were selected, multiple linear regression (MLR) was used to determine the linear relationship of selected parameters to tomato firmness. The average value of each tomato was determined, and the fruit were randomly segregated into calibration and validation sets, with 52 tomatoes in the calibration set and 36 tomatoes in the validation set. The calibration set was used for model development, and the fruit from the validation set were reserved for model testing. MLR analyses were conducted using SPSS Statistics 20 in order to evaluate tomato firmness models. The data recorded in the test conditions were statistically analysed using one way ANOVA to study the effect of tomato maturity stages on tomato firmness and main impact parameters. DUNCAN’s multiple range test was used to compare the means.

A total of 88 whole tomato samples were used in the experiments. Four replicates in the equatorial region were taken on each intact tomato. These four data were then averaged for color, nondestructive and destructive tests. Totally, 352 (88 x 4) measurements were recorded in order to use in the statistical analysis.

RESULTS AND DISCUSSION

The effect of tomato maturity stages on tomato firmness and main impact parameters was determined using one way ANOVA test. As seen in Table 2, tomato firmness decreased from 3.58–1.23 N mm^{-1} significantly during tomato ripening ($P < 0.01$). This implies the softening of the tomato fruit. According to DUNCAN’s multiple range test results, tomato firmness in the light red and red stages was not significantly different ($\alpha = 0.05$). Same trend was also observed in the study conducted by Sirisomboon et al. (2012). The main impact parameters A, t and t_c give direct information about the firmness of tomato. The effect of maturity stages on A and t_c was found to be statistically significant ($P < 0.01$). This effect was not significant for t parameter. These results showed that A and t_c impact parameters were sensitive parameters related to maturity stages. As seen in Table 2, there are clear differences among impact parameters A and t_c according to maturity stages or fruit softening. Hard mature tomato has a maximum acceleration and minimum impact duration, whereas a soft red tomato shows opposite results. Furthermore, the t_c can also be used as an effective indicator of firmness. This occurrence comes from that the soft tomatoes (light red and red stages) has a much less firmness than the intermediate (turning or pink stages) and the hard tomatoes (mature green and breaking stages). Hence, this leads to a prolonged total contact time in the soft peaches. As a sample, impact acceleration-contact time curve for a low-mass impact of a rigid sphere on mature green, pink and red tomato samples is shown in Fig. 3.

Table 2. Measurements of firmness and main impact parameters to six maturity stages for Bandita F1 tomato varieties

Para-meters	Maturity stages					
	Mature green	Breaking	Turning	Pink	Light red	Red
F_T	3.58 ± 0.10^a	2.91 ± 0.15^b	2.21 ± 0.13^c	1.72 ± 0.08^d	1.36 ± 0.11^e	1.23 ± 0.08^e
A	377.27 ± 27.93^a	355.35 ± 17.46^a	314.84 ± 22.55^b	303.97 ± 25.84^c	290.15 ± 29.58^d	270.29 ± 38.47^d
t	2.06 ± 0.19^a	2.09 ± 0.17^a	2.17 ± 0.26^a	2.09 ± 0.13^a	2.09 ± 0.13^a	2.20 ± 0.27^a
t_c	4.58 ± 0.39^a	4.73 ± 0.40^{ab}	5.06 ± 0.42^b	5.12 ± 0.33^c	5.23 ± 0.40^{cd}	5.51 ± 0.54^d

Values are in mean ±SD. At the same row, values with different superscript are significantly different ($P < 0.05$) in means by the DUNCAN's test.

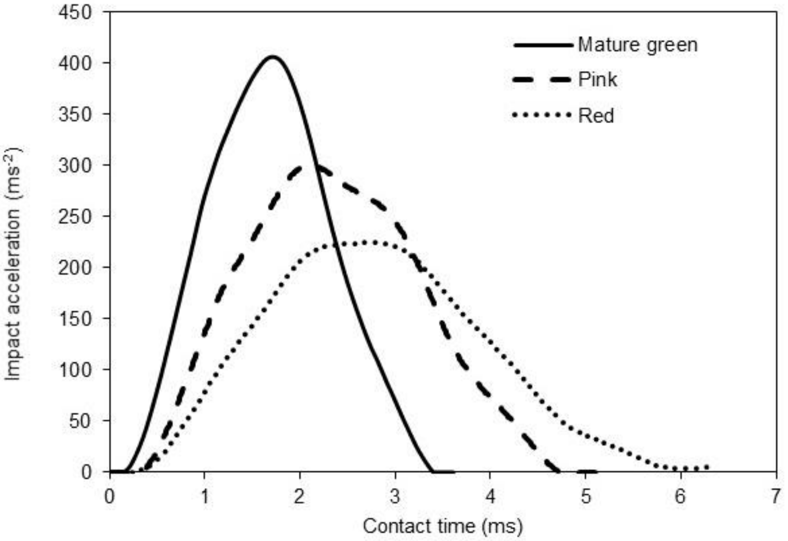

Figure 3. Impact acceleration-contact time curves at three maturity stages of tomato fruit.

The range of physical properties and impact parameters for all the fruits tested were given in Table 3. Furthermore, the 10 measured and derived impact parameters used in this study and correlation coefficients between pairs of parameters were shown in the Pearson correlation matrix in Table 4. As seen in Table 4, the correlations between F_T and nondestructive impact parameters were significant at 1% level except t and $(1/t)^{2.5}$.

Table 3. Range of physical properties and impact parameters for all the fruits tested

Measured Variable	Mean	Minimum	Maximum
m (Fruit mass, g)	103.89	78.94	162.93
D_1 (Equatorial diameter, mm)	60.49	54.38	75.09
H (Height, mm)	48.37	42.97	70.00
D_2 (Thickness, mm)	59.72	51.16	73.94
F_T (Tomato firmness, N mm^{-1})	1.97	0.82	4.75
A (Maximum acceleration, m s^{-2})	309.53	200.14	429.46
t (Time @ A, ms)	2.12	1.71	2.94
t_c (Contact time, ms)	5.12	3.83	6.66
A/t (m s^{-3})	148.03	31.20	68.08
A/t_c (m s^{-3})	61.94	30.05	112.20
A/t^2 (m s^{-4})	71.30	23.15	146.44
A/t_c^2 (m s^{-4})	12.52	4.51	29.32
$(1/t)^{2.5}$ ($s^{-2.5}$)	0.16	0.07	0.26
$(A/t)^{1.25}$ $m^{1.25}$ $s^{-3.75}$	519.91	195.54	997.98
$A^{2.5}$ ($m^{2.5}$ s^{-5})	1,757,467.23	566,689.39	3,822,241.05

Table 4. Correlation coefficients (R) between tomato firmness (F_T) and nondestructive impact parameters

Parameters	A	t	t_c	A/t	A/t_c	A/t^2	A/t_c^2	$(1/t)^{2.5}$	$(A/t)^{1.25}$	$A^{2.5}$
F_T	0.87**	-0.32^{ns}	-0.66**	0.74**	-0.86**	0.65**	0.85**	0.32^{ns}	0.75**	0.92**

**: significant at 0.01 level, ns: non-significant

The use of the 8 impact measurement parameters that was reduced by Pearson correlation matrix can be complicated in real-time application in concerning with 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 firmness assessment. The stepwise regression analysis showed that the A/t, A/t_c^2 and $A^{2.5}$ were the three most dominant parameters with analytical results given in Table 5.

Table 5. Statistical results of the dominant impact parameters according to stepwise regression analysis

Parameters	Beta	t	F value	Prob.>F
Constant		3.774	165.441	0.000
$A^{2.5}$	1.154	8.103		0.000
A/t	-0.837	-4.861		0.000
A/t_c^2	0.586	2.906		0.006

After the dominant impact parameters were selected according to stepwise regression analysis, multiple linear regression (MLR) was used to determine the linear relationship of selected parameters to tomato firmness. In order to search for the best relationship for predicting F_T, three models were fitted to the data using multiple linear regression (MLR). The best among them, based on standard error of calibration (SEC), standard error of prediction (SEV), multiple regression coefficients R^2 and descriptors in the model was selected. The performance of the calibration models for prediction of F_T was tested with validation set. The fruits were randomly segregated into calibration and validation sets, with 52 tomatoes in the calibration set and 36 tomatoes in the validation set. Table 6 shows the results of multiple regression with calibration set of 52 tomatoes when one, two or three of these variables were used in the analysis.

Table 6. Multiple regression models for predicting tomato firmness based only on parameters obtained from the stepwise regression using calibration data sets

	Model: $F_T = \beta_0 + \beta_1 \text{x} A^{2.5} + \beta_2 \text{x} A/t + \beta_3 \text{x} A/t_c^2$				
No. of parameters used	β_0	β_1	β_2	β_3	R^2
1	-0.34	$1.33\text{x}10^{-6}$			0.86
2	0.759	$1.97\text{x}10^{-6}$	-0.015		0.89
3	1.41	$1.65\text{x}10^{-6}$	-0.026	0.127	0.91

A multiple linear regression model which includes $A^{2.5}$, A/t and A/t_c^2 could predict tomato firmness with a coefficient of multiple determination (R^2) and the standard error of calibration (SEC) values of 0.91 and 0.28 N mm^{-1}, respectively. In the case of using the validation data set, R^2 and standard error of validation (SEP) were found to be 0.92 and 0.28 N mm^{-1}, respectively. A comparison of scatter plots of measured F_T values versus computed one for calibration (Fig. 4) and validation (Fig. 5) sets of samples also showed that the measured and predicted tomato firmness values gave very close results. Results showed that a strong and statistically significant improvement in model performance was observed when three impact parameters were used to predict the tomato firmness for both calibration and validation data set. Therefore, the developed MLR model using impact parameters $A^{2.5}$, A/t and A/t_c^2 thus may be able to determine the tomato firmness of greenhouse tomato for harvest and post-harvest assessments.

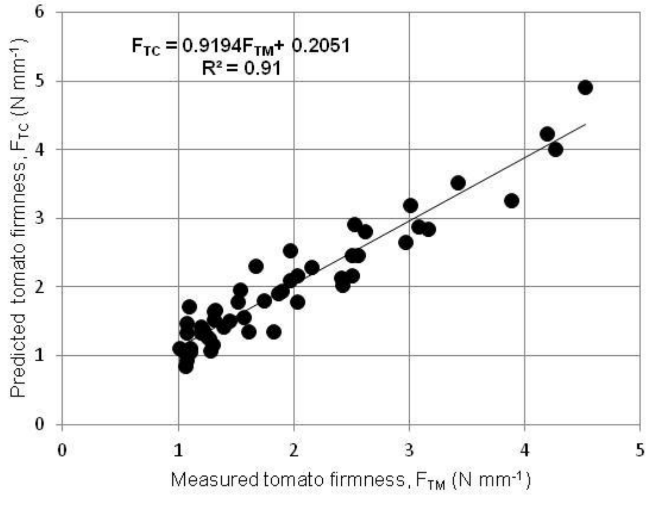

Figure 4. Measured versus predicted tomato firmness of calibration sets of samples.

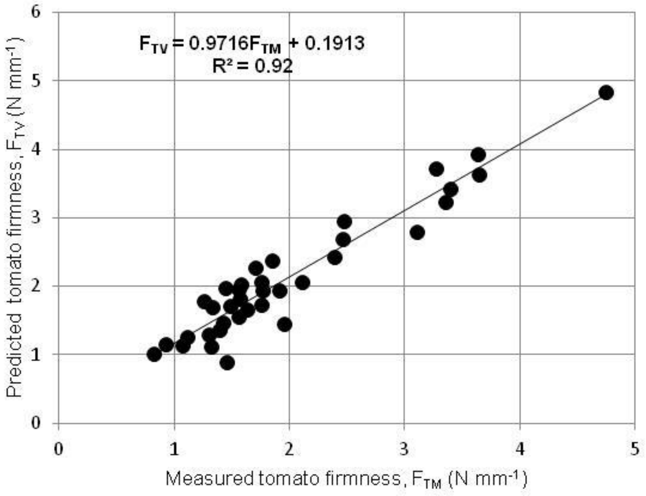

Figure 5. Measured versus predicted tomato firmness of validation sets of samples.

CONCLUSIONS

Bandita F1 greenhouse tomatoes were tested in laboratory conditions by a low-mass impact device to evaluate nondestructively the firmness of tomato. By multiple linear regression (MLR), precise calibration model could be obtained. Precision of the developed model was proved by the validation data sets. A linear model based on three impact parameters extracted by the stepwise regression analysis can predict tomato firmness (F_T) with a coefficient of multiple regression coefficient (R^2) and standard error of the calibration (SEC) of 0.91 and 0.28 N mm^{-1} for calibration data sets. The performance of the calibration model for prediction of F_T showed similar results with validation data sets.

Although this study focuses on the firmness assessment of greenhouse tomatoes, further research based on MLR method is needed in order to develop a more accurate models for prediction of tomato firmness nondestructively by using a wider number of parameters for low-mass lateral impact device.

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