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Effect of the shear-to-compressive force ratio in puncture tests quantifying watermelon mechanical properties

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ABSTRACT

Because texture is a primary driver of watermelon acceptability, the development of methods to test for small differences in texture between new cultivars would be of great utility to fruit breeding efforts. The objective was to investigate the effect of the shear-to-compressive force ratio in puncture tests on watermelon, then design new probes that would improve the test's sensitivity. A new hollow probe design of increased shear force (compactness = 11.6 mm^2/mm^2) was more sensitive at quantifying watermelon tissue mechanical properties when compared to the industry standard Magness–Taylor probe (compactness = 1 mm^2/mm^2). Compressive force applied is constant between the two. The hollow probe was more sensitive to differences between tissue types, though was not able to discriminate between cultivars, using the maximum force value. Based upon the improved performance of the hollow probe with tissue types, a high-shear 'snowflake' probe was designed and compared to the hollow and Magness–Taylor probes. The Magness–Taylor probe misclassified tissue types in 42% of samples tested, while the hollow and snowflake probes performed better, misclassifying 32% and 34% of samples, respectively. This was an improved accuracy over the Magness–Taylor, but the hollow and snowflake probes were not significantly different ($\alpha = 0.05$) from each other. These results suggest that of the two, the hollow probe, due to its simplicity, offers an improvement over the industry standard Magness–Taylor in maximum force parameter applications.

1. Introduction

The importance of texture in watermelons, particularly firmness, has been reflected in various breeding efforts. Tolla et al. (2006) and Davis and King (2007) bred for extra-firm fruit, citing consumer preference and extended shelf life in fresh-cut fruit as motivators. It would be of great utility for breeders to be able to test for small differences in texture between new cultivars of fruit in order to determine if the new breeding material is worth further investigation.

Puncture tests, first developed by Magness and Taylor (1925), are commonly used to analyze the mechanical properties of fruits and vegetables due to their low cost, portability, and ease of use. The test involves the determination of the maximum force and deformation required to push a probe into a sample and cause observable failure in the macrostructure of a material (Mohsenin, 1986; Bourne, 2002). The maximum force parameter has commonly been used in destructive tests as a measure of firmness in various commodities including melons, apples, and pears, due to its simplicity and suitability for use in industrial settings (Sugiyama et al., 1998; Chauvin et al., 2010). From our experience working with plant breeders, we know that hand-held penetrometers are commonly utilized in the field, despite inconsistencies due to differences in individuals using them and the amount of pressure applied.

In general, when solid materials are deformed under applied force from a probe, an increase in force is required to obtain an increase in the depth of probe penetration. When the probe diameter is smaller than the fruit diameter, the process of pushing the probe into fruit tissue produces a combination of shear and compressive forces (Bourne, 1966, 1975; Yang and Mohsenin, 1974). Bourne developed the following equation to describe the contribution of compression and shear to total yield force observed when using a puncture test:

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$$F = K_cA + K_sP + C$$

where F is total yield-point force, K_c is the compressive material coefficient, A is probe contact area, K_s is the shear material coefficient, P is the probe perimeter, and C is a constant (Bourne, 1966, 1975). The compressive force is a function of the probe contact area (K_cA), and the shear force a function of both the probe perimeter (K_sP) (Fig. 1). Both compression and shear are related to area. Compression is related to probe tip contact area. Shear is related to the surface area of the probe penetration "hole", minus the bottom, which is the compression area. By altering either A or P, the applied force is impacted.

Bourne (1966, 1975); Yang and Mohsenin (1974) have manipulated the A-to-P ratio with sets of rectangular and circular probes, alternately varying A or P, to find K_c and K_s of materials including apples, carrots, and margarine. Each found this simple relationship to provide useful insight into characterizing complex differences in compressive and shear properties in foods. Challenges in understanding the mechanical properties each probe measures have made it difficult to compare puncture test data from different puncture probes (Tolla et al., 2006; Yang and Mohsenin, 1974).

Jackman and Stanley (1992) studied the compression and shear forces, testing how tomato ripeness impacts probe measurements (in addition to maximum force) dependent on the compressive and shear material properties of the tissue. They found ripeness affected whether tissue failure was influenced more by shearing or compressive forces. These results stress the need for caution when interpreting force–deformation parameters from puncture tests and the importance of considering both shear and compressive forces and properties of plant tissues.

Puncture tests taken from the watermelon heart tissue are an industry standard for quantifying this fruit's firmness (Tolla et al., 2006; Bang et al., 2004; Sugiyama et al., 1998). However, the edible portion of the fruit is not homogeneous. It is composed of three major tissue types with different mechanical properties. Heart tissue is located in the center and tends to be the firmest part of the fruit. In seedless watermelon varieties (triploids), locule walls divide the fruit into three equal sections. Placenta tissue, which contains pips and seeds, is located on either side of each locule wall and tends to be the least firm. The remaining flesh is considered locule tissue. Though the mechanical properties of the placental, locular and heart tissues in watermelon are not uniform, puncture tests in the heart alone are commonly used to represent the entire fruit. It would be useful to characterize the differences in mechanical properties between tissues and determine if heart tissue is reasonably representative of the fruit as a whole. An additional weakness of puncture tests taken from the watermelon heart tissue is the general lack of sensitivity of this method in discriminating watermelon cultivars and maturities, which makes it difficult to provide quantitative information to evaluate or compare watermelon cultivars, maturities and tissue types based upon their mechanical properties.

Thus the objective of this study was to investigate the effect of the shear-to-compressive force ratio in force–deformation parameters measured by puncture tests on watermelon under ideal laboratory conditions, then use that information in designing new probes that would improve the sensitivity of the puncture test in the comparison of watermelon cultivars. These results may inform development of methods to be applied in the field.

2. Materials and methods

2.1. Magness–Taylor and hollow probe puncture tests with five watermelon cultivars

2.1.1. Plant material

Five seedless triploid watermelon cultivars (Amarillo, Imagination, Petite Perfection, RWT8225, and Distinction) were selected to represent a range of textures. According to breeders, Amarillo is characterized by flesh of low firmness, Imagination by medium–low, Petite Perfection by medium, RWT8225 by medium–high and Distinction by high firmness. Full-ripe stage fruit were harvested the morning of the experiment in July and August 2009 from plants grown by Syngenta Seeds, Inc., in Woodland, CA. Ripeness indicators included drying of flag leaf and tendril adjacent to plant stem, yellowing of the fruit ground spot, and dulling of fruit skin surface.

2.1.2. Hollow probe development

The new hollow probe was designed to explore the influence of compressive and shear watermelon tissue strength on its mechanical properties. In the development of the new probe, the design needed to meet the following criteria: feature the same contact area as the Magness–Taylor solid probe, but increased perimeter; be large enough to minimize clogging with fruit tissue during puncture tests, while small enough to puncture individual watermelon tissue regions; and be easy to manufacture.

The tube shape of the hollow probe was machined from a standard stainless steel tubing (inner diameter 17.09 mm, outer diameter 20.32 mm), with a small hole in the probe side wall as seen in Fig. 2 to minimize clogging. It features the same contact area as the Magness–Taylor solid probe, 95 mm^2, and applies the same compressive force, but increased shear. In order to compare probes, the probes were classified by their silhouette compactness. Compactness is a dimensionless shape parameter that is based upon the ratio of the perimeter squared to the area as illustrated in the following equation:

$$\text{Compactness} = \frac{\text{Perimeter}^2}{4\pi\text{Area}} \tag{1}$$

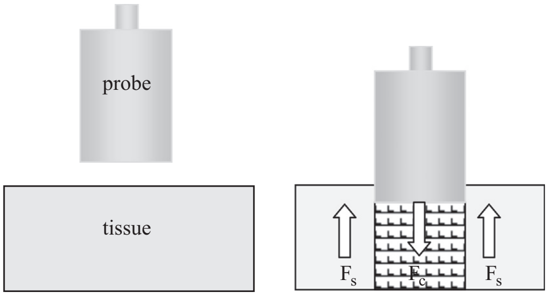

Fig. 1. The application of a puncture probe to a tissue sample generates compressive force, F_c, directly under the probe contact surface, and shear forces, F_s, at the probe's perimeter, as seen on the right. Modified from Bourne (2002).

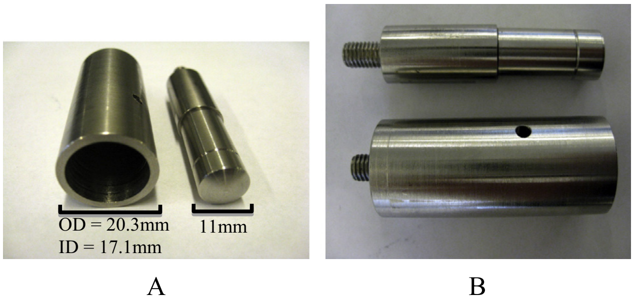

Fig. 2. Front (A) and side (B) views of the hollow probe (left side in A, bottom in B) and Magness–Taylor solid cylindrical probe (right side in A, top in B). The hollow probe features a 17.1 mm inner diameter and 20.3 mm outer diameter. The solid probe is 11 mm in diameter.