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Evaluation of the bruising susceptibility of apple in transport conditions

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Abstract

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Transporting vibration is a major cause of bruising damage in apples. The most previous studies about the bruising susceptibility of apple were conducted using the pendulum device and with a single impact. So their results for transport conditions are not accurate, because the effect of tissue fatigue (caused by cyclic loading) and apple mass have not been considered. In this study, using a vibration simulation of transportation, the effect of vibration parameters (frequency and acceleration) and fruit properties (mass, curvature radius and acoustical stiffness) on bruising susceptibility of Golden Delicious apple were investigated. The results showed that, increasing the vibration acceleration increases the bruising volume. Also increasing the vibration frequency decreased the bruising, but in higher frequencies ($f \geq 13$ Hz), if the acceleration value is greater than 0.5 g, the fatigue phenomenon can reverse this trend and increasing the frequency will increase the bruising volume. Increasing the apple mass, at the acceleration of 0.5 g or more ($a \geq 0.5$ g), increased the bruising volume and at accelerations of less than 0.5 g, reduced the bruising volume. Also results indicated that the apples with high acoustic stiffness and low curvature radius were more vulnerable. In conclusion, the results showed that to improve the handling of apple, arrangement of fruit in the box must be carried out carefully and we hope that findings of this research will help to achieve this goal.

Keywords: apple; transport conditions; bruising; vibration
Abbreviations: R – radius of curvature, S – acoustic stiffness, m – mass, F – frequency, a – acceleration, BV – bruise volume

Introduction

Consumers increasingly demand better quality fruits. Postharvest mechanical damage is responsible for the deterioration in the quality of fresh fruits (Hussein et al., 2017). For most type of fruits such as apple, bruising is the most common type of mechanical damage (Knee and Miller, 2002). Bruise damage is a type of subcutaneous tissue failure without rupture of the skin where the discoloration of injured tissues indicates the damaged spot (Blahovec and Paprštein, 2005; Stropek and Gołacki, 2015). Losses of bruising in apples are not restricted to visual aspects, but higher risk of bacterial and fungal contamination can lead the fruit to a lower shelf-life (Van Zeebroeck et al., 2007a, b; Fadiji et al., 2016b). To study bruising damage, identification of the effective factors such as types of acting forces on the fruit and fruit characteristics (variety, maturity stage, curvature radius, firmness fruit mass and etc.) is necessary (Van Linden et al., 2006; Zarifneshat et al., 2010). Various studies have been conducted which indicate that impact, compression and vibration forces account for the majority of the mechanical damage of horticultural products (Jarimopas et al., 2007; Opara, 2007; Chonhenchob et al., 2009; Ahmadi, 2012; Eissa et al., 2012; Lu et al., 2012). Of these three forces, the vibration force can cause the most bruises which usually occur during transportation and is difficult to avoid (Van Zeebroeck et al., 2006; Fadiji et al., 2016a; Hussein et al., 2017).

Bruise susceptibility of fruit and vegetables is a measure for the response to external loading (Mohsenin, 1986). The most previous studies that performed about the bruising susceptibility of apple are conducted using the pendulum device and with single impact (Rostampour et al., 2013; Hussein et al., 2017). These results for transportation condition can't be correct, because in these studies the effect of tissues fatigue (caused by vibration or repetitive impact) and apple mass has not been considered, while these factors in the bruise susceptibility of apple in transportation condition are very effective.

Therefore, in this research to improve the handling methods, the effect of vibration parameters (frequency and acceleration) and fruit properties (mass, curvature radius and acoustical stiffness) alongside each other, on the bruising susceptibility of apple in simulated transport conditions is studied. Considering the effects of tissue fatigue (created by repetitive impact) and apple mass, the results are valid for transport conditions.

Materials and Methods

Sample preparation

'Golden Delicious' apples were picked from the three marked trees, in harvest season of 2015 from "Nazlo", Urmia region of Iran. Fruits free from physical defects were selected and the effect of these independent variables on the bruising vulnerability of apple was investigated: apple mass (m) at three levels (100 g, 130 g, 160 g), apple radius of curvature in location of impact (R) at two levels (36 mm, 52 mm), apple acoustic stiffness (S) at two levels (40 $Hz^2kg^{2/3}$, 55 $Hz^2kg^{2/3}$), vibration frequency (F) and vibration acceleration (a).

Radius of curvature

Radius of curvature (R) was measured by the same device used by Zarifneshat et al. (2010) and was calculated using the following equation (Mohsenin, 1986) (Fig. 1a):

$$R = \frac{(AC)^2}{8(BD)} + \frac{(BD)}{2} \qquad (1)$$

Acoustic stiffness

Acoustical stiffness gives information about the texture of the whole fruit. It is related to the cell wall mechanical strength and cell wall turgidity. The apples acoustic stiffness (S) were determined, according to acoustical impulse-response method (Van Zeebroeck et al., 2007 b; Ahmadi et al., 2010; Zarifneshat et al., 2010; Lashgari et al., 2017). An acoustic chamber was made and a microphone (ADMP401, Analog Devices) was fixed inside the chamber. The fruits stimulated of four points by a falling piece of wood on the equator, at the opposing side of the microphone (Fig. 1b). By Fast Fourier Transform (FFT), the first resonance frequency was determined and the acoustical stiffness was calculated by following equation (Barikloo and Ahmadi, 2013):

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

where S is the acoustic stiffness (Hz^2 $kg^{2/3}$), f is the first resonance frequency (Hz) and m is the mass of the apple (kg).

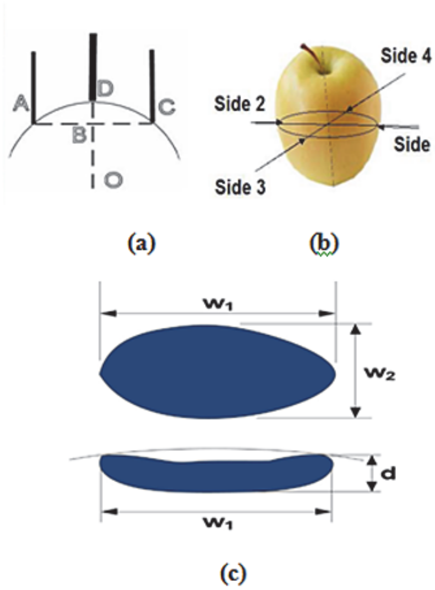

Fig 1. Schematic representation of geometry to calculate the radius of curvature (*a*), stimulated places of apple for measuring the acoustical stiffness (*b*) and elliptical bruise thickness method for bruise volume determination (*c*)

Provide vibration

Three levels of vibration frequency (7.5 Hz, 10 Hz, 13 Hz) and vibration acceleration (0.3 g, 0.5 g, 0.7 g), were used in evaluation the effect of vibration parameters (frequency and acceleration) on apple bruising, as the most repetitive vibration in a truck-bed during fruit transportation in Iran roads (Shahbazi et al., 2010). To provide vibration, a vibration simulator was used, as the same vibrator used by Shahbazi et al. (2010) and Rostampour et al. (2013). This vibration simulator consists of a table on soft springs and attached to it an actuating system. Similar method has used by Van Zeebroeck et al. (2006) and Shahbazi et al. (2010)

to avoid the incorporation of the frequency and acceleration effects, with increasing the vibration frequency, the vibration acceleration must be maintained. To achieve this purpose, according to Eq. 3, in which $\ddot{X}$ is the acceleration (g), f is the frequency (Hz) and X is the displacement amplitude of a vibrating table, with increasing frequency, the displacement amplitude of the vibrating table was reduced to the constant vibration acceleration.

$$\ddot{X} = -4\pi^2 f^2 X \qquad (3)$$

Bruise volume measurement

For full development of bruises and more apparent, measurements were performed after 48 hours of damage. Bruise dimensions were measured and bruise volume (BV) was quantified by following equation (Opara and Pathare, 2014; Fadiji et al., 2016a):

$$BV = \pi \frac{d}{24}(3w_1 w_2 + 4d^2) \qquad (4)$$

where w_1 and w_2 are the bruise width along the major and minor axes (mm) and d is the depth of the bruise (mm) (Fig. 1c).

Statistical analyses

A total of 620 apples were used for conducting the experiments. The experimental data were treated with one-way analysis of variance (ANOVA) to determine the effect of the independent variables (frequency, acceleration, apple mass, radius of curvature in location of impact, acoustical stiffness) on the bruising volume of apples. The means of the treatments were compared with Duncan's multiple range tests, where the significance level was set at 1% and 5%.

Results and Discussion

Effect of frequency and acceleration

Effect of acceleration

On all three levels of frequency due to an increase in the amount of signal energy (Berardinelli et al., 2005), increasing the acceleration increased the bruising value (Fig. 2a). At a frequency of 7.5 Hz, increasing acceleration from 0.3 g to 0.5 g and from 0.5 g to 0.7 g, the increase in the bruising volume of samples was significant) $P < 0.01$. (While at a frequency of 10 Hz and 13 Hz, only increases in acceleration from 0.5 g to 0.7 g caused a significant increase in bruising volume. This behavior can be related to changes in the vertical displacement amplitude of the vibrating table (the severity of the impact to the fruit) and the allowable critical impact height in the apple fruit. Baritelle and Hyde (2000) used this equation for calculating the critical impact height as follow:

$$h_c = C(\sigma_f)^5 (mg^{-1}) \left(\frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \right)^4 \left(\frac{1}{R_1} + \frac{1}{R_2} \right)^{-3} \qquad (5)$$

where h_c is the critical drop height that create bruising; C is a constant; σ_f is the failure stress (Pa); m is the mass of apple (kg); g is the 9.81 earth gravity (m/s^2); $v_{1,2}$ is the Poisson's ratio; $E_{1,2}$ is the elastic modulus (Pa) and R is the curvature radius (m).

According to Eq. 3 at a frequency of 7.5 Hz, the vertical displacement of the vibrating table (the severity of the impact on the fruit) was higher than the higher frequency levels (10 Hz and 13 Hz), and the severity of many impacts was higher than the threshold level of the critical impact of apple fruit. Thus, at a frequency of 7.5 Hz, increasing the vibration acceleration from 0.3 g to 0.5 g and from 0.5 g to 0.7 g and increasing the amplitude of vibration, increased the bruise volume significantly. But, at a frequency of 10 Hz and 13 Hz, the intensity of the impacts was less than the threshold level of the critical impact of apple fruit and increasing acceleration from 0.3 g to 0.5 g no significant difference was found between the bruise volume of the fruit. But increasing acceleration from 0.5 g to 0.7 g, many of the impacts exceeded the threshold level of critical impact and the bruising volume increased significantly.

Effect of frequency

By increasing the frequency from 7.5 Hz to 10 Hz (at all three levels of acceleration) and increasing the frequency from 10 Hz to 13 Hz (at 0.3 g and 0.5 g), the bruising volume decreased (Fig. 2b). This reduction was due to the discontinuity of the impacts, and reduced the impact time on the fruit. But, increasing the frequency from 10 Hz to 13 Hz (at 0.7 g), due to an increase in the number of impacts and creation of fatigue phenomena in the fruit tissues, the bruising volume increased. Therefore, increasing the frequency, in high accelerations, can lead to a fatigue phenomenon. Also, as shown in Fig. 2a, at a frequency of 10 Hz, increasing acceleration from 0.5 g to 0.7 g, the average amount of bruising volume increased by 120%, but at a frequency of 13 Hz this increase was 330%. This difference in augmentation of the bruising volume shows the appearance of a fatigue phenomenon in the fruit tissues. The amount of this increase in bruising volume, with the increase of acceleration from 0.3 g to 0.5 g (at 10 Hz) was 83% and with the increase of acceleration from 0.3 g to 0.5 g (at 13 Hz) was 85%. Comparing these percentages shows the high importance of the amount of acceleration in the intensity of the effect of fatigue phenomena in fruit tissues at high frequency levels.

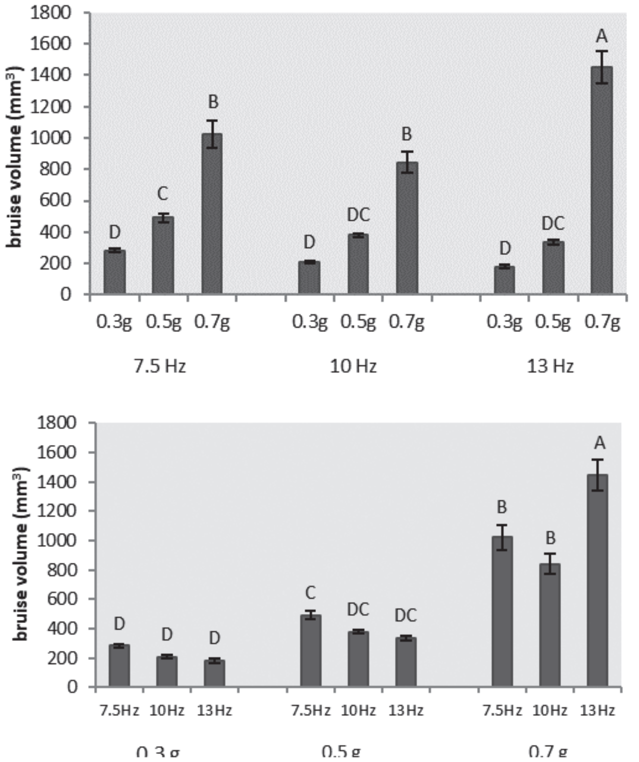

Fig. 2. Effect of acceleration (*a*) and effect of frequency (*b*) on bruise volume

Effect of apple mass

The effect of apple mass on the bruising volume was significant ($P < 0.01$). At acceleration of 0.3 g, the vertical displacement amplitude of the vibrating table (the severity of the impact on the fruit) was less (Eq. 3), and the increase in the mass has led to a lower impact force and reduced the amount of bruising (Fig. 3a). But, increasing acceleration to 0.5 g and 0.7 g, the vertical displacement amplitude of the vibrating table increased and all the fruit were displaced. On the other hand, according to Newton's second law, the force exerted on larger masses is greater and has led to more bruising. Therefore, it can be said that the apple mass, according to the threshold level of acceleration of 0.3 g, can have a dual effect on the bruising volume. Also, the results of the comparison of means showed that by increasing the vibration acceleration, the difference between the bruise volume of the larger and smaller apples becomes more apparent. These results are in agreement with the literature. Van Zeebroeck et al. (2006) have been reported that the relative importance of the apple size on bruise damage could be dependent to the vibration frequency and acceleration amplitude.

At all frequencies, increasing the fruit mass increased the bruising volume (Fig. 3b). At a frequency of 7.5 Hz, a significant difference was observed ($P < 0.05$) between the bruise volume of high mass (160 g) and average mass (130 g) with low mass (100 g). Because at lower frequencies, the vertical displacement amplitude of the vibrating table was higher (Eq. 3) and all the apples were oscillated. On the other hand, according to Newton's second law, lower force is applied to the smaller fruit causing lower bruises.

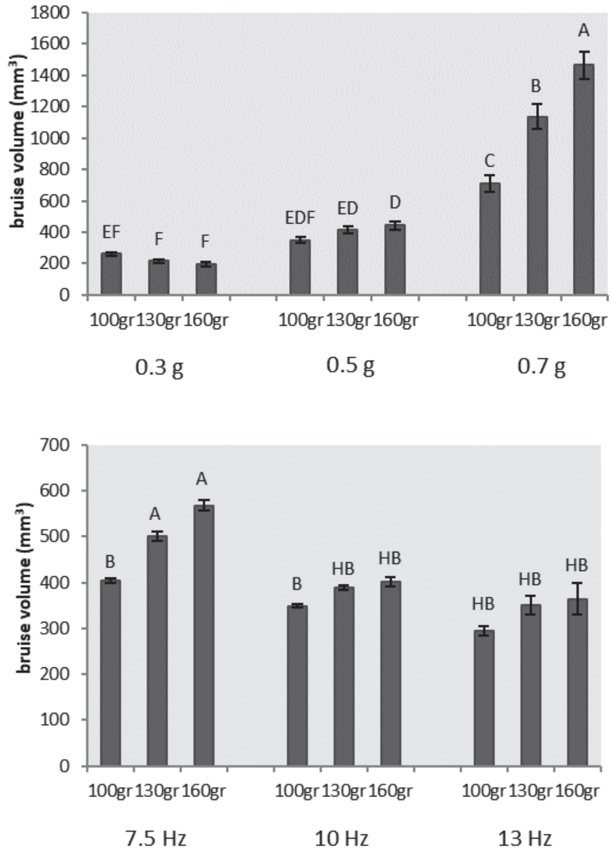

Fig. 3. Effect of apple mass on bruise volume in different levels of acceleration (*a*) and in different levels of frequency (*b*)

Effect of curvature radius

As shown in Fig. 4a, b, the apples with low curvature radius (36 mm) had higher bruise volume in compare with apples with high curvature radius (52 mm) ($P < 0.05$). The following equation confirms this result (Horsfield et al., 1972):

$$\sigma_i = C(mgh)^{1/5}\left(\frac{1-v_1^2}{E_1}+\frac{1-v_2^2}{E_2}\right)^{-4/5}\left(\frac{1}{R_1}+\frac{1}{R_2}\right)^{3/5} \qquad (6)$$

where σ_i is the peak contact stress (Pa); *C* is the constant; *m* is the mass (kg); *g* is the earth gravity (m/s^2); *h* is the drop height (m); $v_{1,2}$ is the Poisson's ratio; $E_{1,2}$ is the elastic modulus (Pa) and *R* is the radius of curvature (m). According to Eq. 6, in low curvature radius, impact is applied to a small spot, so the peak contact stress (σ_i) is more than high curvature radius. The high stress causes fruit tissue to reach biological yield point earlier and bruise volume to be greater. But the following equation that in it, the bruise volume is assumed to be the same as the contact surface shows an opposite effect of curvature radius on bruise volume (Siyami et al., 1988):

$$BD = 4.624\left(\frac{mhR^2}{4F_{mt}}\right)^{1/5} \tag{7}$$

where, *BD* is the bruise diameter (mm); *m* is the mass (kg); *R* is the radius of curvature (m); *h* is the drop height (mm) and F_{mt} is the Magness-Taylor force, for 11 mm probe (kg). Eq. 7 indicates that larger radius of curvature leads to a larger contact area and hence to a larger bruises volume, but the effect of this equation depending on severity of impact and is correct only in high impact condition. Eq. 7 supports results in decrease difference of bruise volume between two levels of curvature radius, at the frequency of 7.5 Hz (66%) in comparison with 10 Hz (112%) and at the acceleration of 0.7 g (72%) in comparison with 0.5 g (105%). Because with decreasing frequency (in constant acceleration of 0.5 g) and increasing acceleration (in constant frequency of 10 Hz), the vertical displacement amplitude of vibration simulator (severity of impact) increased (Eq. 3). Then this increase is caused that the effect of Eq. 7 more be evident and the bruise for high radius of curvature increases more than low radius of curvature, and the difference in bruise volume of two curvature radius decreases.

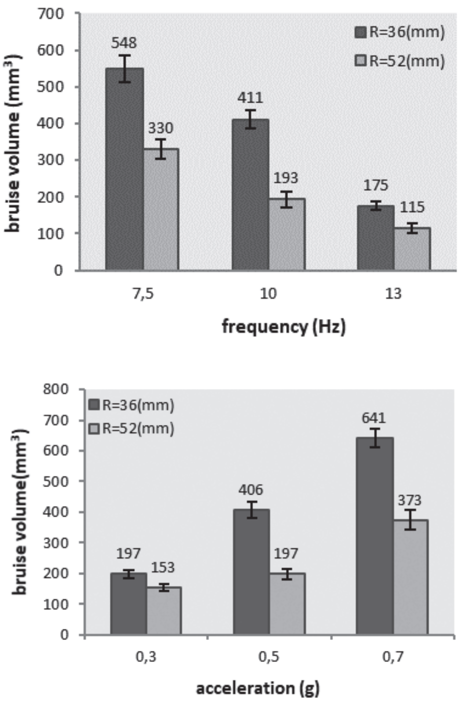

Fig. 4. Effect of curvature radius on bruising in different levels of frequency (*a*) and in different levels of acceleration (*b*)

Effect of acoustic stiffness

The bruise volume has increased with the increase of acoustical stiffness ($P < 0.05$) (Fig. 5a, b). Previous studies (Duprat et al., 1997; Landahl et al., 2004) indicated that the acoustic stiffness has a positive relationship with the elastic modulus and according to Eq. 6, increase in the elastic modulus increases the bruise volume. On the other hand, some researchers as Abbott and Lu (1996) and Duprat et al. (1997), found a positive correlation between apple acoustic stiffness and Magness-Taylor firmness, and reported that stiffer apple due to higher firmness are more resistant to bruising. In conclusion, it seems that acoustic stiffness has a dual effect on the bruising of apples. In low intensity of impacts, the high stiffness reduces bruise volume. But in high impacts according to Eq. 6, the high stiffness increases bruise volume. This conclusion is agreement with the results of this research.

As shown in Fig. 5a, with increasing frequency from 7.5 Hz to 10 Hz, vertical displacement amplitude of vibration simulator (intensity of impact) decreases (Eq. 3) and bruise volume for high and low stiff apples decreases. Also with increasing frequency, the number of impact increases and bruise volume for high and low stiff apples increases (tissues fatigue), but this increase for high stiff apples is more than of low stiff apples. Therefore, difference bruise volume of high and low stiff apples at the frequency of 10 Hz (106%) is more than 7.5 Hz (60%). With increasing frequency from 10 Hz to 13 Hz, bruising (tissues fatigue) in high stiff apples increases more than low stiff apple, but due to very more decreasing in intensity of impacts, bruising in high stiff apples decreases very more than low stiff apples.

As shown in Fig. 5b, with increasing acceleration from 0.3 g to 0.7 g, difference bruise volume of high and low stiff apples was increased (for high stiff apples 224% and for low stiff apples 140%), because with increasing acceleration, vertical displacement amplitude of vibration simulator (intensity of impact) increases (Eq. 3) and according to Eq. 6, the bruise volume in high stiff apples increases more than low stiff apples.

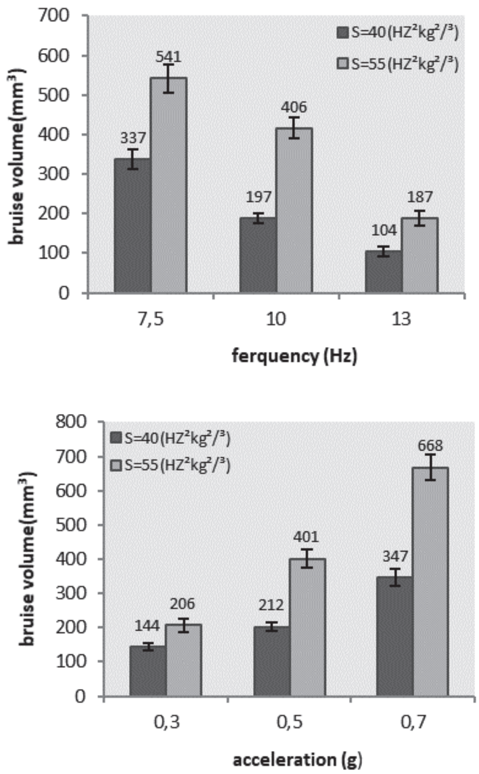

Fig. 5. Effect of acoustical stiffness on bruising in different levels of frequency (a) and in different levels of acceleration (b)

Conclusions

In this research the effect vibration parameters (frequency, acceleration) and apple properties (mass, curvature radius, acoustical stiffness) on the bruising susceptibility of Golden Delicious apple was investigated and significant main effects as well as significant interactions effects were discussed. The results showed that, increasing the vibration acceleration increases the bruising. Also, increasing the vibration frequency decreases the bruising, but in higher acceleration values, the fatigue phenomenon can reverse this trend. The results showed, generally apples with more mass and high acoustic stiffness are more vulnerable. Thus, for reducing the damage, sorting and separating the fruits, and more accurately in packaging fruits with more mass and high stiffness is necessary. Also since fruits with radius of curvature less are more vulnerable, therefore, in arrangement of fruit in the box must be careful and low curvature radius of the fruit is not in contact with the floor box. This arrangement can help to reduce damage.

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