



The effect of compressibility, loading position and probe shape on the rupture probability of tomato fruits



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ARTICLE INFO

Article history:

Received 9 February 2013

Received in revised form 7 June 2013

Accepted 16 June 2013

Available online 24 June 2013

Keywords:

Tomato

Locule number

Rupture probability

Logistic regression

Robot harvesting

ABSTRACT

In this study, factors affecting the rupture probability of tomato fruits were investigated. The experiments were carried out at five compressibility levels (4%, 8%, 12%, 16% and 20%), four loading positions and two probe shapes. The fruit size, shape and mass did not have a significant effect on the rupture probability. The compressibility was the most important independent variable affecting the rupture probability of tomato fruits in the model. The rupture probability of quadrilocular tomato fruit loaded from the cross-wall tissue was the highest, and the odds of being ruptured was 14.5 times higher for quadrilocular tomato fruit loaded from the cross-wall tissue compared to the locular tissue. The curved probe was much more sensitive than the plate probe for rupturing of tomato fruits during the compression tests. It is clear that these investigated factors need to be considered carefully in design and control of tomato harvesting equipment.

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1. Introduction

Fresh tomato fruits are in great demand because they are an important part of the diet of millions of people worldwide (Pinheiro et al., 2013). According to data from FAOSTAT in 2011, more than 150 million tons of tomato fruits were produced in the world. In total production including fresh consumption production accounted for a part. As the harvesting season is short, the harvesting work is concentrated during a short time period, and labor shortages tend to limit the farm acreage (Li et al., 2008). Therefore, there is a strong desire to mechanize fresh consumption tomato harvesting. However, mechanical damage (i.e., rupturing) is a problem for fresh consumption tomato mechanical harvesting such as robot harvesting (Kondo et al., 1996; Van Henten et al., 2009). The damaged tomato fruits, especially ruptured fruits, will rapidly decay during transport and storage because of bacteria invasion and have little commercial value (Ortiz et al., 2011). To prevent or reduce the mechanical damage, research on the factors that affect the damage of tomato fruits has been conducted since the 1970s (Fluck, 1973; Van Linden et al., 2006; Salamolah et al., 2010).

Previous research on the factors that affect the mechanical damage of fruits can be summarized into two categories. One category is the external factors, such as the impact energy (Van Linden et al., 2006), impact position (Van Linden et al., 2006), impact angle (Desmet et al., 2003), compressibility level (Li et al., 2010) and the

type of material of the contact surface (Idah and Yisa, 2007). The other category is the internal factors, which are closely related to the natural characteristics of the fruit such as the variety (Desmet et al., 2004), ripening stage (Salamolah et al., 2010), and geometrical properties (Van Zeebroeck et al., 2007a). However, mechanical damage is only a qualitative description of the failure behavior of fruits. Quantitative analyses on the mechanical damage of tomato fruit are always carried out using a objective replaceable parameter as the dependent variable, such as damage area (Idah and Yisa, 2007), mechanical properties (Van Zeebroeck et al., 2007b), a sensory evaluation score (Van Linden et al., 2006) or the damage impact energy threshold (Desmet et al., 2003, 2004) for bruise susceptibility calculated by using a logistic regression function, visual evaluation score (Fluck, 1973) or classes (Salamolah et al., 2010) and conductivity scores for fruit tissue (Milczarek et al., 2009).

To sum up, an objective description of mechanical damage of tomato fruits is still far from being realized by far. Rupture damage is one main type of mechanical damage of tomato fruits. In this research, the rupture damage of tomato fruits is quantitatively described using a new dependent variable: the rupture probability based on a visual evaluation score calculated using a logistic regression function. During the mechanical harvesting process, especially during robot harvesting, the compressibility and shape of the robot finger surface are two controllable factors that affect the rupture probability of tomato fruits but have still not been objectively investigated. The compressibility is a percentage ratio of the relative diameter change of a fruit subjected to an external compression force. The shape of the robot finger surface was

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replaced by the probe shape because it is possible to test this factor using the TA-TX2 Texture Analyzer. Importantly, tomato fruits have an internal structure with 3–8 locules (Li et al., 2011a, 2012). Therefore, tri- and quadri-locular fruits were chosen to represent fruits with an odd number of locules (an asymmetric internal structure) and fruits with an even number of locules (a symmetric internal structure) respectively, with the loading position serving as an appropriate independent variable to represent the internal structure of the fruits. The objective of this paper was to objectively investigate the effect of the loading position, the compressibility and the probe shape on the rupture probability of two different structure types of tomato fruits during mechanical harvesting.

2. Materials and methods

2.1. Material

Fresh Fenguan906 tomato fruit, which were uniformly grown at the Ruijing Vegetable Research Institute of Zhenjiang, were chosen for the experiments. They were hand harvested in October 2011 at the light red ripening (half-ripe) stage according to the USDA Standards (USDA, 1991). After being carefully transported to the Key Laboratory of Modern Agricultural Equipment and Technology in Jiangsu Province, the tomato fruits were inspected again to ensure that they were not damaged or infected by worms. The tests were conducted within 24 h at room temperature ($18 \pm 1^\circ\text{C}$, 63–65% RH).

2.2. Measurement of physical parameters

After the chosen tomato fruits were randomly sorted into 40 groups and appropriately labeled, the principal dimensions, that is, the longitudinal height (H), maximum transverse diameter ($L_{\max}$), and minimum transverse diameter ($L_{\min}$), were measured with an electronic digital caliper to an accuracy of 0.01 mm. Subsequently, the geometric mean diameter (D_g), sphericity (Φ) and arithmetic mean diameter (D_a) values were calculated using the corresponding equations (Karababa, 2006). The fresh mass (M) of the tomato fruit was measured using an electronic balance to an accuracy of 0.01 g.

2.3. Experimental setup

A full factorial design was performed, consisting of four loading positions at the equatorial surface of the fruit, five compressibility levels (4%, 8%, 12%, 16%, and 20%) and two types of probes (Plane probe, PP, P100; Curved probe, CP, curvature $\times$ chord length $\times$ width = $22.2\text{ m}^{-1} \times 54\text{ mm} \times 45\text{ mm}$). As shown in Fig. 1, Positions 1 ($T \times CW$) and 2 ($T \times L$) were against the pericarp over a cross-wall and the locular tissue, respectively, of the trilobular fruits and Positions 3 ($F \times CW$) and 4 ($F \times L$) were against the pericarp over a cross-wall and locular tissue, respectively, of quadrilobular fruits. A cross-wall could be identified visually as the valley position between two adjacent fruit shoulders (Li et al., 2011b). The loading positions can represent the internal structure characteristics of the tomato fruit. The plane and curved probes, whose curvatures are 0 and 22.2 m^{-1} , respectively, were used to investigate the effect of different types of curved surfaces on the rupture probability of the tomato fruit.

All of the loading-unloading tests were performed by using a TA-TX2 Texture Analyzer (Texture Technologies Corp., NY, USA) that was equipped with two types of probes for the tests, as shown in Fig. 2. The analyzer was calibrated with a 5 kg weight before the first test. The test speed was set to 0.5 mm/s, which is appropriate

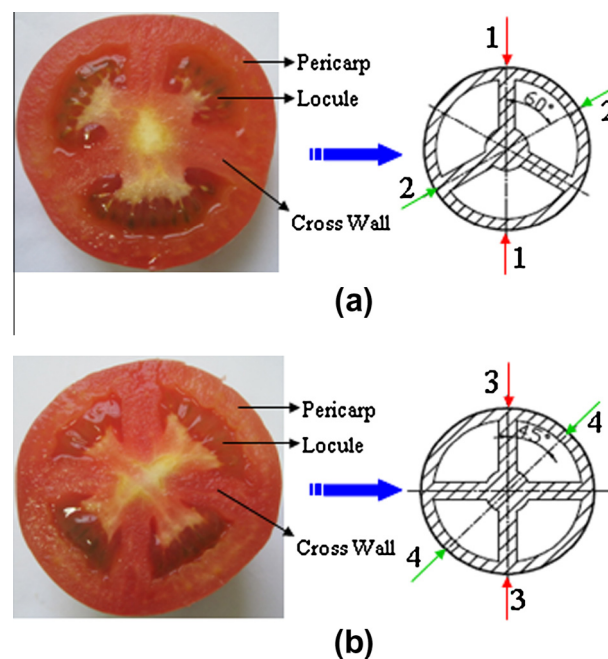


Fig. 1. Tri- and quadri-locular tomato fruits. (a) A trilobular tomato fruit (left) and its simplified equatorial section (right). (b) A quadri-lobular tomato fruit (left) and its simplified equatorial section (right). The numbers 1, 2, 3 and 4 represent loading positions 1, 2, 3 and 4, respectively.

to simulate the grasping speed of a robot finger; the compressibility level and loading position were adjusted to follow the full factorial design. The loading-unloading test is of the typical grasp-release process of the fingers during robot harvesting. All of the loads were located at the equatorial region of the fruit. In total, 200 tomato fruits (five tomato fruits $\times$ four loading positions $\times$ two probe shapes $\times$ five compressibility levels) were tested. Finally, the presence or absence of a crack outside the pericarp of the half-ripe tomato fruits after the test was recorded individually.

2.4. Statistical analysis

All of the statistical analyses were performed using the SAS software, version 9.1.3 (SAS Institute Inc., Cary, NC, USA). The significance level was set at 0.05.

2.4.1. Logistic regression

The tomato fruits showed either a crack or no crack outside their pericarp after the test, which was a binary response. A logistic regression is an appropriate tool to investigate the relationship between a binary response variable and a set of independent variables. Therefore, this method was adapted to investigate the factors that affect the rupture probability of the tomato fruits during mechanical harvesting.

During modeling, the geometric parameters (arithmetic mean diameter D_a , geometric mean diameter D_g , mass M and sphericity Φ) and the external loading factors (compressibility level x , loading position LP and probe shape PS) were considered as a possible set of independent variables. The SAS analyst automatically transformed all of the class into design variables. An appropriate subset of independent variables was automatically selected by a stepwise selection procedure. The variables were entered in the model using the Score χ^2 test statistic and removed from the model using the Wald χ^2 test statistic at a significance level of $\alpha = 0.05$. A model

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