Evolution of Pressure Distribution during Apple Compression Tests Measured with Tactile Sensors

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Abstract

The paper analyses the ability of thin-film tactile sensors in providing information during static compression tests of 'Jonagold' apples (*Malus pumila*) of different ripeness stages. Such sensors are able to measure the contact surface and the interfacial pressure distribution during compression of fruits, this latter being characterised by suitable mathematical parameters. Results of compression tests between two flat steel plates are presented. The differentiated evolution of the pressure distribution according to the fruit maturity is pointed out. Ability of the sensor in evaluating the firmness is also discussed.

INTRODUCTION

A lot of research has been conducted to investigate the effect of maturity on the mechanical behaviour of fruits, either in a dynamic or a static way. The dynamic methods may be classified in two categories. The first type of methods is based on observations made by Clark and Michelson who noticed as early as 1942 that changes in the natural frequencies of intact fruit occur during the ripening process. To use this principle, an external stress is applied to the fruit, able to produce a sudden release of stored elastic energy. Either the apple is submitted to forced vibrations swept through a large range of frequencies (Peleg, 1993, Abbott and Liljedahl, 1994, Liljedahl and Abbott, 1994) or the apple is struck by a mechanical impulse, the audible resonant frequency being measured with a microphone (Chen and De Baerdemaeker, 1995). The second type of methods consists in striking the fruit on a rigid surface and analyzing the impact forces. The sensor used may be a force transducer sensor (Delwiche et al., 1996), a flexible piezoelectric film (Shmulevitch et al., 1996, McGlone et al., 1997) or tactile sensors (Herold et al., 1998). In this last case, the dynamic range was found insufficient to furnish impact force versus time.

Others methods are devoted to static compression methods. Under mechanical loading, fruit exhibits viscoelastic behaviour which depends on both the amount of applied force and the rate of loading (Mohesin, 1970). However, at very small deformations, the behaviour is usually assumed to be elastic. Within the scope of designing non-destructive devices, the measured property is the portion of the force/deformation curve below the bioyield point (Lesage and Destain, 1996). The interest in static compression tests is recently renewed with tactile sensors becoming available on the market. Their main advantage compared to more conventional force or pressure sensors is to provide simultaneously the size of the contact area and a spatial distribution of the pressures to the interface of the bodies in presence. Using such a sensor, Herold et al. (2001) show examples of the surface pressure distribution generated in the contact area of apple fruit loaded to failure.

The general purpose of this work was to study the mechanical behaviour of 'Jonagold' apples of different stages of maturity during static compression tests, by means of tactile sensors. The sensor ability for predicting fruit firmness during sorting process was also evaluated.

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MATERIALS AND METHODS

A set of 120 'Jonagold' apples (Magness-Taylor firmness values comprised between 60 and 70 N) was divided into three equal batches that were tested at different storage times (8 days between each batch) in order to obtain three different ripeness levels. Each fruit was compressed between two flat steel plates (Fig. 1). One of these plates was fixed while the other was mounted on a linear actuator (MLFI 25056 ZR, INA-Schaeffler KG) coupled with a servo motor (HDY 70 C4-44-S, Parker-Hauser GmbH) regulated by a servo controller (COMPAX 1000 SL, Parker-Hauser GmbH). The displacement of the moving plate was regulated to have a constant speed of 5 mm per second.

A tactile sensor (type No. 5051, Tekscan Inc.) with a saturation pressure of 150 PSI was stuck on the moving plate. This sensor provides frames made of 44 x 44 pixels (coded on 8 bits) with a spatial resolution of 1.69 mm² per pixel. The sampling frequency was set at 225 frames per second (maximum value).

Data was treated and analysed with Matlab R12 (The MathWorks, Inc). Since each pixel within the frame had its own sensitivity characteristics, a 'flat field' correction was applied to compensate the non uniform response of the sensor. For each pixel, the following transformation was applied:

$$Ic = \frac{(I - Ib)}{(If - Ib)} \times Mf$$

with Ic being the corrected pressure ; I being the raw pressure; Ib being the pressure of the unloaded sensor ; If being the 'flat field' pressure of a uniform load and Mf the average pressure of a pixel. Pressure unit was Tekscan raw data.

A calibration was also performed to estimate the relation between the applied total force and the raw values provided by the tactile sensor (Fig. 2).

For each frame, the applied total force (Ft) and the contact area (A) were computed. Furthermore for each apple, two reference firmness values were measured using a manual 'Effe-gi' penetrometer (Gullimex FT 327).

RESULTS AND DISCUSSION

During compression tests, even at low applied forces, like Herold et al. (2001), it was visually observed that local failures occurred with as consequence a change in the pressure distribution. More precisely, all the tested fruits presented firstly a pressure increase at the centre of the contact area and when the applied total force exceeded the maximum sustainable (bioyield point 'BYP' defined by Mohesin, 1970), central pressure fell sharply and contact pressure began to increase at the edge of the contact area (Fig. 3). Based on this observation, a dispersion parameter was defined to quantify the contact pressure distribution during the compression and to characterise mathematically the BYP.

Since the contact area had a circular shape, the moment of polar inertia was a well suited parameter for pressure distribution characterisation. This mechanical parameter relates to the mass repartition of a body around its gravity centre. Increasing the mass at the edge of the body will result in a higher moment of polar inertia. In this precise case, pressure values represented masses. Nevertheless, this parameter depended at the same time on the contact area and on the applied total force. The contact area depends on the fruit curvature and the applied total force depends on the fruit firmness. Thus, in order to obtain a parameter depending only on the pressure distribution, a novel dimensionless dispersion parameter was defined according to the following equation:

$$DP = Ip / (Ft \,.\, A)$$

with Ip the moment of polar inertia of the pressure distribution. A low DP value means that the pressure is concentrated in the centre of the contact area, while a high value indicates that the greatest pressure is located at the edge of the contact area. As presented on Figure 4, a sudden increase of DP (1,5 mm and 3 mm penetration depth) indicated that failure occurred; the first failure corresponding to the BYP.

This method ensured the automatic detection of more than 90% of the first failures. No significant diminution in the applied total force at these failure events was observed, unlike Herold et al. (2001).

In order to analyse the effect of ripeness on the failure apparition, analyses of variance were performed on the three batches of apples for the penetration depth, applied total force and mean contact pressure measured at the failure point. The results revealed that only the mean contact pressures were significantly different for the three batches. Thus applying a given force on a fruit could lead to different effects depending on the fruit size since the repartition of this force depends itself on the contact area. On the other hand, these results also pointed out that the mean contact pressure values at the BYP decreased from the most fresh apples to the most ripe ones. Thus susceptibility to damage increased with the ripeness when applying quasi-static compression forces.

Analysing the applied total forces when the first failure occurred, it was observed that only two apples on the whole set presented a first failure below a 20 N force. This value was considered as a limit for non destructive compression test. Using data recorded until a applied total force of 20 N, the slopes of the curves total force versus penetration depth and contact area versus displacement were computed. These two values and their ratio were then used to classify the three batches by means of linear discriminant analysis in order to evaluate the performance of the method for sorting apples according to their ripeness. The correct classification rate (cross validation) into three classes was 55 % (Table 1). Most of the misclassified apples belonged to the intermediate class which suggested that the initial ripeness variability inside each batch was relatively high. Considering only the two extreme batches (fresh and most ripe), this rate reached a value of 81 %. However, analysing these results was still difficult due to the lack of objective ripeness reference.

Finally, the sensor abilities to estimate apple firmness under non destructive conditions was evaluated. Since the slope of the curve total force (up to 20 N) versus penetration depth could be compared to the stiffness of classical force versus deformation curve, a linear regression was performed between this slope and the mean ‘Effe-gi’ firmness. Unfortunately, this method did not show good results. An explanation could be found in the evaluation of the firmness reference with the ‘Effe-gi’ penetrometer. Indeed, this apparatus was well suited to estimate the average firmness of a fruit batch but was not suited to measure precisely the firmness of individual fruit, since the penetration speed was not controlled. Further studies would need to be conducted to compare the data provided by the tactile sensor to other firmness reference methods (acoustic method, mechanical impulse method,…).

In conclusion, the results are promising to get a better insight in the comprehension of mechanisms governing the occurrence of damage to fruits. On the other hand, the tactile sensor abilities to sort apples according to their ripeness and to estimate their firmness need to be further investigated.

Literature Cited

Abbott, J.A. and Liljedahl, L.A. 1994. Relationship of sonic resonant frequency to compression tests and Magness-taylor firmness of apples during refrigerated storage. Trans. of the ASAE 37(4):1211-1215.

Chen, H. and De Baerdemaeker, J. 1995. Total least squares technique for estimating the vibration parameters of the apple from the time domain impulse response signal. Journal of Agricultural Engineering Research 61:283-290.

Delwiche, M.J., Arévalo, H., Mehllschau, J. 1996. Second generation impact force response fruit firmness sorter. Trans. of the ASAE 39(3) :1025-1033.

Herold, B., Oberbarnscheidt, B., Truppel, I., Geyer, M. 1998. Detection of mechanical stress and damage of fruit and vegetables. Proceedings of Sensoral 98 International workshop on Sensing Quality of Agricultural Products, Montpellier..

Herold, B., Geyer, M., Studman, C.J. 2001. Fruit contact pressure distributions – equipment. Computers and Electronics in Agriculture 32:167-179.

Liljedahl, L.A. and Abbott, J.A. 1994. Changes in sonic resonance of ‘Delicious’ and ‘Golden delicious’ apples undergoing accelerated ripening. Trans. of the ASAE 37 (3): 907-912.

Lesage, P. and Destain, M.-F. (1996). Measurement of tomato firmness by using a non-destructive mechanical sensor. Postharvest Biology and Technology 8 : 45-55.

McGlone, V.A., Jordan, R.B., Schaare, P.N. (1997). Mass and drop-height influence on kiwifruit firmness by impact force. Trans. of the ASAE 40(5) :1421-1428.

Mohesin, N.N. 1970. Physical properties of plant and animal materials, Vol. 1. Gordon and Breach, New York.

Peleg, K. (1993). Comparison of non-destructive and destructive measurement of apples firmness. J. Agric. Engng Res. 55, 227-238.

Shmulevich, I, Galili, N., Rosenfeld, D. 1996. Detection of fruit firmness by frequency analysis. Trans. of the ASAE 39(3): 1047-1055.

Tables

Table 1. Results for the sorting of apples into three and two classes according to the ripeness and using tactile sensor data.

	Batch				**Batch**		
	Fresh	**Intermediate**	**Ripe**	**Total**	**Fresh**	**Ripe**	**Total**
Nb total	40	38	40	118	40	40	80
Nb correct	27	14	24	65	34	31	65
Rate (%)	67,5	36,8	60	**55,1**	85	77,5	**81,3**

Figures

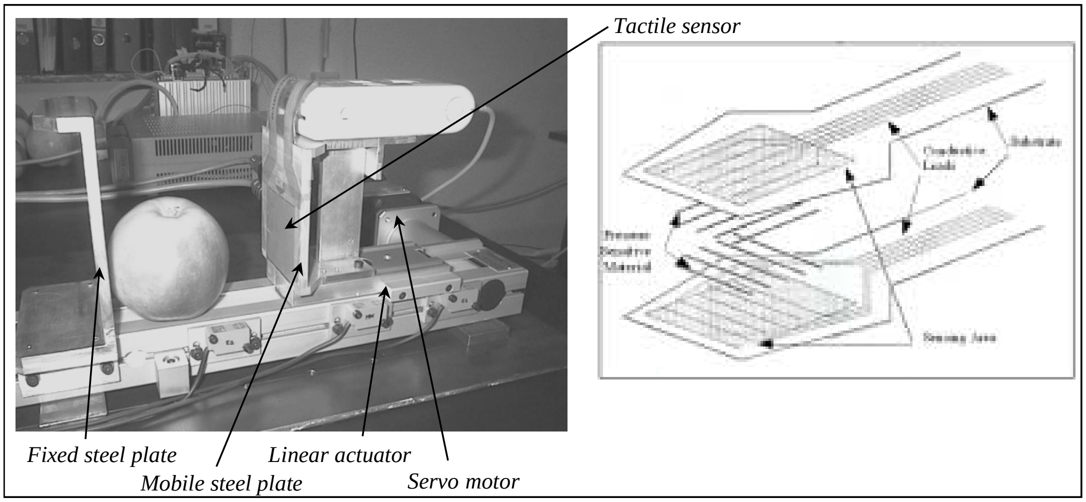

Fig.1. Compression test device and tactile sensor.

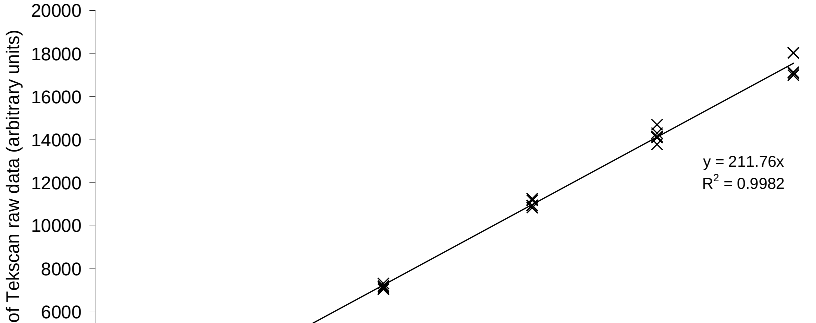

Fig. 2. Calibration of the Tekscan sensor 5051 (150 PSI).

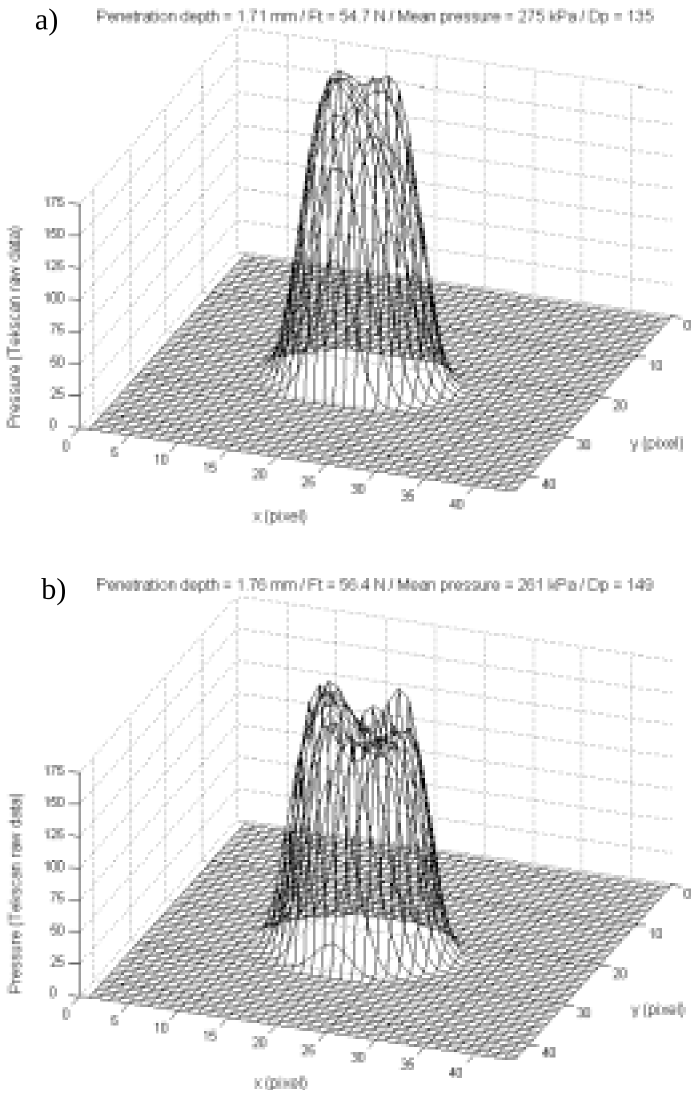

Fig. 3. Example of pressure distributions before (a) and after (b) a failure.

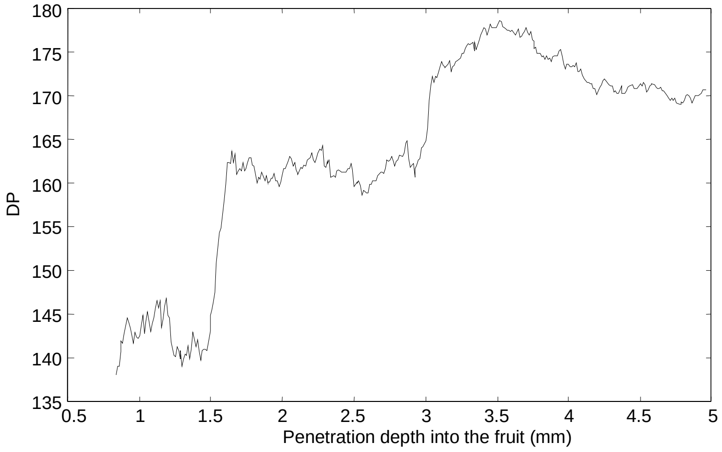

Fig. 4. Evolution of the pressure dispersion parameter during a compression test.