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Design and evaluation a pendulum device to study postharvest mechanical damage in fruits: bruise modeling of red delicious apple

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Abstract

Fruit quality is adversely affected by bruise damage. One of qualitative aspects is the detrimental effect of impact damage. In this research, a pendulum device was developed to study fruit mechanical damage. The bruise prediction models were constructed to apple fruit damage susceptibility (measured by bruise volume) using multiple linear regression analyses. Bruise sensitivity was determined by both impact characteristics (peak contact force or impact energy) and some fruit properties (temperature, ripeness and radius of curvature). Apples were subjected to dynamic loading by means of a pendulum at three impact levels (0.048, 0.14, 0.26 J). Significant effects of acoustic stiffness, temperature and the radius of curvature and some interactions on bruising were obtained 5% probability level with determination coefficient (R^2) of 0.88 and 0.95 for models 1 and 2, respectively. It was concluded that bruise damage of apple fruit will be reduced by increasing temperature and radius of curvature and also by declining acoustic stiffness.

Keywords: dynamic impact; mechanical damage; pendulum; postharvest; regression models.

Abbreviations: BV: Bruise volume, [mm^3], C: Cmpirical constants, [-], D: Bruise diameter, [mm], d: Bruise depth, [mm], dt: Time lapse between successive signals, [s], $E_{1/2:}$ Elastic modulus, [N m^{-2}], $E_{absorbed:}$ Absorbed energy, [J], $E_{elastic:}$ Elastic energy, [J], E_{impact} : Impact energy, [J], $E_{kin:}$ Kinetic energy, [J], f: First resonance frequency, [Hz], g: Gravitational acceleration [9.81 m s^{-2}], $h_{c:}$Critical drop height [m], I: Inertia of the pendulum rod [kg m^2], l: Length of the pendulum rod [m], m : Mass of fruit, [kg], R: Radius of curvature, [mm], S: Acoustic stiffness, [Hz^2 $kg^{2/3}$], T: The temperature of the fruit, [˚C], $t_{-1:}$ Time of the final signal before impact, [s], $t_{n+1:}$ Time of the first signal after the impact, [s], δ : Displacement, [m], $\dot{\delta}$: Deformation rate, [m s^{-1}], ν : Poisson's ratio, [-], ω : Angular velocity of the pendulum, [rad/s], σ_f : Failure stress, [Pa].

Introduction

The bruise damage is considered the most principle and most common type of postharvest mechanical damage. The negative effect of bruise damage contains reduction of fruit juice; moisture loss of a bruised apple may be to a 400% increase compared with an intact apple (Van Zeebroeck et al., 2007c). Among the important factors in fruit bruising, the impact, vibration and compression load noted (Mohsenin, 1986; Lin and Brusewitz, 1994). In order to avoid bruising damage effective factors in the development of bruising should be identified; in other words bruise susceptibility of fruits be surveyed sake find a proper method for detecting bruising. Among the dynamics devices and equipment, impact table and a pendulum device to measure the impact tests in agricultural products are more applicable. The fruit in an impact table dropped upon a flat instrumented surface (solid or cushion) or an instrumented mass falls onto the fruit (Hammerle and Mohsenin, 1966; Fluke and Ahmed, 1972; Diener et al., 1979; Brusewitz and Bartsch, 1989; Chen and Yazdani, 1991; Ragni and Berardinelli, 2001). Due to the location of the impact is not controllable on the fruit and on the other hand, when a conductor truck is used, the friction will cause errors in the measurements, use of a pendulum apparatus instead of an impact table is preferable. Herold et al. (1996) were used of a tactile film (Tekscan® 5051) for measuring static loads concluded that study of the mechanical strength and failure behavior of apple fruit with the Tekscan® method is more accurate than conventional techniques (force sensors). Zapp et al. (1989) and Sober et al. (1990) utilized of dropping the electronic fruit, IS (Instrumented Sphere) onto different surfaces and associating the impact properties to the size of the bruise suffered by apples within a specific size and weight range fell from the same distance onto the same surface in order to estimate of bruise damage. Varith et al. (2001) predicted and compared bruise threshold of apple fruit by applying theory of elasticity and dynamic axial compression (DAC) and paired increasing-height multiple-impacting (PIHMI) techniques. They using the basic concept that bruising occurs when impact induced tissue stress exceeds the failure stress of the fruit tissue as well as using of Hertz theory. An approach for impacting to the fruit is that use of 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. The effect of various fruit factors such as harvest date, maturity, temperature, acoustic stiffness, radius of curvature at the location of impact on the bruising damage of apple and

Table 1. Regression equation of bruise volume (mm^3) of the Red Delicious Apple (V) in relation to peak contact force (PF), temperature (T), acoustic stiffness (S) and radius of curvature (R) as independent variables.

Model 1 *	R^2
BV= 670.079 - 1.449∗PF - 1.964∗T - 9.226∗R - 10.702∗S + 0.145∗PF∗S	0.88

*: minimum probability threshold P≤ 0.05

Table 2. Regression equation of bruise volume (mm^3) of the Red Delicious Apple (V) in relation to impact energy (E_i), temperature (T), acoustic stiffness (S) and radius of curvature (R) as independent variables.

Model 2 *	R^2
BV=505.972 - 284.335∗E_i - 1.704∗T-7.324∗R - 4.96∗S + 41.661∗E_i∗S - 6.233∗E_i∗T	0.95

*: minimum probability threshold P≤ 0.05

tomato respectively by Van Zeebroeck et al. (2007a,b) has been investigated. Bajema and Hyde (1998); Bajema et al. (1998a,b); Van Linden et al. (2006a,b); Van Zeebroeck et al. (2007a,b) and Ahmadi et al. (2010), estimated the bruise model with use of a pendulum device. Detailed information about bruise prediction models for Red Delicious apple is limited. The objective of this work was to design of laboratory equipment for mechanical damage survey and to evolve bruise prediction models for Red Delicious apple include parameters namely peak contact force, impact energy, fruit acoustical stiffness, temperature and radius of curvature as independent variables.

Results and discussion

Bruise prediction model with peak contact force as independent variable

Main effects (peak contact force, temperature, acoustic stiffness and curvature radius) and some interactions were significant at the 5% probability level. Table 1 shows the final model having all of the independent variables. For this model, the plot of predicted bruise volume versus measured bruise volume is depicted in Fig. 1. A good fit was observed between the measured and predicted bruise volume.

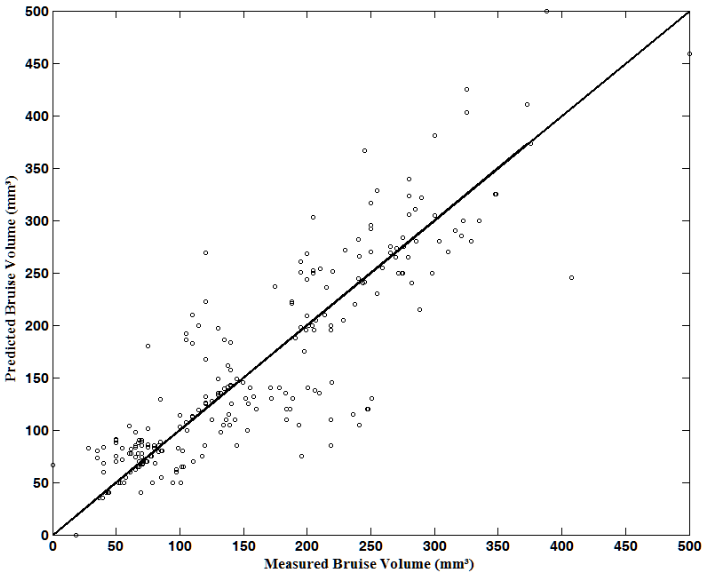

Fig 1. Measured bruise volume (mm3) vs. bruise volume predicted by model 1.

Bruise prediction model with impact energy as independent variable

The results of a multiple linear regression analysis between bruise volume and series of independent variables are presented in table 2. All main factors in this model (model 2) were significant at 5% probability level. Fig. 2 illustrates the predicted bruise volume plotted against the measured bruise volume related to second model. No considerable differences were observed between the predicted bruise volumes of model 1 and model 2 at all impact levels (Fig. 3). Impact levels and some of the interactions with fruit properties had a noticeable influence on the apple fruit bruise damage susceptibility. The high impact level led to the high peak contact stress. Ahmadi et al. (2010); Van Linden et al. (2006a,b) and Van Zeebroeck et al. (2007a,b) reported bruising damage in peach, tomato and apple increase by impact level increasing The impact conditions causing bruising depend on each fruit's tissue structure, dense tissue, with a low volume of air-filled interstitial space (i.e., peach), is sensitive to deep bruises that are typically not visible at the skin surface and will often develop internal cone-shaped and radial fractures when impacted, tissue with a high volume of air-filled interstitial space (i.e., apple) appears to distort in an elastic manner at the contact surface until cell breakage occurs. The elastic area is continuously reestablished further into the fruit until all of the impact energy is either dissipated by cell breakage or stored by elastic membrane distention

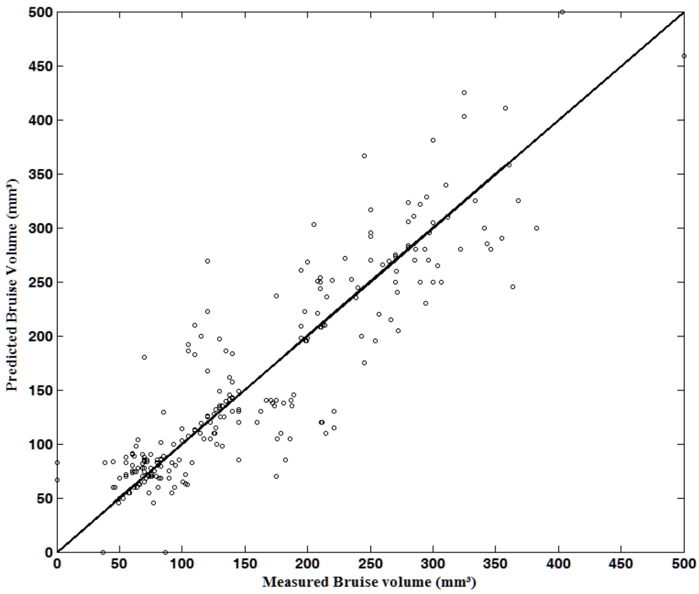

Fig 2. Measured bruise volume (mm3) vs. bruise volume predicted by model 2.

Table 3. Overview of different nominal impact levels applied on the Red Delicious Apple.

	Impact energy (J)		Peak contact force (N)		Bruise volume (mm^3)	
	Average	CV (%)*	Average	CV (%)	Average	CV (%)
Level 1	0.048	9.9	45	5.95	81	11.67
Level 2	0.14	6	79.1	7.1	146	28.28
Level 3	0.26	6.3	106.6	8.6	292	20.6

*: standard deviation as percent of the average

(Schulte-Pason et al., 1992). At low to normal impact levels, which are the most common levels in practice, the fruit properties play a predominant role, but at high impact levels, influence of fruit properties on the bruise damage is inconspicuous.

Effect of apple temperature on bruise volume

Apple temperature has a significant effect ($P<0.05$) on bruise volume. A higher fruit temperature led to less bruising (table 1 and 2, Fig. 4) so, fruit temperature had an inverse effect on the bruise volume. The largest distinction between temperatures in model 1 was remarked at lower impact forces (Fig. 4). This difference ranged from about 22% for the lowest impact (45 N) to 15% for highest impact (106.6 N).
In this study, high temperature reduced the bruise damage. Existing results in references about temperature effects on bruising are inconsistent. Saltveit (1984) reported an incrementally higher bruise volume for fruit at 0-30˚C for two apple varieties. Other researcher deduced no effect of temperature on apple bruising (Schoorl and Holt, 1977; Klein, 1987). Different authors (Van Lancker, 1979; Pang et al., 1992; Thomson et al., 1996; Van Zeebroeck et al., 2007b) reported reduction bruise damage volume and bruise susceptibility with higher temperature for different apple cultivars. The influence of temperature on apple damage bruise susceptibility can be expounded by its effect on apple elasticity and viscosity. Temperature affects stiffness via the activity of enzymes which degrade cell wall. As the cell walls viscosity rised with lowering temperature, the cell walls might get to be more fragile leading to an increased stiffness but decreasing the cell wall inflexibility (Hertog et al., 2004). On the other hand the modulus of elasticity (stiffness) reduces with increasing apple temperature and the modulus of elasticity is positively related to the fruit bruise damage (Van Lancker, 1979; Van Zeebroeck et al., 2007c). The apple temperature generally influenced both tension (strength) of tissue and viscosity of cell wall (Bajema et al., 1998a). With rising of the fruit temperature, failure stress of tissue decreases and failure strain increase therefore reduces elastic modulus and consequently with some sacrifice strength of tissue (Baritelle and Hyde, 2001). Depending on the type of fruit and its physiological status, the relative contributions of temperature and the mechanical rigidity of the cell wall to stiffness might vary. However, metabolic activity and thus softening rate increases with the increase in the storage temperature (Chiesa et al., 1998).

Effect of apple radius of curvature on bruise volume

Apples with low curvature radius had more bruise volume than those with higher curvature radius (Table 1 and 2, Fig. 5). About Second model, the difference in bruise volume between two extremes of apple curvature radius (34 and 46 mm) was about 55% at the low impact energy (0.048 J) and about 38% at the high impact (0.26 J). In this study, more bruise damage resulted in apples with low radius of curvature than apples with higher radius of curvature. Baritelle and Hyde (2001) showed that bruise threshold is a function of

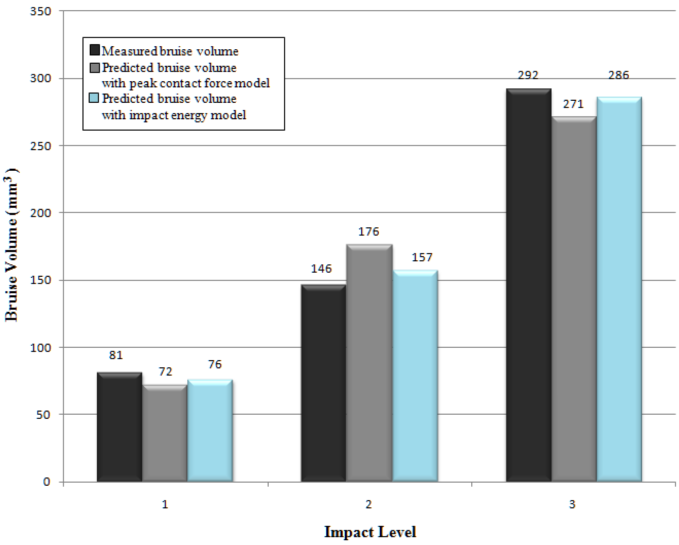

Fig 3. Average of measured and predicted values of bruise volume (mm3) for the apple fruit by models 1 and 2 at different impact levels.

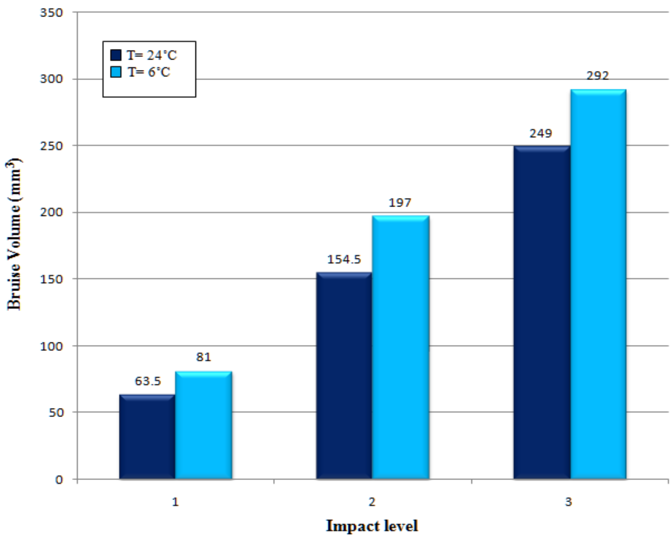

Fig 4. Effect of temperature on the bruise volume (mm3) of apple fruit for each impact peak contact force level. Standard deviation as percent of the average in force level 1 for T=6 ºC was 29.5% and T=24 ºC was 30.9%; in force level 2 for T=6 ºC was 19.4% and T=24 ºC was 21.4%; in force level 3 for T=6 ºC was 19.5% and T=24 ºC was 21%.

fruit tissue, failure stress, impact-induced stress, elastic modulus and fruit mass and curvature radius. The researches concerning the effect of the curvature radius on apple bruise damage are rare (Van Zeebroeck et al., 2007b). Baritelle and Hyde (2000) derived and used the following equation to calculate bruise threshold (critical drop height) with consideration the peak contact stress equivalent to the failure stress:

$$h_c = C(\sigma_f)^5 \frac{1}{mg}\left(\frac{1-\nu_1^2}{E_1}+\frac{1-\nu_2^2}{E_2}\right)^4\left(\frac{1}{R_1}+\frac{1}{R_2}\right)^{-3} \quad (1)$$

They derived that a higher radius of curvature led to a lower impact-induced stress and thus increased a bruise threshold drop height. Van Zeebroeck et al. (2007b) found that at the low impact level, higher radius of curvature reduced bruise damage, but at the high impact, higher radius of curvature increased bruise damage. The conclusion of current research showed that bruising damage is more sensitive to curvature radius at low impact level (the curvature radius role is dominant at low impact).

Effect of apple acoustic stiffness on bruise volume

The result showed that the bruise volume increased with the increase acoustic stiffness (Table 1 and 2, and Fig. 6). The significant interaction term between acoustic stiffness and peak contact force (model 1) indicated that, the bruise volume for the acoustic stiffness of 39 Hz^2 $Kg^{2/3}$ was up to 38% more than one having 27 Hz^2 $Kg^{2/3}$ at low impact force (45 N), and up to 35% higher at high impact level (106.6 N).
Fruit firmness measurement is a suitable approach to monitor fruit softening and to predict bruising injury during harvest and postharvest handling. According to Roth et al. (2005) acoustic stiffness substantially depends on the initial stiffness and positively related to Magness Taylor firmness. Stiffness however, is a rather complex texture trait which differs with ripening stages. It is mainly a mechanical stiffness measurement of the fruit tissue that depends on the cell wall turgidity and cell wall mechanical strength (Hertog et al., 2004). Both reduce during maturity and ripening by moisture loss and by enzymatic alterations of cell wall. Since the acoustic stiffness is positively and directly associated to the modulus of elasticity (Duprat et al., 1997; Landahl et al., 2004; Van Zeebroeck et al., 2007b), the effect of elastic modulus on the bruising injury will be discussed. Baritelle and Hyde (2001) demonstrated that stiffness of tissue decreases with the decrease of turgor and in apple and potato diminished stiffness results in the raise of failure strain, as well as increasing tissue strength. Hence, tissues that are both stronger and less stiff enhance bruise threshold. On the other hand, reducing relative turgor (i.e., during storage) can decrease tissue modulus of elasticity (stiffness) which in turn becomes a specimen more self cushioning, by redistributing an applied force over a larger area of the fruit's surface. Modulus of elasticity, bio-rupture force and rupture stress were all found to decrease as the duration of storage increased (over maturity) (Vursavus and Ozguven, 2003). Crisosto et al. (2001) showed that the relationship between bruising and firmness altered according to bruising impact level. In our study, the effect of the acoustic stiffness on bruising was large at the low impact level.

Materials and methods

Design and construct of the pendulum

The pendulum consisted of a 0.577 m long arm with an aluminum chap to sitting the sensors. Via force sensor and acceleration sensor that was attached to the impactor the data (force, displacement and displacement rate) were obtained to estimate the parameters. The impactor was mounted to a

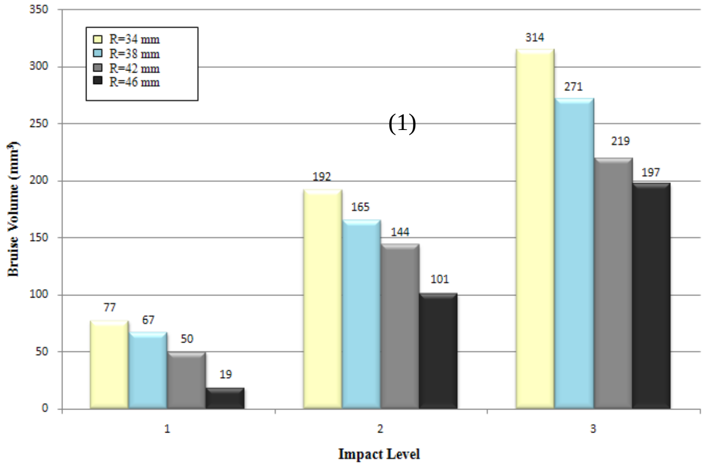

Fig 5. Effect of curvature radius on bruise volume (mm3) of apple at 24˚C for each peak contact force level in relation to model 1. Standard deviation as percent of the average in force level 1 for R=34 was 33.1%, R=38 was 13.5%, R=42 was 15.8% and R=46 was 5.48%; in force level 2 for R=34 was 10.6%, R=38 was 7.8%, R=42 was 6.8% and R=46 was 21.5%; in force level 3 for R=34 was 16.4%, R=38 was 9.2%, R=42 was 14.3% and R=46 was 3.8%.

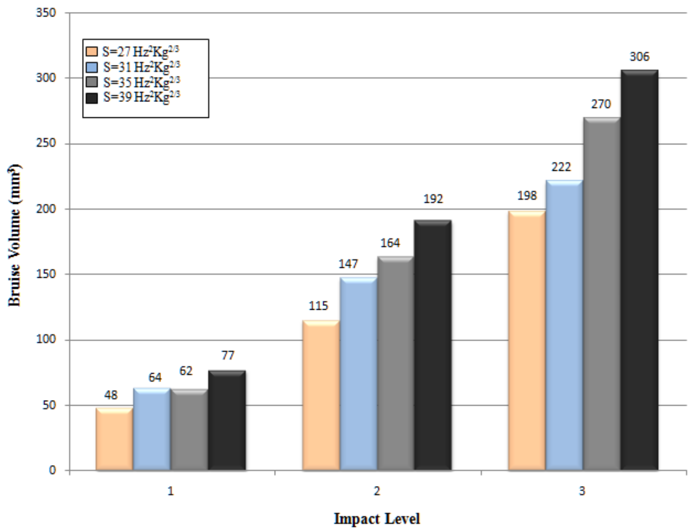

Fig 6. Effect of acoustic stiffness on the bruise volume (mm3) of apple fruit at 24˚C for each peak contact force level in relation to model 1. Standard deviation as percent of the average in force level 1 for S=27 was 47%, S=31 was 13.7%, S=35 was 11.6% and S=39 was 33.1%; in force level 2 for S=27 was 21.7%, S=31 was 7.9%, S=35 was 8.3% and S=39 was 10.6%; in force level 3 for S=27 was 3.7%, S=31 was 15.4%, S=35 was 10.3% and S=39 was 15.6%.

force sensor (PCB 208c02, PCB piezotronics, USA, sensitivity: 10.97 mV/N). An accelerometer was attached at the same location (PCB 320c33, PCB Piezotronics, USA, sensitivity: 105.2 mV/g). An incremental optical encoder (Autonic E 5058, Resolation 0.018, Korea) was mounted at the hinge of the pendulum rod (Fig. 7). A Data acquisition and analyzer (ECON, AVANT Lite, model: MI-6004) was used to analysis data. Description of the parameters that calculated by the pendulum through the energy approach is as follows:

Absorbed energy is calculated by deducing rebound energy of the impact. The impact and elastic energy are obtained from the calculated kinetic energy of the pendulum rod respectively just before, and just after impacting.

$$E_{impact} = E_{kin}(t_{-1})$$

$$E_{elastic} = E_{kin}(t_{n+1})$$

$$E_{absorbed} = E_{impact} - E_{elastic} \tag{2}$$

The kinetic energy of the pendulum rod is calculated as follow equation:

$$E_{kin}(t) = \frac{1}{2} I\omega^2(t) = \frac{1}{2}\frac{I\dot{\delta}(t)^2}{L^2} \tag{3}$$

The displacement rate of the impactor during impact is obtained from the system instantaneous position as:

$$\dot{\delta}_i = \frac{\delta_{i+1} - \delta_{i-1}}{2dt} \tag{4}$$

The impact and elastic energy can be calculated from the impact and rebound angle respectively, applying the potential energy law. The disadvantage of this method is that errors on the impact and elastic energy quantity are made because of the friction at the pivot of the pendulum rod and the energy loss due to rod vibration during rebound (Van Zeebroeck et al., 2007b).

Choice, maintenance and preparation of the fruits

The apple variety Red Delicious was used in the experiments. The apples were harvested in 2011 from “Abbas Abad” district, Hamedan, Iran. Apples were hand-picked at an educational-research orchard to insure their freshness and avoid damage during harvesting and transporting. The apples were harvested at random from the same four trees in the orchard. Fruits were stored in optimal conditions (3˚C, 85% RH) during measurement, with maximum storage before the measurement being six days. Fruits were kept at desired temperature for 10 hr prior to starting the measurements. The apples at 6˚C were measured within 15 min to minimize fruit warming in the measuring room at 24˚C. 120 apples were used in experiments that divided into six groups. For each temperature-impact level combination, 20 apples were tested. Each apple was impacted once. Apples were placed on the pendulum anvil then, were impacted by an impactor (Fig. 8b). The bruise volume was considered dependent variable in the bruise estimation models. The bruise volume was measured 48 hr after impact and determined based on method used by Chen and Sun (1981):

$$BV = \frac{\pi}{6} dD^2 \tag{5}$$

Bruise diameter (width across the major axis of the bruise in the location impact), depth and permanent deformation above the contact plane were measured using the digital vernier calipers (0.01mm). Bruise prediction models included either the impact energy (kinetic energy of pendulum rod just before the collision) or the peak contact force as independent variables along with other variables. The independent variables were used in the regression models were:

- ❖ Impact energy (E_i) (J)
- ❖ Peak contact force (F) (N)
- ❖ Tow apple temperatures (T): 6 and 24˚C
- ❖ Curvature radius of apple (R) at the location of impact
- ❖ Apple acoustic stiffness (S) ($Hz^2Kg^{2/3}$)

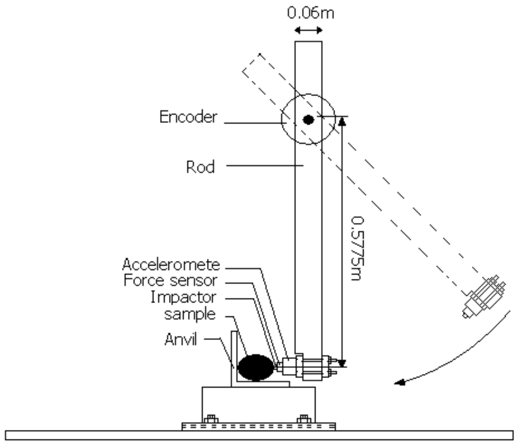

Fig 7. Schematic representation of the pendulum rod and anvil. The positions of the different sensors and of the impacted body “fruit” are indicated.

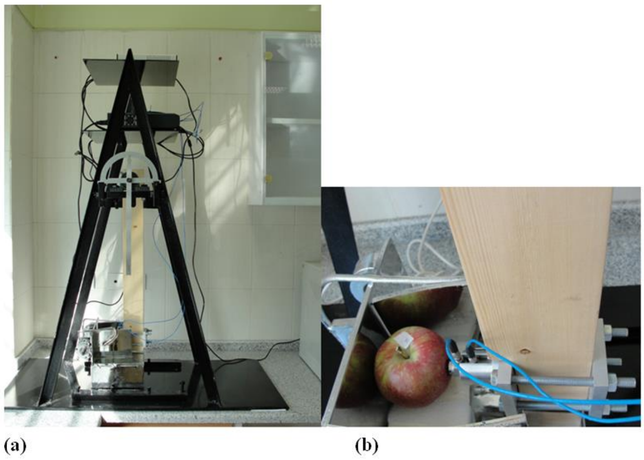

Fig 8. (a) General view of the pendulum device for measuring impact force and impact velocity of the apple fruit and (b) the anvil and rod of the pendulum at beneath the frame.

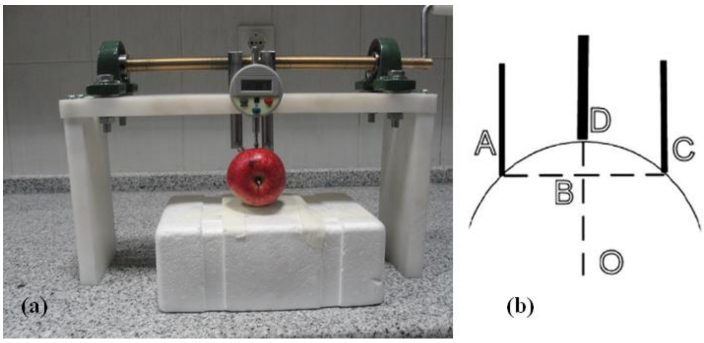

Fig 9. (a) General view of the curvature meter and (b) schematic representation of geometry to calculate the radius of curvature of the apple fruit.

Three nominal impact levels were used as summarized in table 3. The applied impact energy levels were chosen above the critical impact level of apple. All three impact level was recorded during mechanical harvest, handling and transporting. The lower limit of the applied impact level was based on the measured impact force and acceleration during handling and transporting, but the higher impact level was in mechanical harvester. The exact impact energy and peak contact force were recorded and logged to a data file for each impact.

The radius of curvature was measured locally at the fruit contact area by means of a non-commercial radius of curvature meter (Fig. 9b). The radius of curvature was determined as the following equation (Mohsenin, 1986) (Fig. 9a):

$$RADIUS = \frac{(AC)^2}{8(BD)} + \frac{(BD)}{2} \qquad (6)$$

Because apple cannot be considered perfect sphere, the harmonic average of curvature radius $R = (2R_1R_2 / (R_1+R_2))$ was accounted based on circumferential (R_1) and meridian radius of curvature (R_2).

The apple acoustic stiffness was specified on preconditioned fruit based on the acoustic impulse-response technique (De Baerdemaeker et al., 1982; Chen and De Baerdemaeker, 1995; Schotte et al., 1999; Landahl et al., 2000; De Ketelaere and De Baerdemaeker, 2001; Diezma et al., 2006; Wang et al., 2006; Van Zeebroeck et al., 2007a,b). A constructed apparatus was used to measure acoustic stiffness. The acoustic response of each fruit was measured by the fruit collision with an impactor and detecting the generated sound by a microphone (Standard, 8851/8852, Resolution: 0.1dB) on the opposite side and saved in a data file for processing. The acoustic stiffness was calculated as:

$$S \cong f^2 m^{2/3} \qquad (7)$$

Statistical analyses

The dependent variable was the bruise volume (BV) of apple. In the first model independent variables were peak contact force (PF), curvature radius of apple at contact location (R), apple acoustic stiffness (S) and temperature of apple (T). The second model was similar to the first model except that PF was replaced by the impact energy (Ei). A backward multiple regression method was applied to choose the relevant independent variables influencing the dependent variable using 5% significance level. Furthermore, in order to verify the accuracy of multiple regression models, a chi-square test was carried out using the predicted and experimental data. SPSS software (version 16) was used for data analysis.

Conclusions

The main aims of the study were design and construction of laboratory equipment that are essential in the study of postharvest mechanical and to determine the best reliable statistical model among linear multiple regressions, to estimate the apple (Red Delicious) fruit bruising susceptibility by bruise volume. Bruise estimation models contained either the impact energy or peak as independent variables, together with the fruit properties (acoustic stiffness, radius of curvature and apple temperature). Apple bruising depends on the radius of curvature at the contact area, apple temperature and acoustic stiffness. Effects of the fruit characteristics on the bruise volume are summarized below:

Higher apple temperature led to decrease bruising. Bruise volume increased with the increase of acoustic stiffness.

Lower curvature radii led to higher bruising damage.

No significant difference was observed between predicted bruise volume of models with peak contact force and impact energy.

References

Ahmadi E, Ghassemzadeh HR, Sadeghi M, Moghadam M , Zarif Neshat S (2010) The effect of impact properties and fruit properties on the bruising of peach. J Food Eng 97: 110-117.

Bajema RW, Hyde GM (1998) Instrumented pendulum for impact characterization of whole fruit and vegetable specimens. Trans ASAE 41: 1399- 1405.

Bajema RW, Hyde GM, Peterson K (1998a) Instrumentation design for dynamic axial compression of cylindrical tissue samples. Trans ASAE 41: 747-755.

Bajema RW, Hyde GM, Baritelle AL (1998b) Turgor and temperature effects on dynamic failure properties of potato tuber tissue. Trans ASAE 41: 741-746.

Baritelle AL, Hyde GM (2000) Commodity conditioning to reduce impact bruising. ASAE paper No 00- 6059 St Joseph Michigan.

Baritelle AL, Hyde GM (2001) Commodity conditioning to reduce impact bruising. Postharvest Biol Technol 21: 331-339.

Brusewitz GH, Bartsch JA (1989) Impact parameters related to post harvest bruising of apples. Trans. ASAE 32: 953-957.

Chen H, De Baerdemaeker J (1995) Optimisation of impact parameters for reliable excitation of apples during firmness monitoring. J Agric Eng Res 61: 275-282.

Chen P, Sun Z (1981) Impact parameters related to postharvest bruising of apples. ASAE paper No 81-3041 St Joseph Michigan.

Chen P, Yazdani R (1991) Prediction of apple bruising due to impact on different surfaces. Trans ASAE 34: 956-961.

Chiesa A, Diaz L, Cascone O, Panak K, Camperi S, Frezza D, Fraguas A (1998) Texture changes on normal and long shelf-life tomato fruit ripening. Acta Hortic 464-488.

Crisosto CH, Slaughter D, Garner D, Boyd J (2001) Stone fruit critical bruising thresholds. J Am Pomol Soc 54: 76-81.

De Baerdemaeker J, Lemaitre L, Meire R (1982) Quality detection by frequency spectrum analysis of the fruit impact force. ASAE paper No 79-3060 St Joseph Michigan.

De Ketelaer B, De Baerdemaeker J (2001) Advances in spectral analysis of vibrations for non-destructive determination of tomato firmness. J Agric Eng Res 78: 177-185.

Diener RG, Elliott KC, Nesselroad PE, Ingle M, Adams RE, Blizzard SH (1979) Bruise energy of peaches and apples. ASAE paper No 77-1029 St Joseph Michigan.

Diezma B, Valero C, Garcia-Ramos FJ, Ruiz-Altisent M (2006) Monitoring of firmness evolution of peaches during storage by combining acoustic and impact methods. J Food Eng 77: 926-935.

Duprat F, Grotte M, Pietri E, Loonis D (1997) The acoustic impulse response method for measuring the overall firmness of fruit. J Agric Eng Res 66: 251-259.

Fluck RC, Ahmed EM (1972) Impact testing of fruits and vegetables. Trans ASAE 16: 660-666.

Hammerle JR, Mohsenin NN (1966) Some dynamic aspects of fruit impacting hard and soft materials. Trans ASAE 9: 484-488.

Herold B, Truppel I, Siering G, Geyer M (1996) A pressure measuring sphere for monitoring handling of fruit and vegetables. Comput Electron Agric 15: 73-88.

Hertog MLATM, Ben-Arie R, Róth E, Nicolaï BM (2004) Humidity and temperature effects on invasive and non-invasive firmness measures. Postharvest Biol Technol 33: 79-91.

Klein JD (1987) Relationship of harvest date, storage condition and fruit characteristics to bruise susceptibility. J Am Soc Hortic Sci 112: 113-118.

Landahl S, De Belie N, De Baerdemaeker J, Peirs A, Nicolaï B (2000) Non-destructive and destructive firmness measurments on apples and peaches. International conference on modeling and control in agriculture, horticulture and post-harvest processing. Wageningen, the Netherlands.

Landahl S, Herppich WB, Herold B, Geyer M, De Baerdemaeker J (2004) A comprehensive evaluation of the interactions between produce elasticity and water status. Eur J Hortic Sci 69: 250-257.

Lin X, Brusewitz GH (1994) Peach bruise thresholds using the instrumented sphere. Appl Eng Agric 10: 509- 513.

Mohsenin NN (1986) Physical properties of plant and animal materials. Gordon and Breach Science Publishers, New York.

Pang W, Studman CJ, Ward GT (1992) Bruising damage in apple- to- apple impact. J Agric Eng Res 52: 229- 240.

Ragni L, Berardinelli A (2001) Mechanical behaviour of apples, and damage during sorting and packing. J Agric Eng Res 78: 273-279.

Roth E, Kovacs E, Hertog M, Vanstreels E, Nicolai B (2005) Relationship between physical and biochemical parameters in apple softening. Proceeding of the 5th International Postharvest Symposium (PS’05), ISHS, pp 573-578.

Saltveit M (1984) Effects of temperature on firmness and bruising of Starkrimson Delicious and Golden Delicious apples. HortScience 19: 550-551.

Schoorl D, Holt JE (1977) The effects of storage time and temperature on the bruising of Jonathan, Delicious and Granny Smith apples. J Texture Stud 8: 409-416.

Schotte S, De Belie N, De Baerdemaeker J (1999) Acoustic impulse-response technique for evaluation and modeling of firmness tomato fruit. Postharvest Biol Technol 17: 105-115.

Schulte-Pason NL, Brown GK, Timm EJ (1992) Apple impact damage thresholds. Appl Eng Agric 8: 55-60.

Sober SS, Zapp HR, Brwon GK (1990) Simulated packing line impacts for apple bruise prediction. Trans ASAE 33: 629-636.

Thomson GE, Cotter DF, Daly PA (1996) Temperature effects on bruise darkness of granny smith. Golden delicious and Jonathan apples. NZ J Crop Hortic Sci 24: 99-101.

Van Lancker J (1979) Bruising of unpeeled apples and potatoes in relation with temperature and elasticity. Lebensm Wiss Technol 12: 157-161.

Van Linden V, De Ketelaere B, Desmet M, De Baerdemaeker J (2006a) Determination of bruise susceptibility of tomato fruit by means of an instrumented pendulum. Postharvest Biol Technol 40: 7-14.

Van Linden V, Scheerlinck N, Desmet M, De Baerdemaeker J (2006b) Factors that affect tomato bruise development as a result of mechanical impact, Postharvest Biol Technol 42: 260-270.

Van Zeebroeck M, Van Linden V, Darius P, De Ketelaere B, Roman H, Tijskens E (2007a) The effect of fruit properties on the bruise susceptibility of tomatoes. Postharvest Biol Technol 45: 168-175.

Van Zeebroeck M, Van Linden V, Darius P, De Ketelaere B, Roman H, Tijskens E (2007b) The effect of fruit factors on the bruise susceptibility of apples. Postharvest Biol Technol 46: 10-19.

Van Zeebroeck M, Van Linden V, Roman H, De Baerdemaeker J, Nicolaï BM, Tijskens E (2007c) Impact damage of apples during transport and handling. Postharvest Biol Technol 45: 157-167.

Varith J, Hyde GM, Baritelle AL, Sattabongkot T (2001). Fruit and vegetable bruise threshold prediction using theory of elasticity and tissue failure properties. ASAE Paper No 01-6139 St Joseph Michigan.

Vursavus K, Ozguven F (2003) Determining the strength properties of the Dixired peach variety. Turk J Agric For 27: 155-160.

Wang J, Teng B, Yu Y (2006) The firmness detection by excitation dynamic characteristics for peach. Food cont 17: 353-358.

Zapp HR, Ehlert SH, Brown GK, Armstrong PR, Sober SS (1989) Instrumented sphere performance: dynamic measurements and demonstration, ASAE Paper No 89-0008 St Joseph Michigan.