African Journal of Biotechnology Vol. 9(12), pp. 1816-1826, 22 March, 2010
Available online at http://www.academicjournals.org/AJB
ISSN 1684–5315 © 2010 Academic Journals

Full Length Research Paper

Effect of tomato internal structure on its mechanical properties and degree of mechanical damage

Zhiguo Li*, Pingping Li* and Jizhan Liu

Institute of Agricultural Engineering, Jiangsu University, 212013 Zhenjiang, China.

Accepted 5 March, 2010

As different tomatoes have different locular cavities and a particular tomato material is inhomogeneous, the effect of tomato internal structure on its mechanical properties and degree of mechanical damage may be significant during the gripping process with robot fingers. This was studied using the loading-unloading experiment as well as the observation of shelf life. The results showed that the plastic strain energy, E_p, peak force, F_{max} and degree of elasticity, r_c, were not significantly affected by the internal structure of three-locular tomato before its failure, but loading slope, r_k, was. The degree of elasticity, r_c and loading slope, r_k, were significantly affected by the internal structure of four-locular tomato before its failure, but the plastic strain energy, E_p, and peak force, F_{max}, were not. The compressibility ε was the most important explanatory variable in the model of the degree of mechanical damage to tomato. The internal structure of four-locular tomato had a significant effect on its degree of mechanical damage, but the internal structure of three-locular tomato does not. Excluding the covariates, at the same compressibility, the degree of mechanical damage was greatest under the condition of *F*CW* and lowest for *F*L* their difference was 21.3%. The discrepancy of the medium degree of mechanical damage was slight under the condition of *T*CW* and *T*L*, respectively.

Key words: Tomato, internal structure, mechanical properties, degree of mechanical damage, analysis of covariance.

INTRODUCTION

Tomatoes (*Lycopersicon esculentum* Mill.) are commercially important vegetable worldwide, whose internal structure characteristic differs from each other. They always have different locular cavities, though grown from the same plant. The common tomatoes usually have three to seven locular cavities. In addition, the biological material of tomatoes is inhomogeneous, and an intact tomato has pericarp, cross-wall, locular gel and seeds tissue etc. (http://en.wikipedia.org/wiki/Tomato). The mechanization of harvesting and post-harvest handling always cause different degrees of bruising to tomatoes (Aworh and Olorunda, 1981; Olorunda and Tung, 1985; Mohsenin, 1986; Shanfeng, 2001; Lixin and Zhiwei, 2004; Xiaojun et al., 2007; Raji and Oriola, 2007) and the affected tissue, including cell walls, undergoes enzymatic degradation. This can result in a rapid enzymatic breakdown of the cell wall polysaccharides, observed as soft spots (bruises) on the fruit (Hetong et al., 2002; Yun et al., 2005; Linden and Baerdemaeker, 2005, Linden et al., 2008; Xiubing et al., 2009). This is not only restricted to the visible damage which may also result in higher risk of bacterial and fungal contamination and lower shelf life, but also, other physiological changes such as water loss, color change, etc. (Dobrzanski and Rybczynski, 2002; Zeebroeck et al., 2007). The value of such tomatoes depreciates greatly. Some evidences showed that the larger the degree of mechanical damage, the more serious effect it has on global trade (Altisent, 1991).

Since the 1990s, some researchers have focused on the mechanical properties of tomato. Thiagu et al. (1993) studied the mechanical properties of two varieties at

---

*Corresponding authors. E-mail: lizhiguo0821@126.com (Z.G. Li), lipingping@ujs.edu.cn (P.P. Li). Tel: +0086-511-88780010.

Abbreviations: ***F*CW***, Four-locular tomatoes at cross wall tissue; ***F*L***, four-locular tomatoes at locular tissue; ***T*CW***, three-locular tomatoes being loaded at the cross wall tissue; ***T*L***, three-locular tomatoes at locular tissue; **GLM**, generalized linear modeling; **ANCOVA**, analysis of covariance; **RGB**, red, green, blue; **NMR**, nuclear magnetic resonance.

various stages of maturity by whole fruit compression test. Gonzalez et al. (1998) observed the effects of compression on the structure of red tomato using magnetic resonance imaging. Wang et al. (2006) characterized the mechanical behavior of single tomato fruit cells. Arazuri, (2007) studied the influence of mechanical harvest on the physical properties of processing tomato. Jizhan et al. (2008) conducted tests of compression from transversal and longitudinal directions on tomato fruit at different ripening phases and tests of bending and stretching on tomato peduncle. Lien et al. (2009) developed a non-destructive method for assessing the maturity of tomatoes using the mechanical properties of the fruit under the falling impact test. Other researches focused on the factors that affect the degree of mechanical damage of tomatoes. The influencing factors mainly consist of the external factors and the internal factor. The former includes impact energy, packaging materials, method of handling and drop height, etc. (Linden et al., 2006a, 2006b; Idah et al., 2007; Raji and Oriola, 2007). The latter includes variety, texture, maturity, shape and harvest date etc. (Thiagu et al., 1993; Kerstens et al., 2000; Linden et al., 2006b; Zeebroeck et al., 2007; Lien et al, 2009). Besides these, there are researches that focused on the bruising sources such as puncture injury, impact damage and mode of transportation etc. (Desmet et al., 2002, 2003, 2004a, b; Allende et al., 2004). Different levels of impact energy will result in the differences in bruise susceptibility (Zeebroeck et al., 2003; Linden et al., 2006a). The bruising is considered to be a two step process, in which mechanical damage occurs first and then the affected tissue shows as soft spots on the surface within the first 2-3 days after impact (Linden et al., 2005, 2006b). Existing work on the major methods of detection and evaluation of the degree of bruise include: 1) The red, green, blue (RGB) image analysis (Laykin et al., 1999), the Vis/NIR spectroscopy technique (Xingyue et al., 2005; Jun et al., 2005), the laser scattering of blue laser light (Sotome et al., 2004) and nuclear magnetic resonance (NMR) method (Milczarek et al., 2009). These methods were proved to be effective by experiments. However, they detected severe damage in which the skin was no longer intact (Linden et al., 2006). 2). logistic statistical functions were applied to evaluate the bruise susceptibility of fruits and vegetables (Lammertyn et al., 2000; Desmet et al., 2003; Vanstreels et al., 2002; Linden and Baerdemaeker, 2005). 3). More recently, the bruise volume was applied on the determination of the bruise susceptibility of apples (Sukontasukkul et al., 2004; Zeebroeck et al., 2007). The measure of the bruise volume seems promising at first sight but the method is destructive for fruits and depends on homogeneous materials. This is not suitable for tomatoes, especially for tomato harvesting robot. However, research on the effect of tomato internal structure on its mechanical properties and degree of mechanical damage is rare. During the gripping process with robot fingers, different compressibility will lead to varying degree of mechanical damage. However, the study of the tomato's bruising degree from the compressibility has not yet been shown.

Since different tomatoes have different locular cavities and a particular tomato material is inhomogeneous, the effect of tomato internal structure on its mechanical properties and degree of mechanical damage maybe significant during the gripping process with robot fingers. This issue was studied by the loading-unloading experiment and observation of shelf life.

MATERIALS AND METHODS

Fruit materials and instrument

The experiments were conducted in September 2009 at the Education Ministry Key Laboratory of Modern Agricultural Equipment and Technology Jointly Constructed with Jiangsu Province. Fresh market 'Fenguan 906' tomatoes (Lycopersicon esculentum Mill.) were used in this study. This cultivar fruit is mid-early ripening, which is suitable to plant at the season of spring and out-of - season. Therefore, the planting areas of 'Fenguan 906' tomatoes cover some major areas in China (Fenma, 2001; Zhihong et al., 2006). Since the stiffness of tomatoes at the light red stage is larger than the red stage, the tomato at this ripening stage is convenient for storage and transportation (Allende et al., 2004; Lien et al., 2009), at a period optimal for harvesting tomatoes. Therefore, the research focused on tomatoes in the light red ripening stage. The fruits in this experiment were from the Ruijing Vegetable Research Institute of Zhenjiang. 160 three-locular and 160 four-locular tomatoes were hand harvested at the light red ripening stage according to US Department of Agriculture (USDA) standards (USDA, 1991). Extremely large or small tomatoes were excluded. After careful transportation to the laboratory, the tomatoes were inspected again to ensure that they were uniform, non-damaged and not attacked by worms. In addition, the experiment was conducted within 24 h.

The experiments were conducted using loading-unloading test at room temperature by means of a TA-TX2 Texture Analyzer (Texture Technologies Corp., NY, USA). The analyzer was calibrated with a 5 kg weight before the first test. It was equipped with a 100 mm diameter plate for the impact test. Equipment settings were as follows: test speed, 0.5 mm/s (quasistatic loading); distance, 10 mm into the tomato; compressibility was 4, 8, 12, 16 and 20%, respectively. The test positions on the cross section of tomato are 1 cross wall tissue and 2 locular tissue as shown in Figure 1. The position 1 (Figures 1b and c) corresponds to the valley between two adjacent fruit shoulders (Figure 1a), and position 2 (Figures 1b and c) corresponds to the middle of one fruit shoulder (Figure 1a).

A typical loading-unloading curve (F-D) is shown in Figure 2. AB is the loading stage while BC is the unloading stage. The loop area, ABC, is defined as the plastic strain energy $E_p = E_s - E_e$(mJ). The strain energy E_s is the internal stored energy of tomato throughout its volume as external loading deforms the tomato, which is the area under the force-distance curve during loading (Figure 2). The elastic strain energy, E_e, is the released energy from tomato during unloading, which is the area under the force-distance curve during unloading. The deformation, D_p, of tomato corresponding to point C is the plastic deformation; D_e is elastic deformation of tomato. Thus, the degree of elasticity, $r_c = D_e / (D_e + D_p)$ (dimensionless). The degree of elasticity r_c is a measure of the damping characteristics of the fruit. The slope of line AB is loading slope r_k, which is a ratio of force to distance within the region of fruit's elastic deformation. The abscissa of point B is the deformation D ($D = D_e + D_p$) of tomato under the corresponding compressibility, while the y-axis of point B is the peak force F_{max}(N) the tomato received.

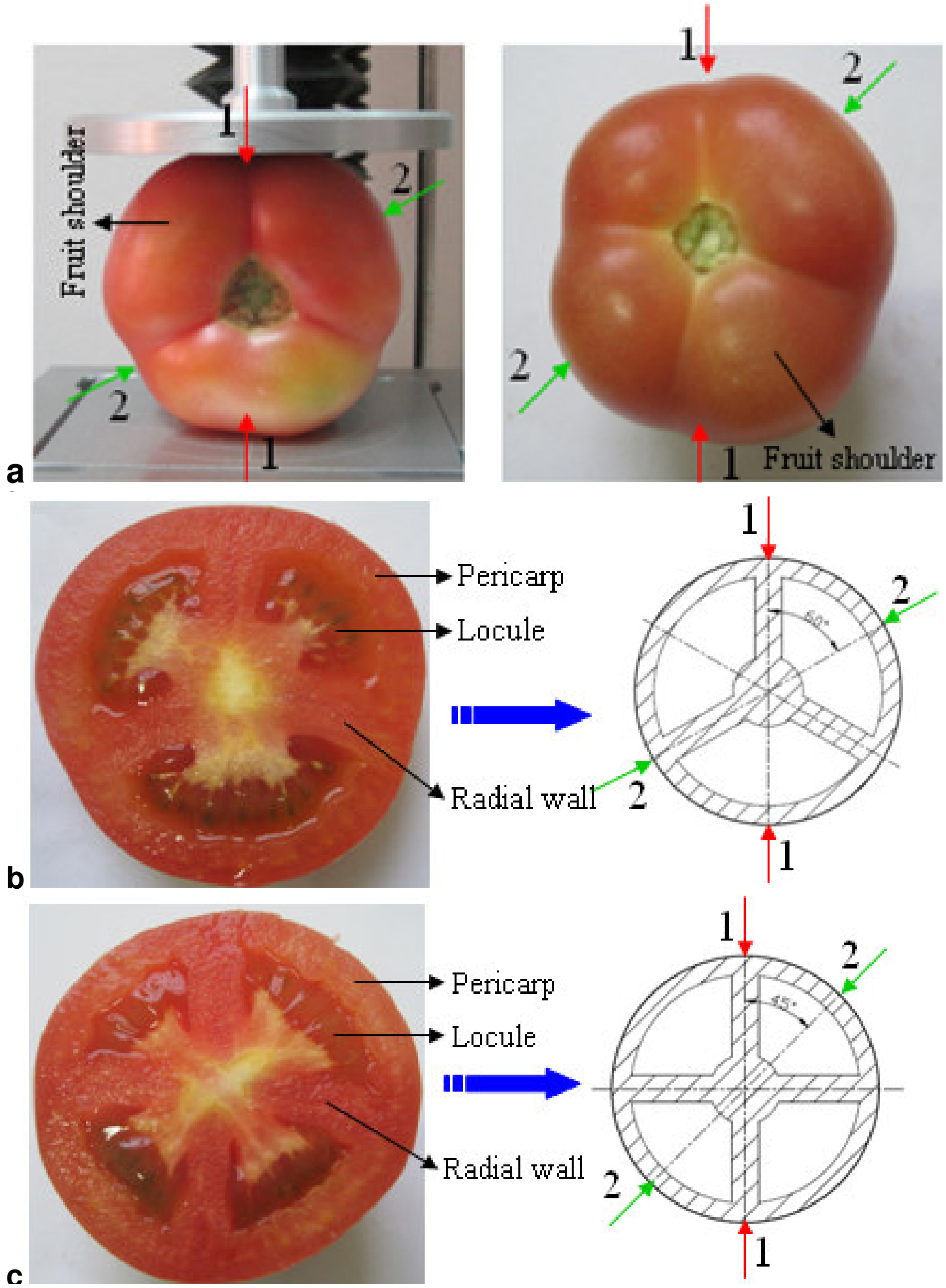

Figure 1. Three-locular and four-locular tomatoes, their cross sections and simplified structures. (a) Three-locular (left) and four-locular tomato (right), (b) the cross section of three-locular tomato (left) and its simplified structure (right), (c) the cross section of four-locular tomato (left) and its simplified structure (right).

Experimental design

Locule number and test position are indicators of the internal structure characteristics of the fruit. To study the effect of tomato internal structure on its mechanical properties and degree of mechanical damage, a full factorial design was performed. The factors include: 1) Two locular numbers (three-locular: T and four-locular: F). The three-locular tomato indicates that the fruit has asymmetric internal structure, which represents the tomatoes within 3, 5 or 7 locules; while the four-locular tomato indicates the tomato has symmetric internal structure, which represents the tomatoes within 4, 6 or 8 locules. The 110 tomatoes of each type of locular numbers were randomly assigned to their treatment. 2) Two test positions at the fruit's surface (locular: L and cross-wall: CW tissue). Locular tissue is the pericarp over the locules, whereas cross wall tissue is the pericarp located over the septum or radial wall. 3) Five compressibility (4, 8, 12, 16 and 20%). All compressions were located at the equatorial region. Fruits were kept at room temperature at 24℃ for incubation after test. The shelf life of 200 tomatoes (10 tomatoes × 2 locular number × 2 locations × 5 compressibility) are

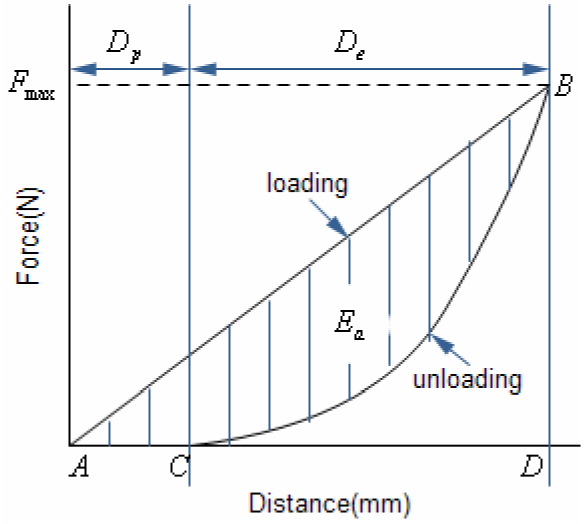

Figure 2. Loading-unloading curve.

observed once per day. The physical parameters of tomatoes were measured before the treatment.

Physical parameters measurement and mechanical damage evaluation

Physical parameters measurement

The tomatoes were divided into ten groups after being labeled. Ten tomatoes were taken from each group and their principal dimensions, that is, the longitudinal height *H*, the compression diameter L_c (the height between the upper contact point and lower contact point under uncompressed), the maximum transverse diameter L_{max} , and minimum transverse diameter L_{min} were measured with a electronic digital caliper to an accuracy of 0.01 mm. Then the geometric mean diameter (D_g), sphericity (Ψ) and arithmetic mean diameter (D_a) values were calculated using the following formulae (Goyal et al., 2007; Kilickan and Guner, 2008). The sphericity is a shape index of fruit, which indicates the difference between the actual shape of fruit and the sphere (Zue, 1994). The geometric mean diameter and the arithmetic mean diameter are the indexes of particle diameter of fruit, which integrate the size of all directions (Kang and Song, 2006).

$$D_g = (HL_{\max}L_{\min})^{1/3} \tag{1}$$

$$\varphi = \frac{(HL_{\max}L_{\min})^{1/3}}{H} \tag{2}$$

$$D_a = \frac{(H + L_{\max} + L_{\min})}{3} \tag{3}$$

Mechanical damage evaluation

The bruised tomato can be classified into two types after test, severe bruise damage with crack under the skin and medium-slight damage without crack (Linden et al., 2006). The inner layer tissue of severe bruised tomato is exposed because of crack. The microbe directly propagates on the surface and the mildew stain comes into being. The separation between phenols matter and enzyme is broken because the cellularity of medium-slight bruised tomato is destroyed, which cause a series of enzymatic reaction and the color become brown at the compressed point. Meanwhile, the fruits respiration is increased, which lead to a series of biochemical reactions, water loss and pericarp cellular atrophy (Linden and Baerdemaeker, 2005; Hetong et al., 2002; Xingqian, 1992). As a visible factor, the changes of the fruit appearance exert direct influence on the value of merchandise trade. In this study, the shelf life of severe bruised tomato was defined by the storage time from the first day of test to the day that the mildew stain appeared. In addition, the shelf life of medium-slight bruised tomato was defined by the storage time from the first day of test to the day when the cripple of bruised tissue appears in this study.

Different compressibility cause varying degrees of mechanical damage to tomato that produce different shelf lives. Thus, under the condition of certain compressibility, the degree of mechanical damage to tomato can be evaluated by the shelf life in this research. The compressibility ε was defined (Gonzalez et al., 1998) by:

$$\varepsilon = \frac{L_c - L}{L_c} \times 100\% \tag{4}$$

Where, L_c represents the compression diameter and *L* is the diameter of the tomato during compression. The compressibility used in this study were 0, 4, 8, 12, 16 and 20%.

The shelf life of tomato is *t* days at a compressibility of 0%. This means that the tomato is intact without any degree of mechanical damage. The shelf life is t_1 days at the compressibility ε, showing that the degree of mechanical damage η will be defined by:

$$\eta = \frac{t - t_1}{t} \times 100\% \tag{5}$$

Statistic analysis

The degree of mechanical damage to tomato is affected by several factors, which can be described as qualitative variables, such as locular number, test position, and quantitative variables, such as compression and fruit physical parameters. As an appropriate statistical method to analyze this problem, the analysis of covariance (ANCOVA) was adopted. ANCOVA is a general linear model with many factor variables (qualitative) and continuous variables (quantitative), which merges analysis of variance (ANOVA) and the regression for continuous variables. The uncontrollable quantitative variables are regarded as covariates in ANOVA, then the effect of qualitative variables on dependent variable is analyzed when the effect of covariates is excluded, so that the qualitative variables are more accurately evaluated (http://en.wikipedia.org/wiki/ANCOVA). During the process of ANCOVA, the interaction between covariates is absent, so does the interaction between a covariate and a factor. Equation 6 shows the ANCOVA model:

$$P_i = \alpha_0 + \sum_{k=1}^{m}\alpha_{1k}x_{ik} + \sum_{k=1}^{m}\sum_{p=1}^{m}\alpha_{1kp}x_{ik}x_{ip} + \sum_{j=1}^{n}\alpha_{2j}C_{ij} + \varepsilon_i \tag{6}$$

Where, P_i is dependent variable defined by the degree of mechanical damage to tomato in the *i*th group in this study; groups were defined by the locular number × probe type × location combination; the independent variables x_{ik} and C_{ij} is qualitative variables and quantitative variables, respectively, which indicates main effect of

Table 1. Mechanical parameters extracted from the loading-unloading test and fruit physical parameters for all the tomatoes at the light red ripe stage.

Mechanical and fruit physical parameters	Compressibility ε					
	0	4%	8%	12%	16%	20%
E_p(mJ)□	0	7.21 ± 1.97	42.16 ± 15.41	101.17 ± 35.99	209.09 ± 59.38	368.73 ± 128.9
F_{max}(N)□	0	9.44 ± 2.55	25.97 ± 8.16	38.54 ± 10.16	54.88 ± 13.47	63.13 ± 13.5
r_c□		0.63 ± 0.09	0.59 ± 0.07	0.55 ± 0.05	0.5 ± 0.05	0.41 ± 0.05
r_k□		3.62 ± 0.89	4.85 ± 1.29	4.59 ± 1.02	4.53 ± 1.03	4.5 ± 1.13
L_c(mm)□		64.40 ± 4.65	65.56 ± 6.47	67.27 ± 5.98	65.83 ± 4.32	67.13 ± 5.91
φ		0.92 ± 0.04	0.92 ± 0.02	0.91 ± 0.02	0.93 ± 0.03	0.92 ± 0.02
D_g(mm)□		61.30 ± 3.77	62.88 ± 4.96	63.04 ± 5.52	62.47 ± 3.88	63.62 ± 4.79
D_a(mm)□		61.56 ± 3.82	63.16 ± 5.06	63.43 ± 5.57	62.75 ± 3.90	63.92 ± 4.89

□ = Mechanical parameters; □ = fruit physical parameters.

factor and covariates; m, n is the number of factor and covariate, respectively; α_0 is the intercept of ANCOVA model; α_{1k} and α_{2j} refer to the kth factor and the jth covariate respectively, which describes the importance of corresponding variable; α_{1kp} similarly relates to the interaction between the kth and pth factor; ε_i is random error.

As a statistical procedure, ANCOVA makes certain assumptions about the data entering into the model. Only if these assumptions are met, at least basically met, will ANCOVA yield valid results. Specifically, ANCOVA assumes that the errors ε_i are normally distributed and homoscedastic (http://en.wikipedia.org/wiki/ANCOVA). The full model of multivariate analysis of variance is employed to test which factors will significantly have an effect on the dependent variable. A backward stepwise procedure is used to eliminate the insignificant factors in the model and the significant level for staying in the model was set at 5%. This means that all main effects and cross-product terms have a significant level below 0.05 ($P < 0.05$). At last, all significant variables were sorted out. The comparison method is used to look for the levels of selected independents, which significantly affected the dependent variable with Student-Newman-Keul (SNK) multiple-range test. The parameters of model 6 are estimated and predicted by generalized linear modeling (GLM). The statistical model which can determine the bruising degree of tomatoes in different internal structure characteristics was then established. Then eliminating the effect of covariate on dependent variable, the accurate effect of tomato internal structure on its mechanical properties and degree of mechanical damage was analyzed. Finally, residual analysis was used to test the homoscedastic assumption. Kolmogorov-Smirnov D statistic is used to test the assumption of normal distribution. If the assumptions are met, it indicates that the previous conclusions are correct and credible. If not, ANCOVA analysis was repeated after finding out the causes. All statistical analyses were performed using statistical analysis system (SAS) software, Version 9.1.3 (SAS Inc., Cary, NC, USA).

RESULTS

Loading-unloading test

The data on mechanical, fruit physical parameters and the shelf life led to an appropriate evaluation of the degree of mechanical damage to tomato. Table 1 lists the information extracted from the loading-unloading test and from the fruit physical parameters measurement. The data represent joint values for all the tomatoes per compressibility group. Five compressibilities were applied, resulting in five sets of corresponding mechanical parameters. Data represent average values ± standard deviations of all tomatoes: 2*2*10 per compressibility. Mechanical parameters were found to be significantly different among the compressibilities by the coefficient comparison of variation, as shown in Figure 3. Obviously, plastic strain energy, E_p, and peak force, F_{max}, increased with the lifting of applied compressibility as shown in Table 1. This is consistent with the findings of other researchers (Linden et al., 2006). However, the degree of elasticity r_c decreased with increasing applied compressibility and the loading slope was the highest with the compressibility of 8% and the lowest with the compressibility of 4%. In contrast to the mechanical parameters, none of the fruit physical properties had significantly different average values with the changes of the compressibility. This illustrated that the fruit grouping was well-balanced and the data obtained by the loading-unloading test were not bias because distinct characteristics of fruit was associated with compressibility or test group. All parameters mentioned were explanatory variables of the obtained dataset.

Effect of tomato internal structure on its mechanical properties

The mechanical parameters (E_p, F_{max}, r_c and r_k) after loading-unloading test at the locular (L) and cross wall (CW) tissue of tomatoes for five compressibilities were presented, as shown in Figure 4. T*CW, T*L, F*CW and F*L indicate three-locular tomatoes being loaded at the cross wall tissue , three-locular tomatoes at locular tissue, four-locular tomatoes at cross wall tissue, and

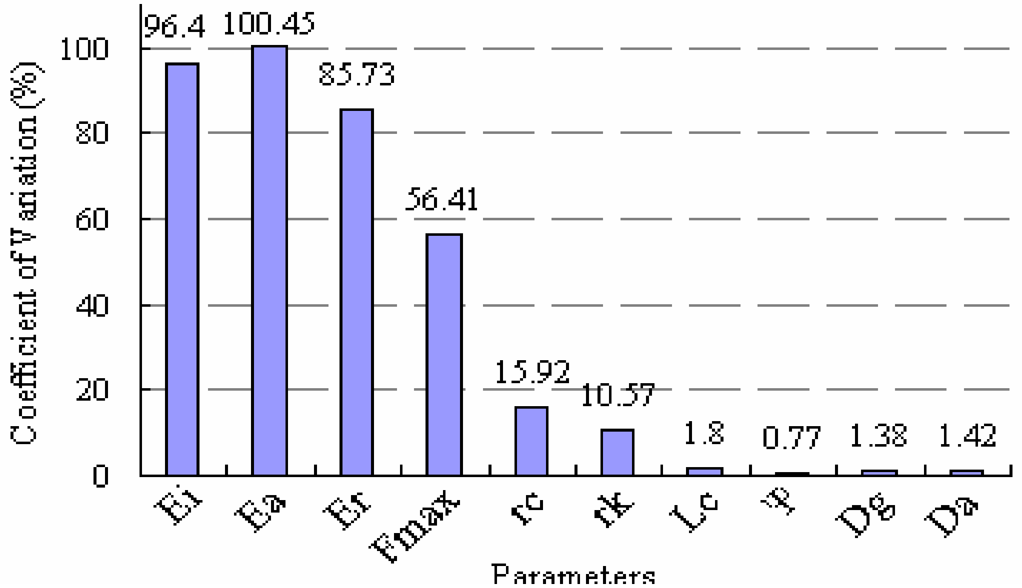

Figure 3. Coefficient of variation to the compress and fruit physical parameters.

four-locular tomatoes at locular tissue, respectively.

Three-locular tomato

The correlation between various mechanical parameters of three-locular tomato and five different compressibilities are shown in Figures 4 a1, b1, c1 and d1.

Plastic strain energy, E_p, (Figure 4a1): When the compressibility was less than 16%, the loading position had no significant effect on the plastic strain energy for three-locular tomato. When the compressibility was more than 16%, the loading position had a gradual significant effect, and the differences of plastic strain energy value of tomatoes being loaded at two loading positions increased with increasing compressibility. When the compressibility was 20%, the plastic strain energy of tomatoes being loaded at the cross wall tissue was 1.14 times more than that at the locular tissue.

Peak force F_{max}, (Figure 4b1) and degree of elasticity r_c, (Figure 4c1): Obviously, loading position had no significant effect on the peak force and degree of elasticity for three-locular tomato. The peak force loaded at the locular tissue of tomatoes is slightly greater than that at the cross wall tissue when the compressibility was less than 12%. When the compressibility was more than 12%, the peak force loaded at the locular tissue was slightly smaller than that at the cross wall tissue. The degree of elasticity of the tomato being loaded at the locular tissue was slightly greater than that at the cross wall tissue per compressibility.

Loading slope r_k, (Figure 4d1): Loading position had a significant effect on the loading slope for three-locular tomato. When the compressibility was less than 12%, the loading slope in the test of tomatoes being loaded at the locular tissue was greater than that in the test tomatoes being loaded at the cross wall tissue. While the compressibility was more than 12%, the loading slope for the locular tissue was smaller than that for the cross wall tissue. When the compressibility was 4%, the loading slope for the locular tissue was 1.32 times more than that for the cross wall tissue. When the compressibility was 20%, the loading slope for the cross wall tissue was 1.09 times more than that for the locular tissue.

According to the above test results, loading position had no significant effect on the mechanical properties (E_p, F_{max} and r_c) of three-locular tomato when the compressibility was less than 16%. This is because the structure of three-locular tomato is symmetric and has not failed. No matter which position of the cross section of the tomato between two loading positions is parallel loaded, the mechanical properties will not be significantly different before the tomato internal structure fails. However, loading position had a significant effect on the loading slope for three-locular tomato, and the reason may have relations with the probe diameter (Plocharski and Konopacka, 2003; Khazaei and Mann, 2004; Lu et al., 2005). The plastic strain energy was significantly affected by loading position when the compressibility was more than 16%; the reason maybe that the internal structure of tomatoes had started to fail gradually. Statistical results after test showed that the cracked probability of tomatoes being loaded at cross wall tissue and locular tissue was 83.33 and 66.67%, respectively, when the compressibility was 16%. Both the cracked probability for cross wall

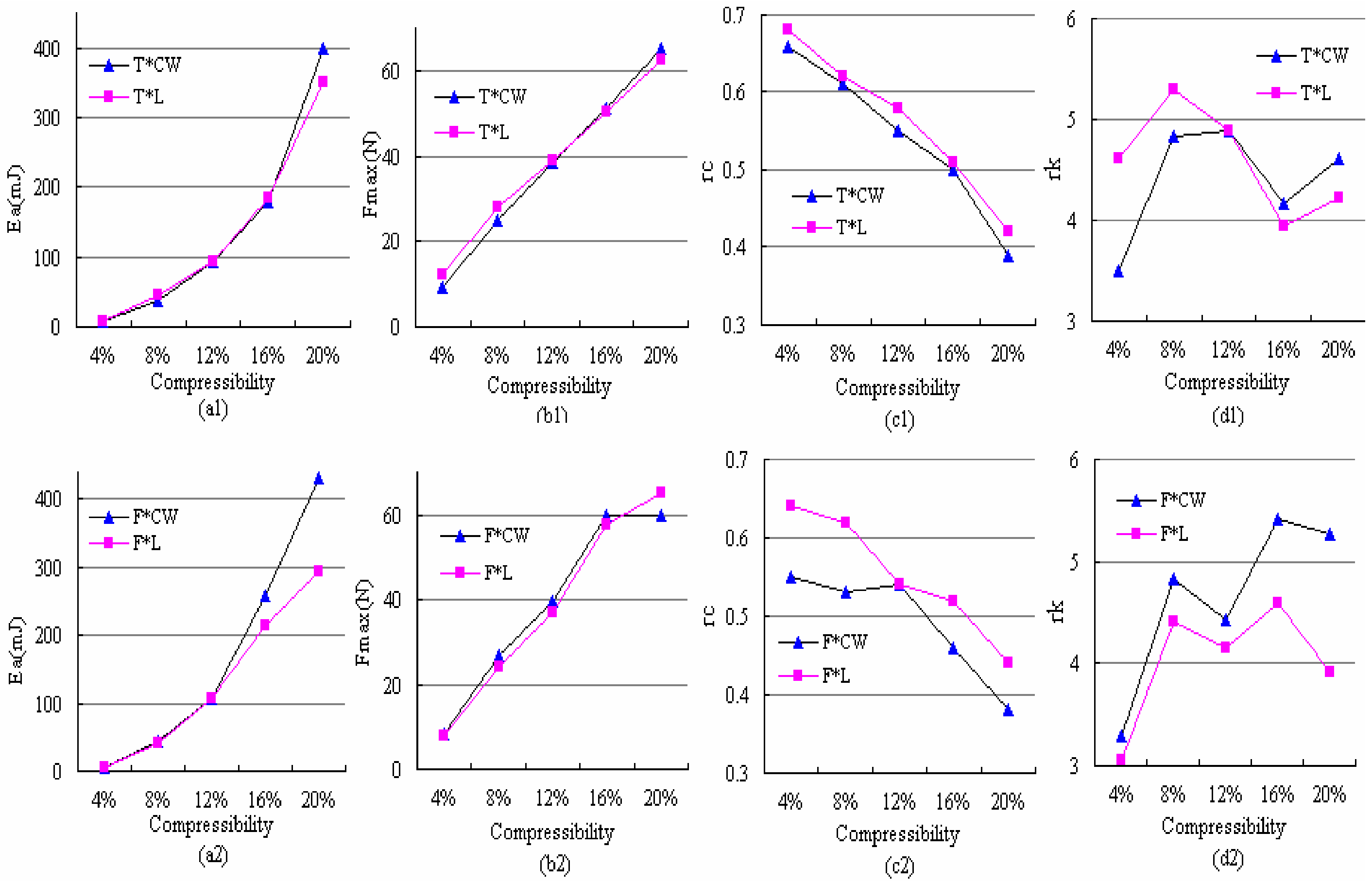

Figure 4. The mechanical parameters (E_a, F_{max}, r_c and r_k) during the tomato was loaded at cross wall and locular tissue for five compressibility.

tissue and locular tissue were 100% when the compressibility was 20%. Additionally, Gonzalez et al. (1998) showed that the lower placental tissue had fracture to the columella and the right placental tissue had started to fracture at 20% compressibility, which further proved the correctness of the above supposition.

Four-locular tomato

The connection between various mechanical parameters of four-locular tomato and five compressibilities are shown in Figures 4a2, b2, c2 and d2.

Plastic strain energy E_p, (Figure 4a2): When the compressibility was less than 12%, the loading position had no significant effect on the plastic strain energy for four-locular tomato. When the compressibility was more than 12%, the loading position had a gradual significant effect, and the differences of plastic strain energy value of tomatoes being loaded at two loading positions increased with increasing compressibility. When the compressibility was 16 and 20%, respectively, the plastic strain energy of tomatoes being loaded at the cross wall tissue, accordingly, was 1.22 times and 1.47 times more than that at the locular tissue.

Peak force F_{max}, (Figure 4b2): Obviously, loading position had no significant effect on the peak force for four-locular tomato. The peak force loaded at the locular tissue of tomatoes was slightly greater than that at the cross wall tissue when the compressibility was less than 16%. When the compressibility was more than 16%, the change of the peak force loaded at the locular tissue was slight, which indicated that the cross wall tissue might have failed. However, the peak force loaded at the locular tissue was still increasing.

Degree of elasticity r_c (Figure 4c2): Loading position had a significant effect on the degree of elasticity for four-locular tomato. The degree of elasticity of the tomato being loaded at the locular tissue was greater than that at the cross wall tissue per compressibility. The maximum ratio of degree of elasticity at two positions reached up to 1.16:1 at 4%. This showed that the ability of elastic recovery of the four-locular tomato being loaded at the locular tissue was higher than that at the cross wall

Table 2. Selected explanatory variables.

Source	F value	Pr > F
Compressibility ε	135.5	< 0.0001
Location	9.14	0.0085
Structure × Location	5.82	0.0135

Table 3. Test for multiple comparisons of means.

SNK Grouping	Mean	level
A	0.4591	CW
B	0.3522	L

SNK, Student-Newman-Keul

tissue.

Loading slope r_k, (Figures 4d2): Loading position had a significant effect on the loading slope for four-locular tomato. The loading slope in the test of tomatoes being loaded at the locular tissue was smaller than that in the test tomatoes being loaded at the cross wall tissue per compressibility. The maximum ratio of loading slope at two positions reached up to 1.34:1 at 20%. This illustrated that if the tomato had the same deformation, the gripping force of robot fingers given to the cross wall tissue must be greater than that given to the locular tissue.

According to the above test results, the compressibility of 12% was a key point that the mechanical parameters of four-locular tomato changed. The reason was that the cross wall tissue of four-locular tomato might start to fail when the compressibility was more than 12%. Figure 3c2 shows that the degree of elasticity of tomato suddenly decreased when the compressibility was more than 12%; the plastic deformation greatly increased and the plastic strain energy also increased with increase in compressibility. The statistical results after test showed that the cracked probability of tomato being loaded at cross wall tissue and locular tissue was 33.33 and 16.67%, respectively, when the compressibility was 12%; the cracked probability was 50 and 16.67%, respectively, when the compressibility was 16% while it was 100 and 83.33%, respectively, when the compressibility was 20%. Therefore, the results further proved the correctness of the above supposition.

Effect of tomato internal structure on its mechanical damage degree

Shelf life of fruit acts as the bridge to connect the degree of mechanical damage of fruit and the compressibility. By calculating the shelf life, the mechanical damage degree of fruit in each experimental group was obtained, and then the model of mechanical damage degree of tomato was set up using ANCOVA.

The model of mechanical damage degree of tomato

Determination of explanatory variables and test for multiple comparisons of means: The factors that may affect the degree of mechanical damage to tomato include the tomato internal structure, such as locular number and loading position, the mechanical parameters, such as ε, E_p, F_{max}, r_c and r_k, and the physical parameters, such as L_c, D_g, Φ, D_a. After the ANOVA, the selected explanatory variables entering into the model of degree of bruise are shown in Table 2. The main effect of locular numbers had no significant effect on the degree of mechanical damage to tomato ($\alpha = 0.05$), so did the fruit physical parameters. These accords with general observation (Linden et al., 2006) that the set model based on the degree of mechanical damage to tomatoes did not include the fruit physical parameters. The effect of internal structure on the degree of mechanical damage mainly manifested in the main effect of loading position and the interaction effect between locular number and loading position. The factors, which had significant effect on the degree of mechanical damage to tomato, would be regarded as the explanatory variables of model. After the test for multiple comparisons of the qualitative explanatory variables selected, the results obtained are shown in Table 3. The degree of mechanical damage to tomato being loaded at the cross wall tissue and locular tissue were significantly different ($\alpha = 0.05$).

Modeling: The model of the degree of mechanical damage to tomato was established based on the selected explanatory variables, as shown in Table 4. The goodness of fit R^2 was 0.91 in this model, which indicated that 91% could be explained by this model during the change of mechanical damage degree of tomato. Therefore, this model could describe the mechanical damage degree of tomato efficiently.

It could be concluded from Table 4 that the covariates had a significant effect on the dependent variable, its P value (“Pr > F”) was less than 0.001, so it was far less than α (0.05). Therefore, it was very reasonable to select ANCOVA that can eliminate the effect of covariates during analysis.

The scatter diagram between the residual and predicted dependent are shown in Figure 5a. The distribution of residual was not regular, which indicates that the homoscedastic hypothesis of the error, ε_i, was reasonable. The graph between the empiristic distribution of residual and the fitted cumulative normal distribution are shown in Figure 5b. The results show that the mean of the fitted normal distribution was - 5.551E-17 and the standard error was 0.9634, the Kolmogorov D statistic was 0.0301, the corresponding P value > 0.15 > 0.05 = α, so the former hypothesis could not be rejected and we could deem the population distribution of residual was normal.

Table 4. Model of the degree of mechanical damage to tomato.

Explanatory(X)	Parameter estimate(β)	Standard error	t value	Pr>F
Intercept	- 0.1087	0.0515	- 2.11	0.0521
Compressibility ε	3.6375	0.3125	11.64	< 0.0001
Location CW	0.213	0.05	4.26	0.0007
Location L	0			
Structure* Location T*CW	- 0.1634	0.05	- 3.27	0.0052
Structure* Location F*CW	0		.	
Structure* Location T*L	0.0488	0.05	0.98	0.3445
Structure* Location F*L	0			

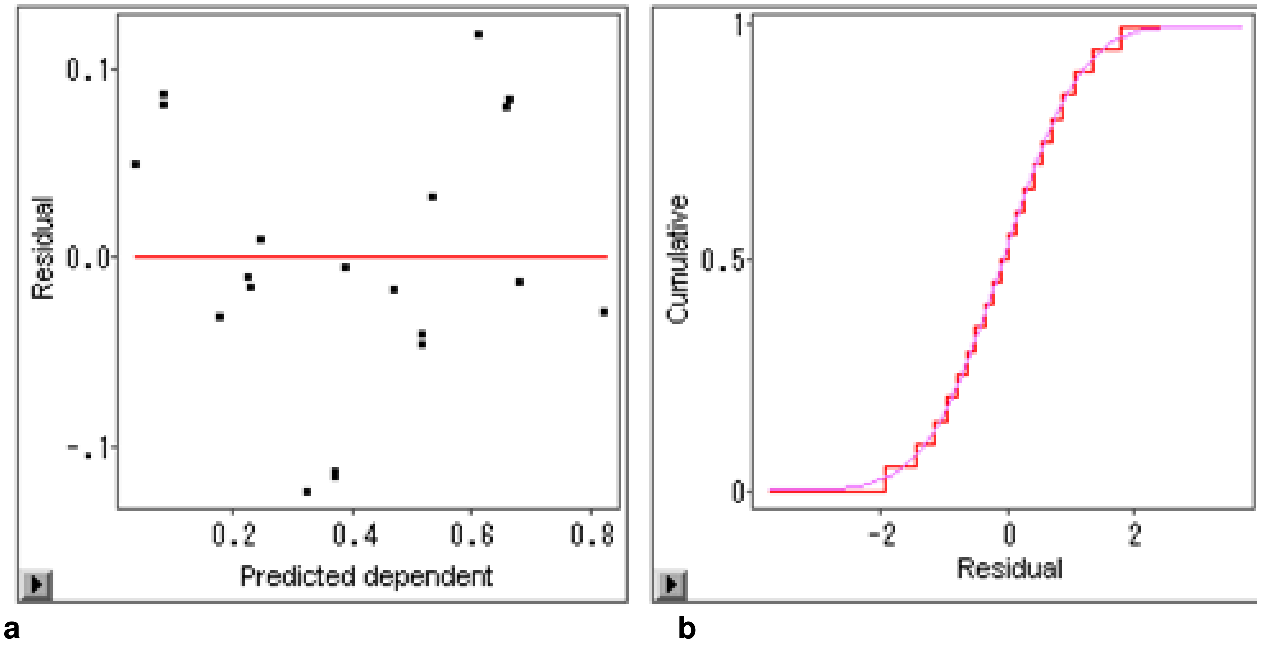

Figure 5. Tests for hypothesis.

Thus, the two hypotheses were met, the established model on the mechanical damage degree of tomato was significative and might be used to explicate the relationship between the degree of bruise and explanatory variables.

DISCUSSION

According to the GLM, the intercept term stands for the effect of the level on dependent variable when the parameters estimate value of the levels in the main effect term is 0. In this model, “Location L” was the level that the parameters estimate value was 0 in main effect term, so the “intercept” term stood for the effect of “Location L” on the degree of mechanical damage to tomato. The other parameters estimated values stood for the relative distance when the effect of corresponding levels on the dependent variable was compared with the intercept term. For example, under the condition of “compressibility 8%”, “four-locular tomato” and “CW”, the degree of mechanical damage to tomato was - 0.1087 + 3.6375*8% + 0 + 0.213 = 39.53%; under the condition of “compressibility 8%”, “four-locular tomato” and “L”, the degree of mechanical damage to tomato was - 0.1087 + 3.6375*8% + 0 + 0 = 18.23%; under the condition of “compressibility 8%”, “three-locular tomato” and “CW”, the degree of mechanical damage to tomato was -0.1087 + 3.6375*8% - 0.1634 + 0.213 = 23.19%, and under the condition of “compressibility 8%”, “three-locular tomato” and “L”, the mechanical damage degree of tomato was - 0.1087 + 3.6375*8% - 0.1634 + 0 = 23.11%.

Comparing the parameters estimated values of each factor in the main effects and the interaction effects, compressibility was the most important explanatory variable for the degree of mechanical damage to tomato.

Excluding the effect of covariates, the cross wall tissue most significantly affected the degree of mechanical damage to tomato. The degree of mechanical damage was greatest under the condition of *F*CW* and lowest for *F*L*, and their discrepancy is 21.3%. The discrepancy of the medium degree of mechanical damage was slight under the condition of *T*CW* and *T*L*, respectively. This illustrated that the internal structure of four-locular tomato had a significant effect on its degree of mechanical damage while the internal structure of three-locular tomato had not. Additionally, the degree of mechanical damage of the four-locular tomato being loaded at the cross wall tissue was larger (16.34%) than that of the three-locular tomato. The degree of mechanical damage of the three-locular tomato for the locular tissue was higher (4.88%) than that of the four-locular tomato. The loading-unloading test was conducted by means of Texture Analyzer in the position control mode. Therefore, if the tomatoes have the same deformation as it is loaded at “F*CW”, “T*CW”, “T*L” and “F*L”, respectively, its degree of mechanical damage is in the order: $\eta_{F*CW} > \eta_{T*CW} \approx \eta_{T*L} > \eta_{F*L}$.

Conclusion

To sum up, the effect of tomato internal structure on its mechanical properties and degree of mechanical damage was studied in detailed with the data obtained from the loading-unloading test and the observation of the shelf life. It can thus be concluded that:

1) The plastic strain energy, E_p, peak force, F_{max}, and degree of elastic, r_c, were not significantly affected by the internal structure of three-locular tomato before its failure, but loading slope r_k was. The degree of elastic r_c and loading slope r_k were significantly affected by the internal structure of four-locular tomato before its failure, but the plastic strain energy E_p and peak force F_{max} were not.

2) The compressibility, ε, was the most important explanatory variable in the model of the degree of mechanical damage to tomato.

3) The internal structure of four-locular tomato had a significant effect on its degree of mechanical damage, but the internal structure of three-locular tomato did not. Excluding the covariates, at the same compressibility, the degree of mechanical damage was greatest under the condition of *F*CW* and lowest for *F*L*, and their discrepancy is 21.3%. The discrepancy of the medium degree of mechanical damage was slight under the condition of *T*CW* and *T*L*, respectively.

The obtained data showed that the effect of tomato internal structure on its mechanical properties and degree of mechanical damage is essential to the steady gripping strategy of harvesting robot. Additionally, the data can be of great help for designers of end-effector and processing equipment in minimizing the mechanical damage resulting from mechanical collision and providing products with high quality for consumers and processors.

ACKNOWLEDGEMENTS

This work was supported by a grant from the National Natural Science Foundation of China (No. 50905076), the Graduate Innovative Projects of Jiangsu Province (No. CX09B_206Z) and the Foundation of Jiangsu Province Educational Committee (No. 09KJD210002). The authors would like to thank the reviewers for their helpful suggestions on the manuscript.

REFERENCES

Aworh OC, Olorunda AO (1981). Effect of packaging on mechanical damage of perishable fruits. Proceedings of the international horticultural society. Ibadan. Nigeria.

Altisent MR (1991). Damage mechanisms in the handling of fruits: Progress in agricultural physics and engineering. John Matthew (Ed.), Commonwealth Agricultural Bureaux (CAB) International, Willingford, UK. pp. 231-255.

Allende A, Desmet M, Vanstreels E (2004). Micromechanical and geometrical properties of tomato skin related to differences in puncture injury susceptibility. Postharvest Biol. Technol. 34: 131-141.

Arazuri S (2007). Influence of mechanical harvest on the physical properties of processing tomato. J. Food Eng. 80(1): 190-198.

Dobrzanski B, Rybczynski R (2002). Color change of apple as a result of storage, shelf-life, and bruising. Int. Agrophys. 16: 261-268.

Desmet M, Lammertyn J, Linden VV (2002). Mechanical properties of tomatoes as related to puncture injury susceptibility. J. Texture Stud. 33: 415-430.

Desmet M, Lammertyn J, Scheerlinck N (2003). Determination of puncture injury susceptibility of tomatoes. Postharvest Biol. Technol. 27: 293-303.

Desmet M, Lammertyn J, Linden VV (2004a). The relative influence of stem and fruit properties on stem puncture injury in tomatoes. Postharvest Biol. Technol. 33: 101-109.

Desmet M, Linden VV, Hertog ML (2004b). Instrumented sphere prediction of tomato stem-puncture injury. Postharvest Biol. Technol. 34: 81-92.

Fenma W (2001). New varieties 906 of tomatoes. Agric. Technol. Services. 8: 5-7

Gonzalez JJ, Mccarthy KL, Mccarthy MJ (1998). MRI method to evaluate internal structural changes of tomato during compression. J. Texture Stud. 29: 537-551.

Goyal RK, Kingsly AR, Pradeep K (2007). Physical and mechanical properties of aonla fruits. J. Food Eng. 82: 595-599.

Hetong L, Fang X, Shaojun C (2002). A review of enzymatic browning in fruit during storage. J. Fuzhou Univ. 30(supp.): 696-700.

Idah PA, Yisa MG (2007). An assessment of impact damage to fresh tomato fruits. AU J.T. 10(4): 271-275.

Jun X, Linden VV, Vanzeebroeck M (2005). Bruise detection on Jonagold apples by visible and near-infrared spectroscopy. Food control, 16: 357-361.

Jizhan L, Pingping L, Zhiguo L (2008). Experimental study on mechanical properties of tomatoes for robotic harvesting. Trans. Chin. Soc. Agric. Eng. 24(12): 64-70.

Kerstens S, Decraemer WFS, Verbelen JP (2000). Viscoelastic properties of cell walls are related to the orientation of cellulose fibrils. In: chanics conference. 27 Augustus-2 September, Freiburg-Badenweiler, Germany. Georg Thieme Verlag, Stuttgart, p. 487.

Khazaei J, Mann D (2004). Effects of temperature and loading characteristics on mechanical and stress-relaxation properties of sea buckthorn berries. Agric. Eng. Int. 1: 1-16.

Kang T, Song J (2006). Physical properties of foods. Southeast university press. Nanjing. pp. 40-47.

Kilickan A, Guner M (2008). Physical properties and mechanical behavior of olive fruits under compression loading. J. Food Eng. 87: 222–228.

Laykin S, Edan Y, Alchanatis V (1999). Development of a quality sorting machine using machine vision and impact.ASAE. 99: 31-44.

Lammertyn J, Aerts M, Linden VV (2000). Logistic regression analysis of factors influencing core breakdown in 'conference' pears. Postharvest Biol. Technol. 20: 25-37.

Lixin L, Zhiwei W (2004). Study of Mechanisms of Mechanical Damage and Transport Packaging in Fruits Transportation. 2004 9th National Conference on Packaging Engineering. 1: 131-135.

Linden VV, Baerdemaeker JD (2005). The phenomenon of tomato bruising: where biomechanics and biochemistry meet. 5th Int. Postharvest Symp.Eds.F Mencarelli and P. Tonutti Acta Hort. p. 682.

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

Linden VV, Ketelaere BD, Desmet M (2006b). Determination of bruise susceptibility of tomato fruit by means of an instrumented pendulum. Postharvest boil. Technol. 40: 7-14.

Linden VV, Sila DN, Duvetter T (2008). Effect of mechanical impact-bruising on polygalacturonase and pectinmethylesterase active and pectic cell wall components in tomato fruit. Postharvest Biol. Technol. 47: 98-106.

Lu R, Srivastava AK, Beaudry RM (2005). A new bioyield tester for measuring apple fruit firmness. Appl. Eng. Agric. 21(5): 893-900.

Lien CC, Ay CY, Ting CH (2009). Non-destructive impact test for assessment of tomato maturity. J. Food Eng. 91(3): 402-407.

Mohsenin NN (1986). Physical properties of plant and animal materials. Structure, physical characteristics and mechanical properties. 2nd updated and revised ed. Gordon and Breach Science Publishers Inc. New York.

Milczarek RR, Saltveit ME, Garvey TC (2009). Assessment of tomato pericarp mechanical damage using multivariate analysis of magnetic resonance images. Postharvest Biol. Technol. 52: 189-195.

Olorunda AO, Tung MA (1985). Simulated Transit studies on tomatoes: effect of compressive load, container, vibration and maturity on mechanical damage. J. Food Technol. 20: 609-678.

Plocharski WJ, Konopacka D (2003) Non-destructive, mechanical method for measurement of plums' firmness. Int. Agrophys. 17: 199-206.

Raji OA, Oriola KO (2007). Packaging and handling methods as sources of mechanical damage in tomatoes in transit. J. Eng. Appl. Sci. 2(9): 1450-1454.

Shanfeng C (2001). The occurrence of the mechanical damage of fruit and preventive measures. Reservation preservation and distribution. 1(1): 19-20.

Sukontasukkul P, Nimityongskul P, Mindess S (2004). Effect of loading rate on damage of concrete. Cement Concrete Res. 34: 2127-2134.

Thiagu R, Nagin C, Ramana KV (1993). Evolution of mechanical characteristics of tomatoes of two varieties during ripening. J. Food Agric. 2(62): 175-183.

USDA (1991). United States Standards for Grades of Fresh Tomatoes. http://www.ams.usda.gov/standards/tomatfrh.pdf.

Vanstreels E, Lammertyn J, Linden VV (2002). Red discoloration of chicory under controlled atmosphere conditions. Postharvest Biol. Technol. 26: 313-322.

Wang CX, Pritchard J, Thomas CR (2006). Investigation of the mechanics of single tomato fruit cells. J. Texture Stud. 1(37): 597-606.

Xingqian Y (1992). Storage, refreshing and procession of tomatoes. China agriculture press. pp. 14-21.

Xingyue H, Yong H, Annia GP (2005). Nondestructive Determination Method of Fruit Quantity Detection Based on Vis/NIR Spectroscopy Technique. Int. J. Information Technol. 11(11): 97-106.

Xiaojun L, Cheng S, Haiyan S (2007). The research of the mechanical damage of fruit and packaging. China packaging, 5(5): 83-86.

Xiubing Z, Aoxue W, Jingfu L (2009). Progress on cell wall hydrolase of tomato fruit. Journal of Northeast Agricultural University. 40(1): 128-132.

Yun D, Ying W, Yunfei L (2005). Biomechanical properties and texture detection of fruits and vegetables during storage and Transportation. Transactions of the CSAE. 21(4): 1-6.

Zue Z (1994). Agrobiology. China agriculture press. Beijing. pp. 5-7.

Zeebroeck MV, Tijskens E, Liedekerke PV (2003). Determination of the dynamical behaviour of biological materials during impact using a pendulum device. J. Sound Vibration, 266: 465-480.

Zhihong F, Shoujin G, Cheng L (2006).Comparison Test for Tomato Varieties. Modern vegetable, 2: 35-37.

Zeebroeck MV, Linden VV, Ramon H (2007). Impact damage of apples during transport and handling. Postharvest Biol. Technol. 45: 157-167.

Zeebroeck VM, Linden VV, Darius P (2007). The effector of fruit factors on the bruise susceptibility of apples. Postharvest Biol. Technol. 46: 10-19.