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Multi-scale engineering properties of tomato fruits related to harvesting, simulation and textural evaluation

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A B S T R A C T

In this study, multi-scale engineering properties related to the harvesting, simulation and textural evaluation of two tomato cultivars at six ripening stages were simultaneously investigated. A potential ripening scale based on the ratio of R:G:B for a given ripening stage was suggested. The geometric mean diameter was most closely correlated with the fruit mass. Tomato fruit feature an irregular shape and asymmetric internal structure at the macro-scale, non-unique tissue thickness at the meso-scale and an irregular change of size, shape and arrangement of single cells at the micro-scale. The hardness and shear strength of fruit at different scales and the single cell mechanics varied with the fruit ripening stage but not the chosen cultivars. The contribution of exocarp to the hardness of whole fruit gradually increased with fruit ripeness. The hardness and shear strength of fruit tissues and the fruit's single cells varied between 0.37 and 2.25 MPa and 0.04 and 11.58 MPa, respectively. This puncture experimental method is well-suited to measure the hardness and shear strength of tomato fruit at different scales and single tomato cell mechanics.

1. Introduction

Numerous large-scale tomato-growing farms are in operation worldwide because tomatoes are a component of the diet of millions of people. Because the harvesting season is short and harvesting work is concentrated during a brief period of time, labor shortages tend to limit the farm acreage (Tanigaki, Fujiura, Akase, & Imagawa, 2008). Additionally, given the long distance between farms and sale markets, the design and development of intelligent equipment for mechanical harvesting, packaging and transport have received increasing attention (Kondo, Yata, Taniwaki, Tanihara, Monta, & Kurita, 2010; Li, Li, Yang, & Wang, 2013). Furthermore, fruits with a distinct multi-scale nature are very susceptible to mechanical damage during postharvest handling; thus, multi-scale modeling, internal damage simulation and postharvest textural evaluation are extremely important (Genard et al., 2007; Ghysels et al., 2010; Ho et al., 2013; Mebatsion, Verboven, Ho, Verlinden, & Nicolai, 2008). Determining the multi-scale engineering properties of tomato fruits is essential to achieve these aims.

Some engineering properties of tomato fruits have been previously investigated. Arazuri, Jaren, Arana, and Perez De Ciriza (2007), Li, Li, and Liu (2011) and Sirisomboon, Tanaka, and Kojima (2012) reported the geometric and mechanical macro-properties of tomato fruits at three different stages of ripeness (Arazuri et al., 2007; Li et al., 2011; Sirisomboon et al., 2012). Hetzroni, Vana, and Mizrach (2011) and Li, Li, Yang, Liu, and Xu (2012) determined the physical and biomechanical properties of the peels and internal tissues of five tomato cultivars at the meso-scale (Hetzroni et al., 2011; Li, Li, et al., 2012). Rancic, Quarrie, and Pecinar (2010) presented the geometric characteristics of the fruits and tissues of two tomato genotypes during fruit development (Rancic et al., 2010). Bargel and Neinhuis (2005) focused on the morphology and biomechanics of skin and enzymatically isolated the cuticular membranes of three tomato cultivars during fruit growth and ripening (Bargel & Neinhuis, 2005).

Tomato fruits are hierarchically structured at the macro-scale, consisting of different tissue types at the meso-scale, each of which is a highly structured arrangement of cells at the micro-scale (Li & Thomas, 2014a, 2014b). However, some important engineering parameters for multi-scale modeling and simulation, such as

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the geometry of the whole fruit, the size and shape of the different tissues, the cell sizes in each tissue and the multi-scale biomechanics, have never been fully determined for single fruit, even though these characteristics significantly differ. Additionally, little is known about the relationship between different physical parameters and the micro-mechanics at the cell level. Therefore, a clear gap in knowledge exists between the published data on fruit engineering properties and the necessary data related to intelligent harvesting, multi-scale simulation and postharvest textural evaluation. The objective of this study was to investigate the multi-scale engineering properties of tomato fruits.

2. Materials and methods

2.1. Materials

The experiments were conducted in May 2014 at Henan Polytechnic University. Fruits of two tomato varieties, *Fendu* 79 and *Omeiya* 333, were used for this study. The tomato fruits were hand-harvested from the Jiaozuo *Manfeng* Vegetable Planting Base at six ripening stages (green, breaker, turning, pink, light red and red) according to the USDA standards (USDA, 1991), as shown in Fig. 1a. These fruits were inspected to ensure that they were not damaged or infested with insects prior to transport to the laboratory. Subsequently, the fruits' surfaces were manually cleaned and dried. In total, 60 tomato fruits (5 samples × 2 varieties × 6 ripening stages) were used to measure the multi-scale geometric characteristics, and 12 tomato fruits (1 sample × 2 varieties × 6 ripening stages) were used for the puncture test.

2.2. Quantification of ripeness

One tomato fruit was randomly selected from each ripening stage (green, breaker, turning, pink, light red and red). These tomatoes were grouped and placed on a blank paper with the support of wedges, as shown in Fig. 1a. A JPEG photo of tomato fruits from front view was then obtained using a digital camera (Canon 95IS, Photo size: 3648 × 2736 pixels). Subsequently, ten pixel points were randomly grabbed from each tomato fruit using a color picker software (ColorPix version 1.1, http://www.colorschemer.com/colorpix_info.php). The three primary color values of grabbed points, namely Red-Green-Blue (RGB), were then based on the automatic transformation provided by the software.

2.3. Multi-scale geometric characteristics measurement

The sampled fruits were labeled and then cut into halves with a sharp knife along the stem–blossom axis (Fig. 2a). One half of each fruit was cut again along the equatorial axis (Fig. 2b). Further descriptions of the tomato fruit anatomy are given in Thomas (1996). The following were measured using an electronic digital caliper (to an accuracy of 0.01 mm): height above the fruit's equatorial axis (section) (H_1); height below the fruit's equatorial axis (H_2); diameter of the equatorial section (D_f); maximum thickness (W_{mmax}), minimum thickness (W_{mmin}), middle thickness of the mesocarp tissue (W_{mmid}); thickness of the septa tissue (W_s); and columella diameter (D_{ct}). Subsequently, rectangular tissue blocks, including the exocarp and some of the adhering mesocarp, were excised and soaked in boiling water for 5 min. The exocarp samples remained after the mesocarp was carefully scraped off using a razor blade. The thicknesses of the exocarp samples (W_e) were then measured with an electronic digital caliper.

As shown in Fig. 2a, some tissue blocks, including the exocarp and mesocarp and some columella tissue blocks, were excised from the sample zones shown in the other half of the fruits. The mesocarp and columella tissue samples were cut into thin rectangular slices (length × width × thickness: 15 mm × 10 mm × 0.5 mm) using a razor blade. The exocarp samples remained after the adhering mesocarp sample was carefully scraped off. These tissue samples were made into temporary mounts and then vertically observed using a Belona BL-SM1280 biological microscope that featured a 130w electronic eyepiece (Captured image size: 1280 × 1024 pixels, Resolution: 96 PPI). The diameters (D_c) (Fig. 2c) of cells in different tomato fruit tissue types were measured with a virtual cross ruler using the image processing software *Future WinJoe* of the eyepiece (Assumption: spherical cell). The reported values of the cell geometric characteristics are the means of 5 cells in corresponding tissues. The multi-scale geometric characteristics of tomato fruits were measured within 24 h of sampling at room temperature (23 ± 1 °C, 56–58 % RH).

2.4. Puncture test

The puncture test, which involves compression and shear components, is one of the most widely used methods for the objective measurement of the biomechanics of fruits. The

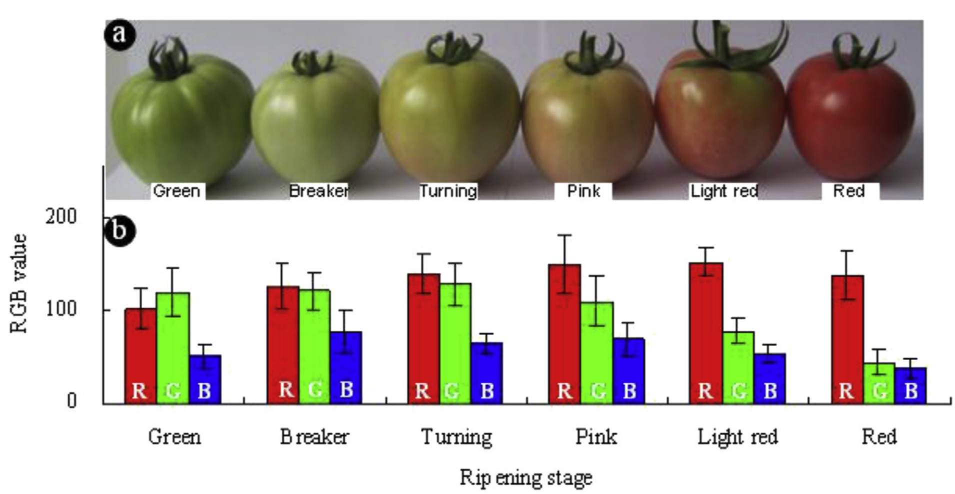

Fig. 1. Tomato fruits at six ripening stages and their corresponding RGB values. (a) Six ripening stages of tomato fruits. (b) RGB values of tomato fruits at the six ripening stages, R-Red, G-Green, B-Blue. Data are expressed as the mean ± SD ($n = 10$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)