Journal of Zhejiang University SCIENCE B
ISSN 1673-1581 (Print); ISSN 1862-1783 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Firmness measurement of peach by impact force response*

Yong-wei WANG, Jun WANG†‡, Chong YAO, Qiu-jun LU

(*Department of Biosystems Engineering, Zhejiang University, Hangzhou 310029, China*)

†E-mail: jwang@zju.edu.cn

Received Apr. 18, 2009; Revision accepted Oct. 12, 2009; Crosschecked Nov. 3, 2009

Abstract: The impact force response of a peach impacting on a metal flat-surface was considered as nondestructive determination of firmness. The objectives were to analyze the effect of firmness, drop height, fruit mass, and impact orientation on the impact force parameters, and to establish a relationship between the impact force parameter and firmness. The effect of fruit firmness, drop height and fruit mass on the impact force parameters (coefficient of restitution, percentage of energy absorbed, and coefficient of force-time) was evaluated. The study found that the coefficient of restitution, percentage of energy absorbed, and force-time impact coefficient were significantly affected by fruit ripeness, but not affected by drop height, impact position (fruit cheek), and mass. The percentage of absorbed energy increased with ripeness, while the force-time impact coefficient and coefficient of restitution decreased with ripeness. Relationships were obtained between the three impact characteristic parameters (force-time impact coefficient, coefficient of restitution, and percentage of energy absorbed) and peach firmness using a polynomial model (R^2=0.932), S model (R^2=0.910), and exponential model (R^2=0.941), respectively.

Key words: Firmness, Peach, Impact force, Coefficient of restitution, Percentage of absorbed energy
doi:10.1631/jzus.B0920108 **Document code:** A **CLC number:** S12

INTRODUCTION

Quick and nondestructive methods for measuring texture are critical for controlling postharvest quality of agricultural and food products. Many methods, including force deformation analysis (Schmilovitch *et al*., 1995; Timm *et al*., 1996; Fu *et al*., 2008), vibration (Abbott and Massie, 1995; Peleg, 1999), acoustics (Sugiyama *et al*., 1998; Wang and Teng, 2006), and ultrasound (Mizrach *et al*., 1997; Wang *et al*., 2006), have been applied in determining the quality of fruits and vegetables. Most of these inspection methods are nondestructive and can be conducted with small force applications and displacements. The impact force inspection method, however, has advantages compared to others, because there is no need for placing a transducer on the surface of the product, nor are any cumbersome devices required to immobilize it.

Research has shown that impact force analysis (IFA), in which fruit is made to impact a stationary force sensor, can determine firmness on a wide range of crops including peaches, apricots, kiwifruits, blueberries, tomatoes, and pears (Delwiche *et al*., 1987; 1989; 1996; Scorza *et al*., 2004; Wang *et al*., 2007; Zhang *et al*., 1994). IFA has a number of advantages. First, there is rapid measurement, as each impact lasts only for milliseconds. Second, impact sensors are inexpensive, and finally samples are easy to handle. While prototype online systems have been developed, none have been commercialized. Handling and orienting the fruit at the grader speeds has proven to be a more difficult problem to solve than initially suspected and the technique seems only suitable for quasi-spherical fruits where orientation is not a significant problem (Delwiche *et al*., 1987; 1989; 1996; Scorza *et al*., 2004; Wang *et al*., 2007; Zhang *et al*., 1994).

The IFA measurements are affected by the fruit mass and impact velocity. In principle, measuring fruit mass and dropping the fruit from a fixed height

‡ Corresponding author

* Project supported by the National Natural Science Foundation of China (No. 30570449) and the Program for New Century Excellent Talents in Chinese University (No. NCET-04-0544)

for IFA firmness measurement is simple. On the line grading situation at processing speeds of several fruits per second, attaining a fixed repeatable drop height may not be easy and mass measurement is not simple. There is, therefore, an attendant increase in firmness measurement error, and it becomes necessary to know the acceptable tolerances, or how to correct for changes in these parameters. In addition, the radius of curvature of the fruit also affects IFA measurements, though for regularly shaped quasispherical fruit the radius is closely related to fruit mass, especially if fruit density is constant between fruit (Delwiche *et al.*, 1987; 1989; 1996; Zhang *et al.*, 1994). Hence it is very important in this study that the employed evaluation parameters were unaffected by mass and dropping height during IFA measurements.

Although firmness information may be improved for greater drop heights (fruit behavior is viscoelastic, which raises the possibility that IFA firmness estimates may change significantly with more energetic impacts and more closely match firmness measured by standard destructive measures like the penetrometer), the fruit can be damaged during higher energy impacts, and it is thus necessary to keep the drop height below the level at which damage is likely. In determining an optimal drop height for IFA measurements, the drop height must be sufficient to provide precision in the force measurements during an impact, but not likely to cause damage.

The specific objectives of the research are: (1) analysis of the effect of firmness, drop height, fruit mass, and impact orientation on the impact force parameters, and (2) establishment of a relationship between the impact force parameter and firmness.

MATERIALS AND METHODS

Peach samples

The test samples (Yidianhong peach) were hand harvested in June 3~17, 2007 from an experimental orchard in the Department of Horticulture (30°10′ N, 120°07′ E), Zhejiang University, China. Twenty peaches each day (a total of 300 peaches) were picked on the morning of the test day. Each day, upon arrival at the laboratory, peaches were again inspected to ensure that they were undamaged and not attacked by worm. After inspection, experiments were conducted within 2 h at room temperature (about 18~22 °C).

Experimental system

The experimental setup consisted of three load cells, signal amplifier, a personal computer (PC) and software to control the experimental setup and to analyze its results. A schematic diagram of the system is presented in Fig.1.

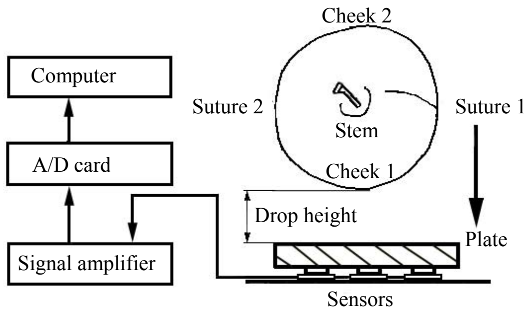

Fig.1 Schematic diagram of the experimental system
A/D: analog to digital

The determination of impact force characteristic required a load cell attached to a mass considerably larger than a peach. A general property of load cells is that they produce a signal not only under compression or tension but from torques as well. When a single load cell is fitted with a platform for bouncing the peach, different points of contact on the platform will cause different torques (Delwiche *et al.*, 1996); hence, no reproducible results. To eliminate the torque effect, we used three load cells (Model CA-108, China-YEC Inc., Yongzhou, China; sensitivity 3.24 mV/N, rise time 10^{-7} s) spaced triangularly and mounted between two aluminum circular plates (a base plate and a platform plate).

The impact force response was detected by an amplifier and a commercial analog to digital (A/D) board connected to the PC, which simultaneously served as the data acquisition system. An optical sensor was used to trigger the acquisition. The signals were sampled at a rate of 20000 samples/s per sensor for a period of 60 ms.

When a spherical object is dropped onto a flat horizontal surface, the force on that surface as a function of time depends on the mass of the sphere, the distance of fall, and the elastic properties of the spherical object. The interrelationships of these variables are not simple, but most are measureable dynamically. Contact force as a function of time $f(t)$, however, is acquired through a computer-controlled data acquisition system, and an approach based solely on $f(t)$ is highly desirable. Typical $f(t)$ curves for multiple bounces in unripe and ripe peaches are shown in Fig.2.

Preliminary tests were performed in order to identify a proper drop height, which did not cause any damage to peach tissue (after 24 h by visual inspection). As a result of preliminary tests, two drop heights of 0.5 cm and 1 cm were selected for all further tests. Drop impacts were conducted at two locations (orientation: cheek 1, cheek 2) along the largest circumference of the fruit. All experiments were conducted using different fruit and each experiment was performed on 10 replicates (i.e., 10 fruits were used per experiment).

Firmness measurement

After the drop impact experiments, the Magness-Taylor (M-T) firmness of each peach (firmness of destructive penetration) was measured at two orientation points (cheek 1 and cheek 2) in the peach equator by using an Instron 5543 Universal Testing Machine. Penetration tests were conducted with the diameter 8 mm diameter by penetrating in 10 mm (Wang and Teng, 2006). The loading rate of the crosshead was 25 mm/min. The M-T firmness was determined to be the mean of the maximum force for two orientation points.

Impact force response

In this paper, the impact force of a peach is considered with the coefficient of restitution, the percentage of energy absorbed, and the coefficient of impact force-time. Impact peak force, contact time, time-to-peak force, and energy parameters were defined similar to previous researchers, i.e., Wan *et al.* (1997) and Yen and Wan (2003), Wang *et al.*(2006; 2007).

1. Typical characteristics of force-time impact curves

In Fig.2, the impact characteristics are shown for two peaches with equal mass but different firmness when dropped from the same height. Fig.2a shows that the bounce time (t) between the two bounces increased with higher firmness. In Fig.2b, the first impact of the peaches is shown. During the process of the peach contacting the platform, the impact force increased from zero to peak value, then declined quickly.

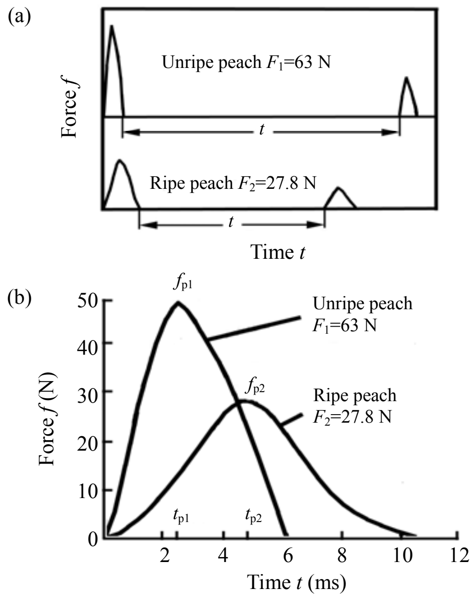

Fig.2 Typical response curves of impact force vs. time. (a) The two bounces; (b) The impact response
F_1, F_2: firmness; f_{p1}, f_{p2}: peak force

2. Force-time impact coefficient

Fig.2b shows the peak force f_p and the time-to-peak force t_p. The force-time impact coefficient c is defined as:

$$c=f_p/t_p. \tag{1}$$

3. Coefficient of restitution

The coefficient of restitution is equal to the ratio of the impulse (force multiplied by time) of the second impact to the impulse of the first impact. Actually, the coefficient of restitution, r, is equal to v_2/v_1, considering two consecutive bounces:

$$r=v_2/v_1, \tag{2}$$

where v_1 is the velocity of peach before impact, and v_2 is the velocity of peach after impact.

Assuming that the interval between the end of the first impact and the beginning of the second impact was 't', and ignoring the resistance of air, when $v_2=g\times(t/2)$, then we can get

$$r=\frac{v_2}{v_1}=\frac{g(t/2)}{\sqrt{2gh}}=t\times\sqrt{\frac{g}{8h}}, \tag{3}$$

where h is the drop height, and g is acceleration due to gravity.

4. Percentage of energy absorbed

After the first impact and rebound, the potential energy is equal to the mechanical energy. The amount of energy absorbed E_a during impact was calculated from the difference between energy at impact and rebound:

$$E_a=mg(h-h_1), \tag{4}$$

where h_1 is the rebound height obtained at time t, and $h_1=[g(t/2)^2]/2$.

The percentage of energy absorbed should be the ratio between energy absorbed and initial energy:

$$E=\frac{mg(h-h_1)}{mgh}\times 100\%=\frac{(h-h_1)}{h}\times 100\%. \tag{5}$$

Statistical analyses

The statistical analysis system (SAS) version 6.12 (SAS Cary, NC) was used to determine F values for an analysis of variance (ANOVA) of ripeness, mass, drop height, and impact position (cheek) versus each of the coefficients.

RESULTS AND DISCUSSION

Effect on peach impact characteristic

To evaluate the effect of peach mass [(95.2±2.43), (120.8±3.21), (145.8±4.78) g; three size classes: small, medium, big], firmness [(21.33±3.11), (46.87±3.56), (72.87±4.35) N; three ripe classes: unripe, ripe, overripe], drop height (0.5, 1 cm), and impact orientation (cheek 1, cheek 2) on the impact force characteristic, statistical analyses of the experimental results were performed using the SAS/STAT procedure (SAS, Institute Inc., USA), and are summarized in Tables 1~3. The magnitudes of the F values indicated the relative effects.

The mean values are shown in Table 1 on the impact characteristic parameters for each mass and degree of ripeness. The percentage of absorbed energy increased, while the force-time impact coefficient and coefficient of restitution decreased with peach ripeness (Table 1). Drop height and cheek are shown to have little effect on the impact parameters (Table 2).

The peak force divided by the time-to-peak force f_p/t_p was significantly affected by ripeness. The reduction in peak force with increased maturity was

Table 1 Impact characteristic parameters under different ripeness and mass

Firmness/ripeness (N)	Mass (g)	Coefficient of restitution r	Percentage of absorbed energy E (%)	Force-time impact coefficient f_p/t_p (N/ms)
18.21~24.10 (21.33±3.11)	95.2±2.43	0.389±0.029	72.90±4.37	6.92±0.43
	120.8±3.21	0.358±0.053	74.30±8.31	6.57±0.57
	145.8±4.78	0.319±0.048	73.00±8.34	7.02±0.63
42.10~49.18 (46.87±3.56)	95.2±2.43	0.498±0.031	65.80±3.40	10.67±0.92
	120.8±3.21	0.479±0.020	65.75±2.65	9.98±0.72
	145.8±4.78	0.415±0.047	62.90±4.10	11.31±0.81
66.87~78.97 (72.87±4.35)	95.2±2.43	0.604±0.053	58.31±6.98	16.85±0.98
	120.8±3.21	0.581±0.061	60.74±3.29	15.90±1.32
	145.8±4.78	0.549±0.062	61.35±5.30	15.80±1.33

Data are expressed as mean±*SD* (10 fruits repeated). Drop height: h=1 cm; Impacting surface: cheek 1; Impact characteristic parameters are omitted under drop height 0.5 cm and cheek 2

Table 2 Impact characteristic parameters under different drop height and impacting surface

Drop height	Impacting surface	Coefficient of restitution r	Percentage of absorbed energy E (%)	Force-time impact coefficient f_p/t_p (N/ms)
1.0	Cheek 1	0.498±0.041	64.70±4.40	9.87±0.82
1.0	Cheek 2	0.499±0.043	65.55±3.65	9.78±0.92
0.5	Cheek 1	0.455±0.047	63.90±5.20	10.11±0.86
0.5	Cheek 2	0.464±0.053	63.31±5.93	10.15±0.91

Data are expressed as mean±*SD* (10 fruits repeated). Mass: (120.8±3.21) g; Firmness: (46.87±3.56) N; Impact characteristic parameters are omitted under other ripeness and mass

Table 3 F values from STAT/ANOVA on the effects

Element	F value		
	r	E	f_p/t_p
Ripeness	21.17*	70.34*	284.90*
Mass	0.11	0.19	2.62
Drop height	1.88	1.03	2.02
Cheek	0.71	2.16	1.68

* Significant at probability P<0.05 level. r: coefficient of restitution; E: percentage of absorbed energy; f_p/t_p: force-time impact coefficient

found also by Lichtensteiger *et al.*(1988). The time to reach the peak force t_p was inversely proportional to drop height and mass and increased with ripeness. The peak impact force f_p increased, as expected, with drop height and fruit mass, but decreased with ripeness.

The f_p/t_p parameter was not affected by drop height, or impact position (cheek). This is consistent with the finding of Wang *et al.*(2006) for impact dynamic resonance frequencies of peach. It is possible, however, that other drop heights (e.g., greater drop heights) do affect f_p/t_p (Teng, 2002).

The f_p/t_p parameter was not affected by fruit mass. This agreed with the finding of Brusewitz *et al.* (1991) for peach. Actually, the peak impact force f_p and the time to reach the peak force t_p increased with drop height and fruit mass. Being independent of fruit mass makes f_p/t_p an important impact parameter to indicate fruit firmness.

The coefficient of restitution was statistically significantly affected by fruit ripeness. From Eq.(3), the coefficient of restitution is related with the ratio of the second impact impulse and the first impact impulse.

Actually, energy absorbed by the peach upon impact increased with drop height and fruit mass. Increasing drop height and mass increases the input energy, which leads to more absorbed energy and potentially more internal failure. However, the percentage of absorbed energy was not affected by fruit mass, cheek and drop height. But this does not suggest that other drop height and mass (e.g., greater drop height and mass) do not affect percentage of absorbed energy.

The percentage of absorbed energy was significantly affected by the ripeness. The percentage of absorbed energy increased with the ripeness. At the low drop heights, there were greater differences in percentage of absorbed energy between two degrees of ripeness. This indicates that percentage of absorbed energy is also a good indicator of fruit ripeness.

Relationship between impact characteristic parameter and firmness

Because mass, drop height, and cheek did not significantly affect the three impact characteristic parameters (Table 3), fruit ripeness (M-T firmness) was only considered in establishing relationship between the impact characteristic parameter and fruit firmness. The relationships between the three impact characteristic parameters and firmness are shown in Fig.3. The S model, polynomial model, and exponential model were used to fit relationships between the impact characteristic parameters and firmness.

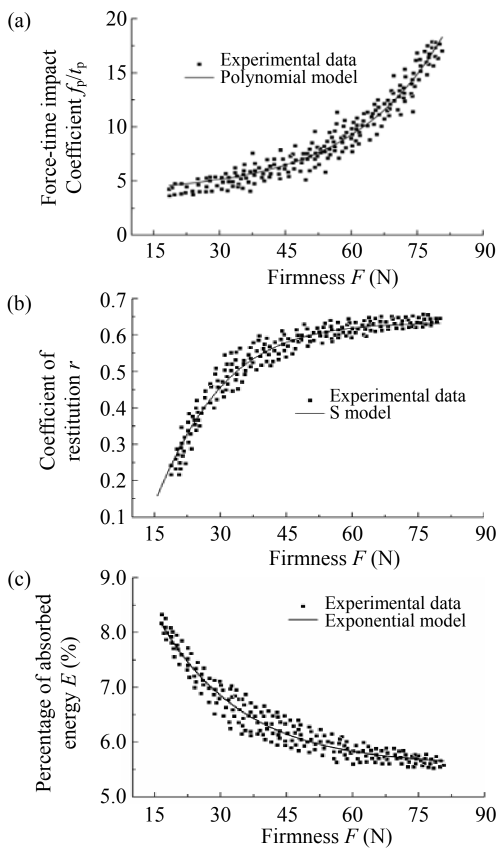

Fig.3 Characteristic parameters vs. firmness. (a) Force-time impact coefficient; (b) Coefficient of restitution; (c) Percentage of energy absorbed

Fig.3 shows that the coefficient of force-time and the coefficient of restitution increased with higher firmness and the percentage of absorbed energy decreased with higher firmness. In Table 4 the coefficients of determination are given for three different

Table 4 The relationship between the characteristic parameters and firmness

Relationship	S model $y=a+(b-a)\Big/\left(1+e^{\frac{x-c}{d}}\right)$	Polynomial model $y=a+bx+cx^2$	Exponential model $y=a+be^{\frac{-x}{c}}$	Fitted model
Force-time impact coefficient (f_p/t_p)	a=33.782 b=4.5122 c=83.341 d=14.171 R^2=0.912	a=9.159 b=−0.280 c=0.0047 R^2=0.932	a=3.819 b=0.3146 c=−21.074 R^2=0.881	Polynomial model
Coefficient of restitution (r)	a=0.5107 b=−2.786 c=−21.575 d=15.521 R^2=0.910	a=0.095 b=0.012 c=0.001 R^2=0.885	a=−26320.550 b=26320.833 c=−7790677.332 R^2=0.722	S model
Percentage of absorbed energy (E)	a=55.753 b=600.76 c=−38.704 d=18.405 R^2=0.938	a=95.70349 b=−1.12117 c=0.00808 R^2=0.893	a=55.64728 b=61.87476 c=19.06214 R^2=0.941	Exponential model

models fitting the ripeness-impact characteristic parameters. It can be seen from the table that the relationship of coefficient of force-time versus firmness was best fitted by the polynomial model, the relationship of coefficient of restitution versus firmness was best fitted by the S model, and the relationship of percentage of absorbed energy versus firmness was better fitted by exponential model.

CONCLUSION

Peaches were dropped onto a platform from heights of 0.5 and 1.0 cm and the force versus time curves for the first and second impacts were acquired. Three coefficients were calculated from these curves and the relationships between these coefficients and ripeness, mass, drop height, and impact position (cheek) were determined. The following are specific conclusions of this study:

1. The effects of drop height, mass, and impact location on percentage of absorbed energy, force-time impact coefficient and coefficient of restitution were not significant.

2. The coefficient of restitution, the percentage of energy absorbed and the force-time impact coefficient were significantly affected by fruit ripeness. The percentage of absorbed energy increased, while the force-time impact coefficient and the coefficient of restitution decreased with ripeness.

3. The relationships between the force-time impact coefficient, the coefficient of restitution and the percentage of energy absorbed and peach firmness are best obtained by using polynomial model (R^2=0.932), S model (R^2=0.910), and exponential model (R^2=0.941), respectively.

References

Abbott, J.A., Massie, D.R., 1995. Nondestructive dynamic force/deformation measurement of kiwifruit firmness (*Actinidia deliciosa*). *Trans. ASAE*, **38**(6):1809-1812.

Brusewitz, G.H., McCollum, T.G., Zhang, X., 1991. Impact bruise resistance of peaches. *Trans. ASAE*, **34**(3):962-965.

Delwiche, M.J., McDonald, T., Bowers, S.V., 1987. Determination of peach firmness by analysis of impact forces. *Trans. ASAE*, **30**(1):249-254.

Delwiche, M.J., Tang, S., Mehlschau, J.J., 1989. An impact force response fruit firmness sorter. *Trans. ASAE*, **32**(1):321-326.

Delwiche, M.J., Arevalo, H., Mehlschau, J., 1996. Second generation impact force response fruit firmness sorter. *Trans. ASAE*, **39**(3):1025-1033.

Fu, X., Ying, Y., Zhou, Y., Xie, L., Xu. H., 2008. Application of NIR spectroscopy for firmness evaluation of peaches. *J. Zhejiang Univ. Sci. B*, **9**(7):552-557. [doi:10.1631/jzus.B0720018]

Lichtensteiger, M.J., Holmes, R.G., Hamedy, M.Y., Blaisdell, J.L., 1988. Impact parameters of spherical viscoelastic objects and tomatoes. *Trans. ASAE*, **31**(2):595-602.

Mizrach, A., Flitsanov, U., Fuchs, Y., 1997. An ultrasonic nondestructive method for measuring maturity of mango fruit. *Trans. ASAE*, **40**(4):1107-1111.

Peleg, K., 1999. Development of a commercial fruit firmness sorter. *J. Agric. Eng. Res.*, **72**(3):231-238. [doi:10.1006/jaer.1998.0367]

Schmilovitch, Z., Zaltzman, A., Hoffman, A., Edan, Y., 1995. Firmness sensor and system for date sorting. *Appl. Eng. Agric.*, **11**(4):555-560.

Scorza, R., Anger, W., Peteson, D., Bett, K., Champagne, E., Beaulieu, J., Ingram, D.A., 2004. Non-Destructive Evaluation of Post-harvest Peach Fruit Softening. *In*: Laurens, F., Evans, K. (Eds.), XIth Eucarpia Symposium on Fruit Breeding and Genetics. ISHS Acta Hort 663, Angers, France, p.269-273.

Sugiyama, J., Katsurai, T., Hong, J., Koyama, H., Mikuriya, K., 1998. Melon ripeness monitoring by a portable firmness tester. *Trans. ASAE*, **41**(1):121-127.

Teng, B., 2002. Studies on the Characteristics of Frequency of Pear and Peach. PhD Dissertation. Department of Agricultural Engineering, Zhejiang University, Hangzhou, China, p.23-35 (in Chinese).

Timm, E.J., Brown, G.K., Armstrong, P.R., Beaudy, R.M., Shifazi, A., 1996. Portable instrument for measuring firmness of cherries and berries. *Appl. Eng. Agric.*, **12**(1):71-77.

Wan, Y.N., Yen, M.H., Ay, C., 1997. Nondestructive maturity inspection of fruits and vegetable by impact. *J. Agric. Machinery*, **6**:21-33.

Wang, J., Teng, B., 2006. Firmness evaluation by drop impact characteristics for peach. *Int. J. Food Prop.*, **9**(3):439-451. [doi:10.1080/10942910600596324]

Wang, J., Teng, B., Yu, Y., 2006. The firmness detection by excitation dynamic characteristics for peach. *Food Control*, **17**(5):353-358. [doi:10.1016/j.foodcont.2004.12.001]

Wang, J., Ying, T.J., Cheng, K.C., 2007. Evaluation of pear firmness by dynamic characteristics of drop impact. *J. Sci. Food Agric.*, **87**(8):1449-1454. [doi:10.1002/jsfa.2781]

Yen, M., Wan, Y., 2003. Determination of textural indices of guava fruit using discriminate analysis by impact force. *Trans. ASAE*, **46**(4):1161-1166.

Zhang, X., Stone, M.L., Chen, D., Maness, N.O., Brusewitz, G.H., 1994. Peach firmness determination by puncture resistance, drop impact, and sonic impulse. *Trans. ASAE*, **37**(2):495-500.