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Nondestructive Dropped Fruit Impact Test for Assessing Tomato Firmness

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A nondestructive method for assessing the firmness of tomato fruit was developed based on the mechanical properties of the fruit under the dropped fruit impact test. The tests were carried out on *Bandita F1* greenhouse tomato variety at six maturity stages for getting a wide range of firmness stage in 2016 season. In the nondestructive dropped fruit impact measurements, impact force and contact time were sensed by a force sensor attached under the impact plate. Other impact parameters were derived from the impact force-contact time curves. Force-deformation ratio at rupture point was used in the measurements of destructive reference parameter and, it was expressed to be tomato firmness (FT). These nondestructive impact parameters were compared with destructive reference parameter for estimating FT.
Ten nondestructive impact parameters were used and, the number of impact parameters being processed were reduced with correlation matrix and stepwise regression analyses. After these processes, simple linear regression (SLR) and multiple linear regression (MLR) were used for model development. Root mean squared error (RMSE), mean absolute error (MAE), mean absolute percentage error (MAPE) and coefficient of determination (R^2) were also used for performance evaluation of modelling approaches used to estimate the tomato firmness. The firmness levels of tomato samples were classified with cluster analysis and, classification performance of developed modelling approaches were tested for classification of tomato samples into three firmness levels. Average firmness values of 135 tomato samples were primarily separated to two groups. 70% and 30% of destructive reference and nondestructive impact parameters were used for calibration and validation data set, respectively. According to results of SLR and MLR statistical analysis, MLR model was found to be the most accurate model for firmness estimation with a RMSE of 0.19 N, MAPE of 5.35%, MAE of 0.10 N and R^2 of 0.85 after validation. Therefore, it can be applied for firmness estimation of *Bandita F1* greenhouse tomatoes with highest accuracy and success rate of 82.93% compared to SLR model in this study.

1. Introduction

Fruit commercially harvested for fresh market must be in the early stages of horticultural maturity to minimize damage during harvest, storage, packing and shipping, and to insure acceptable quality at the retail market (Delwiche and Sarig., 1991). As other fruits, only physical properties such as color and size are not adequate for sorting and grading process of tomato fruits exhibiting visco-elastic, non-homogenous and anisotropic behavior. Flesh firmness is a critical handling parameter for tomato, peach, nectarine, pear, apple, avocado, and kiwi fruits (Delwiche et al., 1996). 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. Several devices related to the classical penetrometer have been developed. While many of these proposed techniques result in reasonably accurate and reproducible estimates, they have a destructive nature, represent mechanical properties at the point of measurements only, and cannot be used as real time measurements for fruit sorting (Lien and Ting, 2014).

At present, researchers have tried various nondestructive techniques such as acoustic, vibration, sonic transmission, ultrasonic transmission, near-infrared, micro-deformation and impact (low-mass impact and dropped fruit impact) for sensing fruit firmness. Researchers have shown interest in using impact techniques for predicting firmness of fruits. Previous studies have shown that dropped fruit impacting of fruits on a load-cell or force sensor can be used to evaluate the firmness of fruits successfully (Delwiche et al.1987; Delwiche et al. 1989; Gutierrez et al. 2007; Lien et al., 2009; Ragni et al. 2010; Lien and Ting, 2014; Mireei et al. 2015).

Most of the research in using impact test for estimation of fruit firmness uses the impact parameters proposed by Delwiche et al. (1987). Prediction based on those parameters may not result in a significantly accurate classification of firmness. The accuracy of firmness estimation can be improved by combining a dropped fruit impact test and most dominant impact parameters extracted with adequate statistical analysis. This study investigated the feasibility of dropped fruit impact in evaluating tomato firmness via optimization of the impact parameters derived through adequate statistical analysis. Therefore, some researchers such as Gutierrez et al. (2007) for peach, Lien et al. (2009) for tomato, Ragni et al. (2010) for kiwifruit, Lien and Ting (2013) for guava fruit and Mireei et al. (2015) for date fruit have used adequate statistical analyses in order to improve the accuracy of maturity prediction of falling impact test on a force sensor.

This study investigated the feasibility of dropped fruit impact in evaluating tomato firmness via optimization of the impact parameters derived through adequate statistical analysis.

2. 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 2016 season. 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. 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. For mature green, breaking turning, pink, light red and red maturity stages, $-0.59<a^*/b^*\leq-0.47$, $-0.47<a^*/b^*\leq-0.27$, $-0.27<a^*/b^*\leq0.08$, $0.08<a^*/b^*\leq0.60$, $0.60<a^*/b^*\leq0.95$ and $a^*/b^*>0.95$ ratios were used, respectively.

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 two equatorial region of each tomato fruit. The load-cell admits a maximum force of 5000 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} (FT).

A nondestructive experimental setup, which is similar to test device developed by Lien et.al. (2009) have been manufactured and used in the experiment. The experimental setup consisted of a force sensor, charge amplifier, and a PC equipped with NI USB6009 DAQ module. Simplified illustration of the experimental setup and photograph of the firmness measurement test device was given in Figure 1.

A fruit was held by a manually manipulated vacuum sucker cup and released to fall freely from an adjustable height onto the force sensor. It is well known phenomenal that falling of the fruit on the force sensor can produce deformation on fruit flesh. Therefore, the free falling height was adjusted to 20mm that does not cause deformation to the fruit flesh as recommended by Lien et al. (2009). Force sensor is piezo electric transducer that generates an analogue signal proportional to the applied drop force. In this work, Dytran model 1051V3 was used as force sensor, which has a 45 kg range and 110mV/kg accuracy. The force sensor response was sampled by using NI USB6009 DAQ at 20 kHz and 16 bit precision.

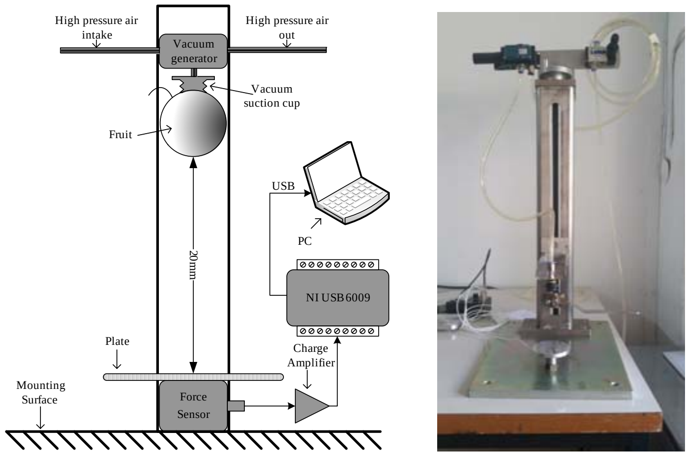

Figure 1: Simplified scheme and photograph of the firmness measurement test device

Figure 2 shows a typical force response of tomato. Important parameters were marked in Figure 2. The recorded impact response data was analyzed to extract some mechanical indices such as first peak force (fp_1), second peak force (fp_2), first impact duration (tc_1), second impact duration (tc_2), latency of first (t_{P1}) and second impact peak force (t_{P2}), time between two peak force (t_{P1-2}) and flying time between two impacts (t_{C1-2}) by using MATLAB. Furthermore, impulse of the first (I_1) and second (I_2) impact were calculated from the area under the first and second impact force-time curve. Totally, ten nondestructive impact parameters were used to predict FT by single linear regression (SLR) and multiple linear regression (MLR) analyzes.

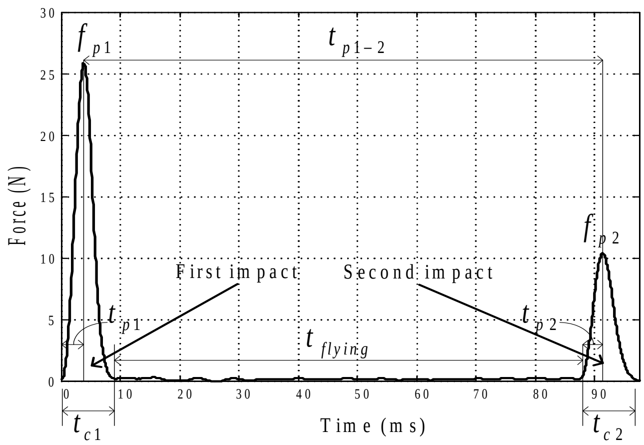

Figure 2: Definitions of impact response

The impact parameters provide neither qualitative nor quantitative information about firmness of tomatoes. Therefore, the impact test measurements were correlated with the results of the destructive reference test measurement. The reference destructive test is only used to indicate the firmness of the tomato samples. In order to classify the tomato samples into several firmness groups, cluster analysis (CA) was introduced to classify the tomatoes, according to test measurements, into different firmness stages. CA was used to search natural grouping trends among samples into soft, intermediate and hard firmness groups. SPSS 19.0 for Windows was used for CA data set.

For analyzing the experimental data set, SLR and MLR were developed and compared to find the best results for prediction the fruit firmness. Experimental data set consisted of 135 samples. For the calibration data set, 70% of the samples was used and for the test set the remaining part. The calibration data set was used for model development, and the fruits from the validation set were reserved for model testing. After the dominant nondestructive impact parameters were selected according to correlation matrix and stepwise regression analysis, SLR and MLR methods were used to determine the relationship of selected parameters to tomato firmness. SLR and 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 impact parameters. DUNCAN's multiple range test was used to compare the means.

In order to compare the simple linear regression (SLR) and multiple linear regression (MLR) models, the root mean square error (RMSE), the mean absolute error (MAE), the mean absolute percentage error (MAPE) and the coefficient of determination (R^2) values were used. According to these criteria, the model that gives a higher value of R^2 and lower values of RMSE, MAE and MAPE were determined as the optimal model. The equations for these criteria and the terms in the equations were expressed as below:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i^{act} - Y_i^{est})^2} \quad (1)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|Y_i^{act} - Y_i^{est}\right| \quad (2)$$

$$MAPE = \left(\frac{1}{n}\sum_{i=1}^{n}\frac{\left|Y_i^{act} - Y_i^{est}\right|}{Y_i^{act}}\right).100 \quad (3)$$

In this expressions, Y_i^{act} is the i*th* measured value, Y_i^{est} is the i*th* estimated value, and *n* is the total number of measurements.

3. Results and discussion

The effect of tomato maturity stages on tomato firmness and ten nondestructive impact parameters were determined using one way ANOVA test. As seen in Table 1, tomato firmness decreased from 3.58 N to 1.16 N significantly during tomato ripening (P<0.01). Among the ten nondestructive impact parameters, I_2 and F_{P2} were found to be the most sensitive parameters related to maturity stages. Maturity stage effect was not significant for t_{C1-2} and t_{P1-2}. These results also showed 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 (t_{c1} and t_{c2}) in the soft tomatoes.

Table 1. Destructive and nondestructive measurements of tomatoes in impact tests at different maturity stages

Parameters	Maturity stages Mature Green	Breaking	Turning	Pink	Light Red	Red
FT (N mm^{-1})	3.58±0.38^e	3.09±0.56^d	2.20±0.47^c	1.74±0.32^b	1.54±0.44^b	1.16±0.21^a
I_1 (N ms)	114.96±11.54^d	116.36±15.05^d	109.49±13.69c^d	102.32±9.85b^c	98.64±11.82^b	89.09±9.62^a
I_2 (N ms)	58.40±6.88^c	55.66±8.77^c	50.48±6.81^b	46.67±4.99^{ab}	47.16±4.70^{ab}	43.30±4.40^a
f_{P1} (N)	35.79±2.27^e	34.34±4.49^e	30.73±3.41^d	27.79±2.27^c	24.30±4.04^b	20.55±2.48^a
f_{P2} (N)	16.82±1.95^f	15.08±2.62^e	12.41±1.74^d	10.90±1.23^c	9.63±1.53^b	8.19±1.05^a
t_{P1} (ms)	3.46±0.30^a	3.61±0.32^{ab}	3.91±0.54^b	3.90±0.46^b	4.29±0.49^c	4.65±0.45^d
t_{P2} (ms)	4.00±0.57^{ab}	3.84±0.38^a	4.28±0.48^{bc}	4.46±0.57^c	5.07±0.56^d	5.61±0.73^e
t_{C1} (ms)	8.17±0.49^a	8.51±0.60^a	9.17±0.86^b	9.35±0.85^b	10.43±1.25^c	11.65±1.22^d
t_{C2} (ms)	8.79±0.84^a	8.79±0.76^a	9.87±1.01^b	10.42±1.25^b	12.02±1.55^c	13.38±1.81^d
t_{C1-2} (ms)	84.14±6.18^a	82.21±2.39^a	80.64±3.22^a	73.17±8.30^c	76.80±6.06^b	77.06±4.67^b
t_{P1-2} (ms)	92.80±6.62^a	90.89±2.59^{ab}	90.13±3.44^{ab}	83.03±8.16^c	87.96±6.16^b	89.58±5.18^{ab}

The 135 tomato samples at different maturity stages used for firmness classification of tomatoes were first subjected to cluster analysis and, it was decided what the firmness groups should be. According to cluster analysis, the SPSS procedure classified the samples into 3 distinguishing clusters such as soft, intermediate and hard firmness groups. Consequently, 32 tomato samples with a mean of 1.39±0.28 N mm^{-1} in the soft group, 39 tomato samples with a mean of 2.23±0.30 N mm^{-1} in the intermediate group and 23 samples with a mean of 3.43±0.40 N mm^{-1} in the hard group were determined . Firmness ranges formed by cluster analysis was FT≤1.79 N mm^{-1}, 1.80<FT≤2.83 N mm-1 and FT≥2.84 N mm^{-1} for soft, intermediate and hard firmness groups, respectively.

Table 2 shows the results of regression models with calibration set of 94 tomatoes when one (SLR) or two (MLR) of these variables were used in the analysis. Furthermore, performance evaluation measures were obtained from the calibration and validation sets and, were presented in Table 3. Here, it can be seen that the RMSE in both data sets of 0.31 N mm^{-1} (calibration set) and 0.19 N mm^{-1} (validation set) were found lowest applying the MLR model. The RMSE of MLR decreased under the validation set compared to calibration set. Same trend was also observed for MAE and MAPE values. It can be stated that MLR model which includes I_2 and f_{P2} impact parameters is always better rated than the SLR which includes f_{P2} impact parameter.

Table 2. SLR and MLR models for predicting tomato firmness based only on parameters obtained from the stepwise regression using calibration data sets

Model: $FT = \beta_0 + \beta_1 I_2 + \beta_2 f_{P2}$				
No. of parameters used	β_0	β_1	β_2	R^2
1	-0.853		0.252	0.85
2	-0.179	-0.026	0.306	0.87

A comparison of measured FT values versus computed one for calibration and validation sets of samples also showed that the measured and predicted tomato firmness values gave very close results for SLR and MLR regression models as seen in Table 3. Furthermore, a strong and statistically significant improvement in MLR model performance was observed when two impact parameters were used to predict the tomato firmness for both data sets.

Table 3. Performance evaluation measures of the two modelling approaches used to estimate fruit firmness

	RMSE	MAE	MAPE	R^2
Calibration (n=94)				
SLR	0.33	0.26	11.99	0.85
MLR	0.31	0.24	11.87	0.87
Validation (n=41)				
SLR	0.20	0.11	6.05	0.83
MLR	0.19	0.09	5.34	0.85

Table 4 shows classification of tomatoes based on the three firmness groups soft, intermediate and hard from the calibration and validation procedures. Regarding the validation results of the SLR model, 4 and 2 fruits were underestimated in firmness class I_{act} and H_{act}, respectively. Furthermore, 2 fruits were also misclassified in firmness class I_{act} instead of H_{act}. By applying MLR model, misclassification were same like in the SLR but, superior performance was found for estimating intermediate firmness class.

Table 4. Performance of the two different modelling approaches used to estimate fruit firmness for classification of tomato samples into established firmness groups.

Calibration (n= 94)		S_{act} n= 32	I_{act} n= 39	H_{act} n= 23	True positives	Success rate (%)
SLR	S_{est}	24	8	0	75	79.78
	I_{est}	5	32	2		
	H_{est}	0	4	19		
MLR	S_{est}	25	7	0	79	84.04
	I_{est}	3	34	2		
	H_{est}		3	20		
Validation (n= 41)		n= 21	n= 14	n= 6		
SLR	S_{est}	17	4	0	33	80.48
	I_{est}	0	12	2		
	H_{est}	0	2	4		
MLR	S_{est}	16	5	0	34	82.93
	I_{est}	0	14	0		
	H_{est}	0	2	4		

Firmness groups defined as S=soft (FT≤1.79 N mm^{-1}), I=intermediate (1.80<FT≤2.83 N mm^{-1}), H=hard (FT≥2.84 N mm^{-1}).

Looking at the success rates of the validation sets, the highest value of 82.93% was reached applying the MLR model, followed by SLR model with 80.48%. The results of the success rates were also in agreement with the outcomes of all other performance measures in Table 3. Based on this analysis, it is recommended that in addition the success rate, at least three further measures of RMSE, MAE, MAPE and R^2 should be used in model evaluation for the firmness estimation of tomato fruits.

4. Conclusions

This study presented that the MLR modelling can be used to estimate the tomato firmness. Tomatoes were tested in laboratory conditions by a non-destructive drop force device to obtain experimental firmness data set. Input parameters were peak forces and impact durations. Data set separated as calibration and validation data sets. SLR and MLR models are supplied with these data sets. By MLR, more precise prediction model could be obtained. Precision of the developed model was proved by the validation data sets which is 30% of the total data set. A MLR model can predict FT with a R^2 of 0.85 for validation data set. Results also showed that a strong and significant prediction performance was observed when I_2 and fp_2 impact parameters were used to predict the FT for MLR model. Therefore, the developed MLP model using force parameters thus may be able to determine the tomato firmness of greenhouse tomato for harvest and post-harvest assessments. Although this study focuses on the firmness estimation of 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 dropped fruit impact test.

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