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NON-DESTRUCTIVE MEASUREMENTS OF APPLE FIRMNESS USING FRICTION AND IMPACT SENSORS

Czesław Puchalski[1], Stanisław Sosnowski[2], Gerald H. Brusewitz[3]

[1]Department of Agricultural Mechanization, University of Rzeszów
ul. Ćwiklińskiej 2, 35-601 Rzeszów, Poland
e-mail: cpuchal@ar.rzeszow.pl
[2]School of Engineering and Economics, ul. A. Mickiewicza 10, 39-100 Ropczyce, Poland
[3]Department of Bio-systems and Agricultural Engineering, Oklahoma State University, USA

Abstract. Firmness is commonly used as an indicator of the state of fruit maturity and its quality. Two apple cultivars, Gloster and Idared, were investigated within 105 storage days. Friction test parameters, impact test parameters, and penetrometer firmness measurements were recorded for ten replications of each cultivar and storage time. Two impact firmness parameters were obtained from each force vs. time impact test; the impact force as the peak force (maximum force) and the end force which presents the last contact point of the pluger with the sample. Completing the friction test, the maximum force and curve slope during the initial loading were derived. Storage time and apple variety had a significant effect on both friction and impact test parameters. The changes in friction parameters with storage varied with the apple variety. Peak and end impact forces decreased with increasing storage time, up to 6.7% and 8.1% respectively. The largest changes, up to 105%, during 105 days of storage were in friction maximum force. Penetrometer firmness was more highly correlated with impact parameters than with friction test parameters.

Keywords: friction test, impact test, non-destructive measurements, apple firmness

INTRODUCTION

Firmness is commonly used as an indicator of the state of the maturity of fruit and of its quality. Firmness is usually measured by a hand-held penetrometer as the force required to puncture surface flesh with a blunt cylindrical tip and remains as the industry standard for determining quality. Many problems have been reported with the consistency of penetrometer firmness measurements caused by the sheer and compressive strength of the tissue and the lack of correlation to consumer perceptions of texture [1,7]. Researchers have investigated the potential for using impact force as a method for detecting firmness. Sensors developed by dropping fruit [3] have limitations due to the effect of variability on the fruit mass and the radius of curvature at the contact point. Others investigators [4,5] used probe-like impact sensors with stationary fruit struck by an instrumented mass. They found that the impact force is a function of the material properties of the fruit and such sensors could be integrated with existing packaging line equipment.

The friction sensor is a new approach developed by Puchalski [5] who found that the structure of the outer layer of the fruit is more important than its internal flesh in determining firmness. Fruit tissue behavior in relation to the contact with the sensor probe can be tested instrumentally under different conditions to determine quality indices. Corey et al. [2] in using a scanning electron microscope observed the ripening of watermelons, which was accompanied by changes in the appearance and quantity of surface waxes. Wax has an amorphous structure which influences skin roughness; therefore this could be an indicator of fruit quality.

The purpose of this paper is to investigate the application of non-destructive methods such as friction and impact sensors and correlate the data to destructive penetrometer measurements of apple firmness.

MATERIALS AND METHODS

Two apple cultivars, Gloster and Idared were harvested from a commercial orchard at Albigowa, in south-eastern Poland. Fruit intended for storage was harvested on the 26th. of September. Before being placed in cold storage it was visually graded according to size and maturity to obtain uniform material for investigation. When stored at 1°C and 96% RH, the weight loss was less than 3% after 105 days; indicating good apple storage conditions. On six dates during storage (every 21 days), samples were taken and equilibrated overnight at 20°C in an open laboratory. They were numbered consecutively and randomly as removed from the storage without regard for any indication of ripeness. Mass, diameter, friction test parameter, impact test parameter, and penetrometer firmness measurements were recorded for ten replications of each cultivar and storage time.

Friction test. This test was done using a friction test machine (fig. 1). The measuring pivot with the friction test surface is mounted at the head of the Zwick machine. A set of clamps with adjustable jaws holds the apple, precluding fruit rotation, during the application of friction.. Just before applying a sample pressure to the surface of the fruit undergoing testing, the pressure was adjusted to 10 N.

Testing was done at a traveling distance of 10 mm with a sliding speed equal 4.17 mm s^{-1} (chosen on the basis of preliminary tests). Two friction test surfaces were used; plastic and steel. Data was presented in the form of charts, friction force versus displacement. Two parameters were derived from the charts; maximum force and slope of curve during initial loading [5].

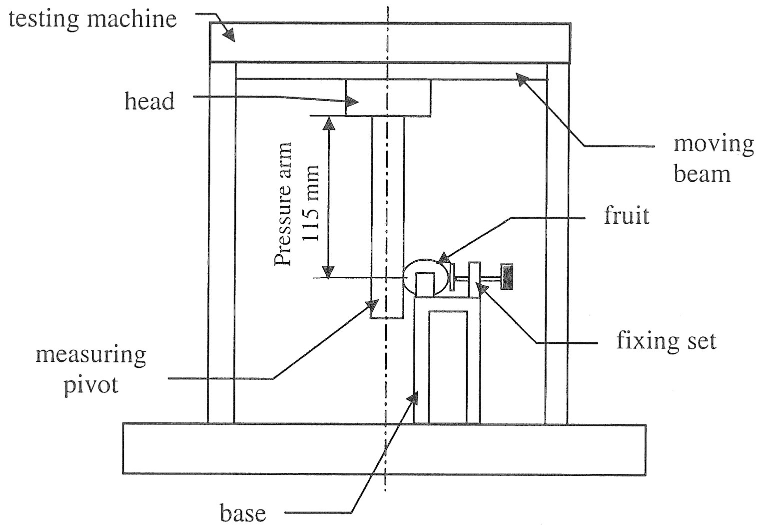

Fig. 1. Measuring stand for non-destructive friction test

Impact test. The stand for impact test (fig. 2) consists of an impacting plunger with a blunt cylindrical tip, 11.1 mm in diameter attached to the end of a plate spring. The plate spring is coupled to the force transducer mounted on the pendulum arm, which is supported by two bearings to minimize friction. The fruit is placed in an adjustable holder which rigidly prevents the sample from moving during impact. The pendulum arm is held at the selected angle by an electromagnet to produce the desired impact energy. The signal from the force transducer is transmitted to a computer and analyzed. Impact energy of 105 mJ was chosen to produce an impact without noticeable bruising. Impact was accomplished by allowing the pendulum to swing into the stationary fruit. Two impact firmness parameters were obtained from each force vs. time impact test; the impact force as the peak force (maximum force) and end force which presents the last contact point of the pluger with the sample [5]. Measurements were done on two opposing sides of each fruit away from the stem.

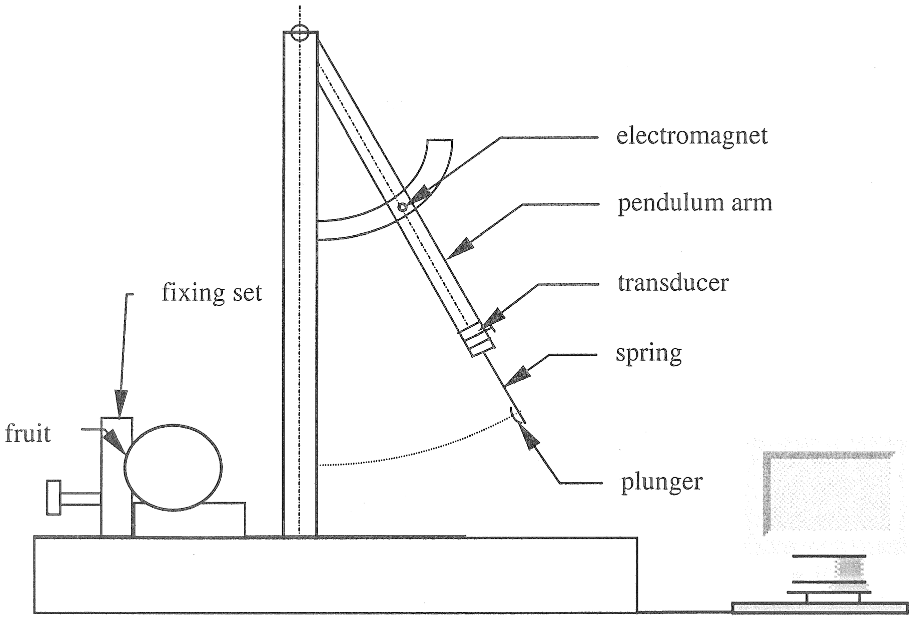

Fig. 2. Measuring stand for the non-destructive impact test

Penetrometer firmness measurements. The penetrometer test was conducted with an 11.1 mm diameter, cylindrical-tip probe mounted on the load cell of a Zwick universal testing machine moving at 60 mm min^{-1} until it penetrated 8 mm into the flesh of the fruit. Force versus deformation data was recorded. From this data, the penetration firmness parameter was obtained as the maximum force, which is comparable to the hand penetrometer reading.

RESULTS AND DISCUSSION

Effect of storage days and variety

The statistical analysis of variance (ANOVA) showed a significant effect (at $p < 0.01$) of storage time on the parameters obtained from friction and impact tests for the Gloster and Idared varieties (tab. 1).

The trend of the friction parameters was different between the two apple varieties (fig. 3). Generally, the friction force and initial force – time slope for Gloster decreased during the 105 days of storage. The average decreases in these parameters were 26.3% and 19.4%, respectively. Probably, it is affected by such factors as changes in surface wax structure and its softening with time. For the Idared variety, there was a different relationship; during longer storage, there was an increase in friction force and slope. These changes were about four times larger compared to the Gloster (averages increases were 105% and 65.5%, respectively). This may be caused by an increase in adhesion between the apple and the flat friction surface resulting from the smoothing of the apple's surface with ripening. This is consistent with observations on the Gala variety [6] and was confirmed by microscopic analysis [2].

Table 1. Analysis of variance (p – probability, – value of test function)

Type of test	Parameter	Gloster		Idared	
		p	*F*	p	*F*
Friction	Friction force	0.00	21.6	0.00	21.4
	Slope of curve	0.00	5.8	0.00	10.2
Impact	Peak force	0.00	21.9	0.00	31.1
	End force	0.00	10.5	0.00	9.2

Figure 4 shows the effect of storage time on impact test parameters for both varieties tested. The change with time was more pronounced for impact parameters than for friction parameters. Peak and end impact forces decreased significantly with storage time. Similar results were found for friction parameters with Gloster apples. During the 105 days of storage, peak and end forces changed up to 6.7% and 8.1%, respectively.

The firmness of the Gloster averaged 72.3 N, which was higher than the 57.1 N for the Idared (tab.2). Differences between varieties were more evident for impact parameters than for friction parameters. The largest differences were up to 5% and up to 10% was observed within storage for maximum force and end force, respectively.

The average values of the impact and friction parameters along with their variation coefficients for the 105 days of storage are presented in table 2 for each variety. The higher values of variation coefficient, up to 25.7% for friction force of Idared, were found for friction test parameters compared to impact parameters.

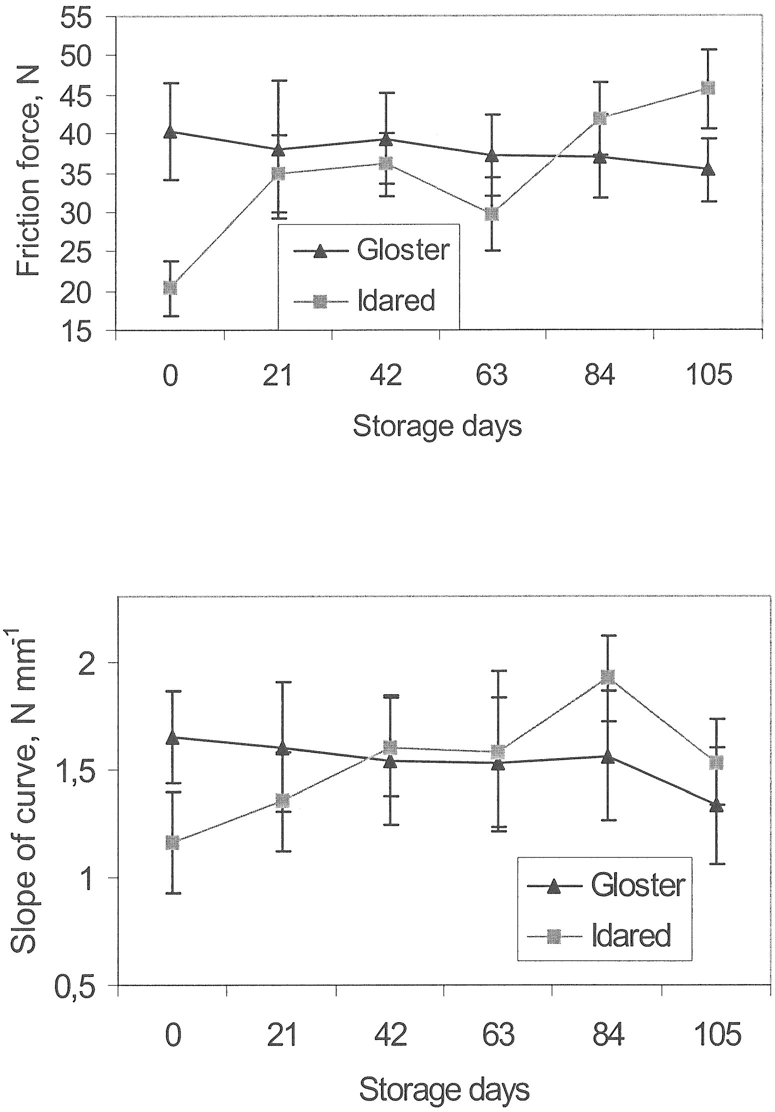

Fig. 3. Effect of storage days on parameters from friction test for Gloster and Idared, vertical bars represent S.D. for ten replications

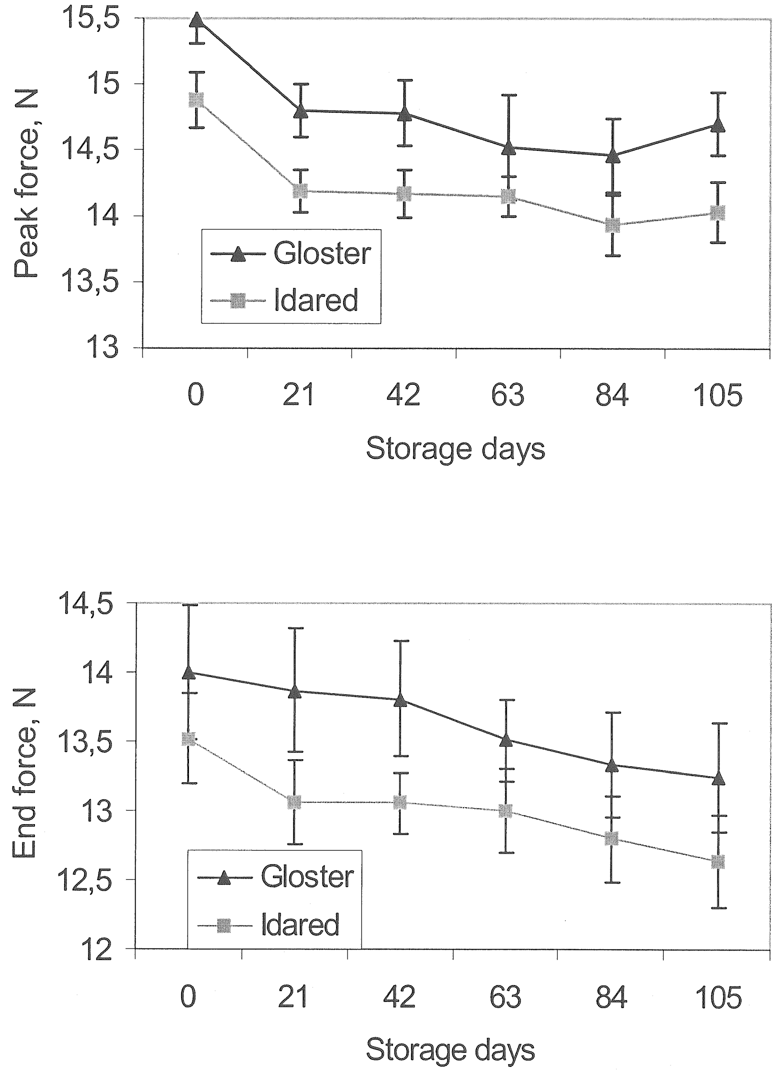

Fig. 4. Effect of storage days on parameters from impact test for Gloster and Idared, vertical bars represent S.D. for ten replications

Table 2. Average values of tested parameters and C.V. (%) (Variation coefficient) within storage for Gloster and Idared

Parameter	Mean	S.D.	C.V.
	Gloster		
Penetrometer firmness (N)	72.30	15.20	21.0
Friction force (N)	37.88	1.76	6.3
Slop of curve (N mm^{-1})	1.53	0.11	7.2
Peak force (N)	15.29	0.37	2.7
End force (N)	13.62	0.32	2.6
	Idared		
Penetrometer firmness (N)	57.10	10.90	19.1
Friction force (N)	34.78	8.92	25.7
Slop of curve (N mm^{-1})	1.52	0.26	17.1
Peak force (N)	14.42	0.36	2.5
End force (N)	13.03	0.23	2.0

Regression equation models

All the curves presented were developed as either linear or second-degree polynomial equations. The relationships between the parameters obtained from friction and the impact parameters for storage time and the two varieties (Gloster and Idared) are presented in tables 3 and 4. Steel as a tested friction surface, produced the best results; therefore it is recommended for future testing. Linear relationships fit the data very well for maximum friction force against steel and end force from impact test, for both varieties versus storage days. However, second degree polynomials were necessary to obtain good results for the impact parameters. The slope of the linear relationships being about 400% higher for Idared in comparison with the Gloster indicates which is more affected by variety for the friction test.

Table 3. Relationship between parameters determined from friction test and storage time (x = days) for two tested surfaces against Gloster and Idared

Parameter	Variety	Regression equation	R^2
		Gloster	
Friction force	steel	$-0.04x + 40.0$	0.81
	plastic	$0.003x + 27.0$	0.03
Slope of curve	steel	$-0.002x + 1.66$	0.71
	plastic	$-0.0001x + 0.02 + 1.4$	0.35
		Idared	
Friction force	steel	$0.195x + 24.4$	0.74
	plastic	$0.04x + 26.7$	0.38
Slope of curve	steel	$0.005\ x + 1.28$	0.54
	plastic	$0.003x + 1.49$	0.42

Table 4. Relationship between parameters determined from impact test and storage time (x = days) for Gloster and Idared

Parameter	Tested surface	Regression equation	R^2
Peak force	Gloster	$-0.0071x + 15.17$	0.58
		$0.0002x^2 - 0.026\ x + 15.43$	0.93
	Idared	$-0.0069x + 14.59$	0.65
		$-0.0001x^2 - 0.020x + 14.77$	0.86
End force	Gloster	$-0.0078x + 14.03$	0.96
		$-0.0005x^2 - 0.0092x + 12.55$	0.90
	Idared	$-0.007x + 13.39$	0.88
		$-0.00005x^2 - 0.0101x + 13.43$	0.89

Correlation coefficients

The correlation coefficients between parameters derived from friction and impact tests with penetrometer firmness for Gloster and Idared apples are given in table 5. All the coefficients are significant at $p = 0.05$. The coefficients of correlation ranged from 0.68 to 0.93. Generally, higher values were obtained with impact parameters than with friction parameters.

Table 5. Correlation coefficients between tested parameters and penetrometer firmness for Gloster and Idared

Parameter	Penetrometer	Friction parameters		Impact parameters	
	Firmness	Friction force	Slope of curve	Peak	End force
		Gloster			
Firmness	1.00	0.77	0.76	0.71	0.93
Friction force		1.00	0.82	0.73	0.85
Slope of curve			1.00	0.46	0.63
Peak force				1.00	0.79
End force					1.00
		Idared			
Firmness	1.00	–0.83	–0.81	0.91	0.68
Friction force		1.00	0.80	–0.91	–0.66
Slope of curve			1.00	–0.83	–0.21
Peak force				1.00	0.63
End force					1.00

CONCLUSIONS

1. Variance analysis showed that the storage time and apple variety had a significant effect on both friction and impact test parameters.
2. The changes in friction parameters with storage varied with the apple variety. For Idared, friction parameters increased while for Gloster they decreased with storage time.
3. The peak and end impact forces decreased with increasing storage time, up to 6.7 and 8.1% respectively.
4. The largest changes, up to 105%, during 105 days of storage were in friction maximum force.
5. Usually the degree of polynomial equations fitted the maximum friction force and impact parameters versus the storage time immediately; at other times it came later.
6. Penetrometer firmness was higher correlated with impact parameters than friction test parameters.

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NIENISZCZĄCE POMIARY JĘDRNOŚCI JABŁEK PRZY ZASTOSOWANIU TESTÓW TARCIA I UDERZENIA

Czesław Puchalski[1], Stanisław Sosnowski[2], Gerald H. Brusewitz[3]

[1]Uniwersytet Rzeszowski, Zakład Mechanizacji Rolnictwa, ul. Ćwiklińskiej 2, 35-601 Rzeszów
e-mail: cpuchal@ar.rzeszow.pl
[2]Wyższa Szkoła Inżynieryjno-Ekonomiczna, ul. A. Mickiewicza 10, 39-100 Ropczyce
[3]Zakład Biosystemów i Inżynierii Rolniczej, Oklahoma State University, USA

Streszczenie. Jędrność jest powszechnie stosowanym wskaźnikiem oceny stopnia dojrzałości i jakości jabłek. Obiektem badań były jabłka dwóch odmian, Gloster i Idared, przechowywane w chłodni przez okres 105 dni. W okresie badań wykonano testy tarcia, uderzenia i pomiary jędrności metodą tradycyjną przez wciśnięcie wgłębnika, w dziesięciu powtórzeniach dla dwu odmian w okresie zbioru. Dwa parametry oceny jędrności określono na podstawie krzywej siła – czas uzyskanej z testu uderzenia, siłę uderzenia jako tzw. pik na wykresie (siła max) i siłę końcową, która reprezentuje ostatni punkt kontaktu czujnika z materiałem. W czasie wykonywania testów tarcia mierzono siłę max i współczynnik nachylenia krzywej siły-przemieszczania. Stwierdzono istotny wpływ okresu przechowywania i odmiany na parametry testu tarcia i uderzenia. Zmiany parametrów tarcia w okresie przechowywania były istotnie zależne od odmiany. Siły uderzenia, max i końcowa wykazywały tendencję malejącą w okresie przechowywania. Zmiany tych parametrów wyniosły odpowiednio 6,7 i 8,1%. Siła tarcia charakteryzowała się największą zmiennością w okresie 105 dni przechowywania. Obniżenie wartości tej cechy wyniosło 105%. Parametry określone na podstawie testu uderzenia silniej korelowały z jędrnością określoną metodą tradycyjną, w porównaniu z parametrami testu tarcia.

Słowa kluczowe: test tarcia, test uderzenia, nieniszczące pomiary, jędrność jabłka