



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 mm²/mm²) was more sensitive at quantifying watermelon tissue mechanical properties when compared to the industry standard Magness–Taylor probe (compactness = 1 mm²/mm²). 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.

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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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$$F = K_c A + K_s P + C$$

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 ($K_c A$), and the shear force a function of both the probe perimeter ($K_s P$) (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 quanti-

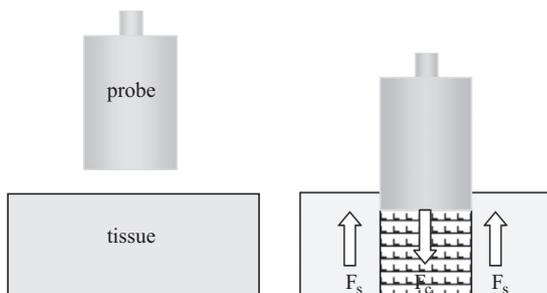


Fig. 1. The application of a puncture probe to a tissue sample generates compressive force, F_c , directly under the probe contact surface, and shear forces, F_s , at the probe’s perimeter, as seen on the right. Modified from Bourne (2002).

tative 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 mm², 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:

$$\text{Compactness} = \frac{\text{Perimeter}^2}{4\pi\text{Area}} \quad (1)$$



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.

For this study, the compactness was normalized by including the 4π constant in the denominator of Eq. (1) so that the Magness–Taylor solid cylindrical probe had a compactness value of $1 \text{ mm}^2/\text{mm}^2$. Using this definition, the hollow probe had a compactness of $11.6 \text{ mm}^2/\text{mm}^2$.

2.2. Experimental design for Magness–Taylor vs. hollow probe comparison in puncture tests

Two, 2.5 cm thick, adjacent transverse slices were cut from the middle 5.0 cm of each fruit, one slice for each type of puncture probe being evaluated. Slices ranged from 6 to 10 in. in diameter, pending on cultivar type. Each slice was kept intact (Fig. 3) for puncture tests performed with a texture analyzer (TA.XT2 Texture Analyzer, Texture Technologies Corp., Scarsdale, NY, USA). An 11 mm diameter Magness–Taylor type solid cylindrical probe (Abbott, 1999) was used to sample one slice, and a UC Davis hollow probe (ID 17.09 mm, OD 20.32 mm) to sample the other. Both probes fit into the TA.XT2 Texture Analyzer in the same manner. Probes punctured the flesh to a depth of 8 mm at 1 mm/s penetration rate. Heart tissue was sampled only once due to limited tissue availability, while placental and locule were evaluated twice per probe per slice as illustrated in Fig. 3. Eight fruit per cultivar were sampled.

Following the protocol used by Gonzalez et al. (2010) in a study analyzing onion mechanical properties, a set of force–deformation measurements was recorded for each puncture test, and the following parameters were derived as illustrated in Fig. 4: maximum force (N) or hardness (Bourne, 2002), the initial slope or stiffness calculated as the gradient of the line connecting the origin of the curve to 20% maximum force (N/mm) (Mohsenin, 1986), bioyield force (N), bioyield slope (N/mm), deformation at bioyield (mm), work before maximum force (N mm) which indicates the toughness and was calculated as the area under the curve from the origin of the curve to maximum force (Mohsenin, 1986), work after maximum force (N mm) calculated as the area under the curve from maximum force to 90% strain, deformation at maximum force (mm), and number of peaks defined as a change in slope sign followed by an increase in the force above 0.15 N.

ANOVA and Tukey–Kramer HSD at $\alpha = 0.05$ were used to compare Magness–Taylor solid and hollow probe puncture test mean parameters. PCA plots of puncture probe test parameters were also obtained.

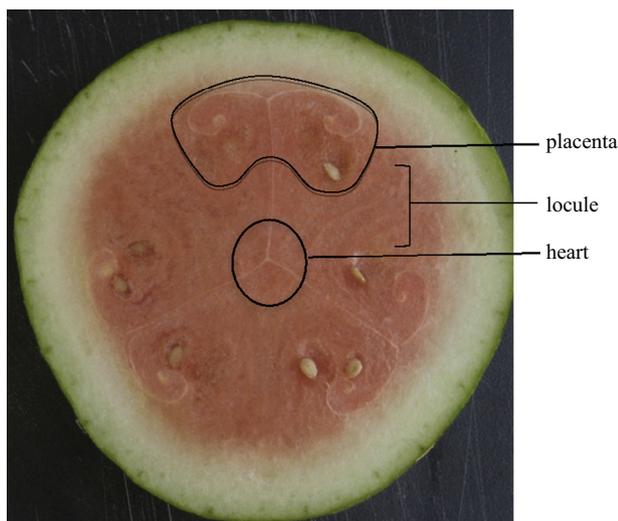


Fig. 3. Watermelon tissue diagram with tissue regions where texture measurements were taken.

2.3. Comparison of Magness–Taylor, hollow and snowflake probes

Six additional prototype probes were designed with high shear properties. The probes were manufactured using computer numerical control (CNC) manufacturing technology and the surface roughness manufacturing tolerance on the final probe exterior was 1 mm (ASME B46.1, 2009). These probes had compactness values ranging from 6.8 to $35.5 \text{ mm}^2/\text{mm}^2$, and were designed to provide a range of perimeter-to-area characteristics in an attempt to further enhance the sensitivity of the puncture test and fully investigate the benefits of increasing the ratio of shear to compressive force. The hollow probe had a compactness that was about an order of magnitude higher than the industry standard Magness–Taylor solid puncture probe ($11.6 \text{ mm}^2/\text{mm}^2$ vs. $1 \text{ mm}^2/\text{mm}^2$), providing a significant increase in the ratio of shear to compressive force. The six prototype probes were evaluated for ease of manufacture, ease of cleaning and ability to distinguish tissue types in preliminary tests. The ‘snowflake’ probe (compactness = $25.2 \text{ mm}^2/\text{mm}^2$) performed the best in preliminary testing. This probe, along with the hollow probe, which was the easiest to manufacture and clean, were selected for comparison to the industry standard Magness–Taylor solid puncture probe. The snowflake probe has a similar design to the hollow probe, with a 9.3 mm inner diameter, 19.1 mm outer diameter, and eight half circles of 7.7 mm diameter bored out of the perimeter of the pipe, giving it the ‘snowflake’ appearance.

2.3.1. Experimental design for comparison of Magness–Taylor, hollow and snowflake probes in classification of watermelon cultivar and tissue types using mechanical properties

Fascination, a large and relatively firm cultivar, and Petite Perfection, a medium firmness personal-size cultivar (Syngenta Seeds, Inc., Fresno, CA) were selected for the comparison of the Magness–Taylor probe with the hollow and snowflake probes. The anatomy of the tissues differs by cultivar. Thus four different cultivar–tissue combinations studied will be referred to as follows: Heart_{Fascination} = Fascination heart tissue, Placenta_{Fascination} = Fascination placental tissue, Heart_{Petite Perfection} = Petite Perfection heart tissue, Placenta_{Petite Perfection} = Petite Perfection placental tissue. The four cultivar–tissue regions were defined to elucidate within and between cultivar tissue differences assessed by puncture probes. Three 2.5 cm thick transverse slices were cut from the middle 7.5 cm of each fruit and the probe type selected for measurement of heart and placenta within each fruit was randomized within the three slices. Puncture tests to a depth of 8 mm, at a rate of 1 mm/s, were carried out on heart and placental tissue in each slice using a texture analyzer (TA.XT2 Texture Analyzer, Texture Technologies Corp., Scarsdale, NY, USA). In total, each of the three probes was applied to the heart tissue 20 times in each of the two watermelon cultivars (40 times total). Each probe was applied to the placenta tissue 30 times in each watermelon cultivar (60 times total).

2.3.2. Statistical analysis of cultivar and tissue type classification

Quadratic (i.e., the within-class covariance matrices were not assumed to be equal) Bayesian discriminant analysis (Duda et al., 2001; Khattree and Naik, 2000) was performed to assess the ability of each probe to predict the identity of watermelon cultivar and tissue types from individual puncture probe measurements. This classification method creates a single multivariate discriminant function for each probe using two or more of the mechanical properties shown in Fig. 4. Stepwise selection was used to determine which mechanical properties showed the greatest discriminatory power, as measured by Wilks’ lambda. Internal cross-validation was used to determine the number of properties used in creating the discriminant functions. The model development and analysis

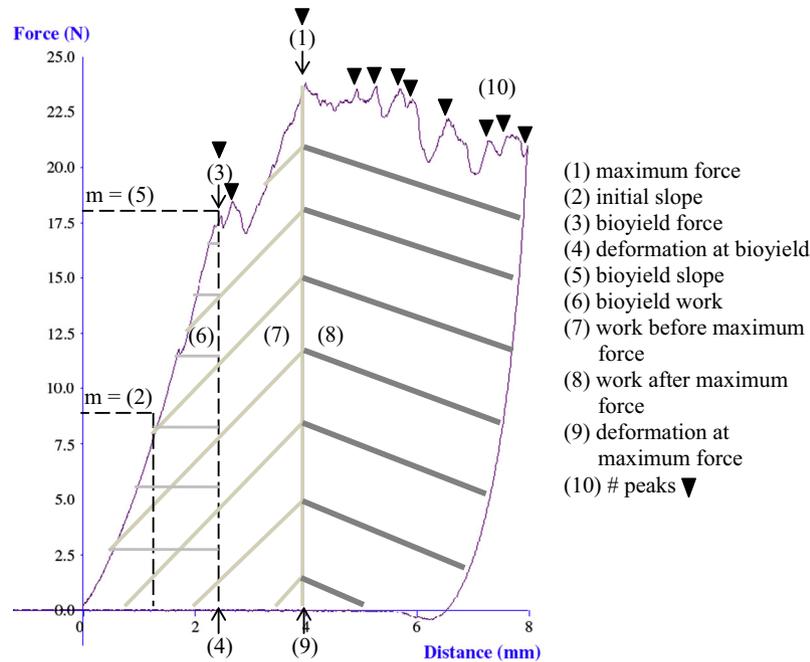


Fig. 4. Parameters recorded from a representative force–deformation curve obtained from texture analysis using various puncture probes.

of the cultivar and tissue type classification results was conducted using the JMP 8.0 statistical software (SAS Institute Inc., Cary, NC, USA).

3. Results and discussion

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

The Magness–Taylor and hollow probes were expected to perform differently based on previous work done by Bourne (1966, 1975), Yang and Mohsenin (1974) and deMan (1969) analyzing the compressive and shear properties of materials with a selection of puncture probes. These studies found linear relationships between puncture probe perimeter, contact area, and applied force. However, as far as the authors can determine, this study is the first use of a hollow probe of this design, where the Magness–Taylor and hollow probe had identical contact area. The force required to puncture a material depends on the area and perimeter of the puncture probe, and the compressive and shear strengths of the material.

Mean measurements obtained with the Magness–Taylor solid and hollow probe puncture tests were compared by ANOVA and Tukey–Kramer Honest Significant Difference (HSD) test in order to evaluate the ability of each probe to discriminate differences in mechanical properties between watermelon cultivars and tissue types. There were 10 different mechanical property parameters derived from the puncture tests, e.g. maximum force, initial slope, bioyield force, deformation at bioyield, bioyield work, work before maximum force, work after maximum force, deformation at maximum force, and number of peaks. Each parameter was compared by cultivar and tissue. Despite relatively large standard deviations for each data set analyzed, significant differences were identified at $\alpha = 0.05$. Non-significant results were not included in Table 1.

A PCA plot of the 10 texture parameters from the solid and hollow probes reveal slight differences in their performance (Fig. 5). The measurements loaded largely in similar directions and magnitudes, indicating that the two probes capture a very similar set of

information. After two factor rotations of Fig. 5B by the Varimax rotation method, it appears that the hollow probe has the parameters slightly more spread out than the solid probe. Regarding the bioyield deformation parameter, the solid probe loads directly along positive y-axis while the hollow probe results load slightly along the negative x-axis. The work before maximum force parameter loads into quadrant I for the solid probe, while it loads relatively weakly into quadrant II for the hollow probe. These observations suggest that the different balance between shear and compression properties of the probes affect the measurement of deformation at bioyield and work before maximum force.

Principal components 1 and 2 of the solid probe (Fig. 5A) account for 44.2% and 32.6% of variation in the data, respectively while PC1 and PC2 of the hollow probe (Fig. 5B) account for 40.4% and 26.7% of variation, respectively. Because the first two principle components explains such a large portion of the overall variance, this suggests the parameters measured from the puncture tests may be adequate to quantitatively differentiate various cultivars.

Regarding cultivar discrimination, the Magness–Taylor probe more clearly grouped cultivars. Use of the mean maximum force parameter allowed the Magness–Taylor probe to differentiate the firmer cultivars, Distinction and RWT8225, from the softer cultivars, Imagination and Amarillo (Table 1). Petite Perfection overlapped between the two groups. This statistical ranking mirrors the same expected trend in firmness as described by breeders – Amarillo and Imagination as low in firmness, RWT8225 and Distinction as high in firmness, and Petite Perfection falling in the middle as medium firmness. The hollow probe also distinguished the firmest, Distinction, from the softest, Amarillo. However, the intermediary cultivars were not differentiated. The difference is small, though the Magness–Taylor appears more robust in this application.

Mohsenin (1986) defined initial slope in the mechanical property profile as a measure of stiffness. Bourne (2002) also related initial slope to the stiffness of a material under load. For an ideal elastic material (e.g. a metal spring), stiffness is the slope of the linear force vs. deformation relationship. The initial slope values obtained using both the Magness–Taylor puncture and hollow probes broadly grouped the cultivars into three statistically significant groups (a, b, c), with some overlap between the three (Table 1).

Table 1
Comparison of instrumental mechanical property measurements with the Magness–Taylor and UC Davis hollow probes by cultivar and tissue type.

Measurement	Maximum Force (N)		Initial slope (N/mm)		# Peaks	
	Probe					
Cultivar	Solid	Hollow	Solid	Hollow	Solid	Hollow
Amarillo	10.7 ± 2.7 ^b	13.5 ± 3.3 ^{bc}	1.8 ± 0.7 ^c	3.6 ± 1.8 ^{bc}	14.1 ± 6.0 ^c	27.0 ± 8.7 ^c
Imagination	10.8 ± 3.5 ^b	12.4 ± 2.8 ^c	4.1 ± 3.4 ^a	3.4 ± 1.5 ^c	30.5 ± 14.5 ^a	29.4 ± 11.0 ^c
Petite Perfection	13.2 ± 5.9 ^{ab}	15.6 ± 6.0 ^{ab}	2.6 ± 1.1 ^{bc}	4.5 ± 3.5 ^{abc}	24.1 ± 8.7 ^{ab}	35.7 ± 13.3 ^b
RWT8225	13.9 ± 6.7 ^a	16.7 ± 4.9 ^{ab}	4.1 ± 3.2 ^a	5.1 ± 2.5 ^{ab}	28.9 ± 13.5 ^{ab}	42.6 ± 8.0 ^a
Distinction	15.0 ± 4.7 ^a	16.1 ± 4.7 ^a	3.9 ± 1.7 ^{ab}	5.3 ± 2.8 ^a	22.8 ± 10.4 ^b	30.9 ± 13.6 ^{bc}
Heart	15.3 ± 4.5 ^a	17.9 ± 4.5 ^a	2.9 ± 1.3 ^b	3.8 ± 2.4 ^b	20.6 ± 9.9 ^b	26.5 ± 12.2 ^b
Locule	13.9 ± 5.2 ^a	15.7 ± 5.2 ^b	4.2 ± 3.4 ^a	5.2 ± 3.2 ^a	31.6 ± 13.4 ^a	40.2 ± 11.8 ^a
Placenta	10.8 ± 3.0 ^b	12.5 ± 3.0 ^c	2.7 ± 1.5 ^b	3.8 ± 1.7 ^b	18.9 ± 8.4 ^b	29.8 ± 10.3 ^b

Mean values with standard deviation are given. Mean values sharing a common letter group within cultivars or tissue types were not significantly different by the Tukey–Kramer HSD method ($\alpha < 0.05$).

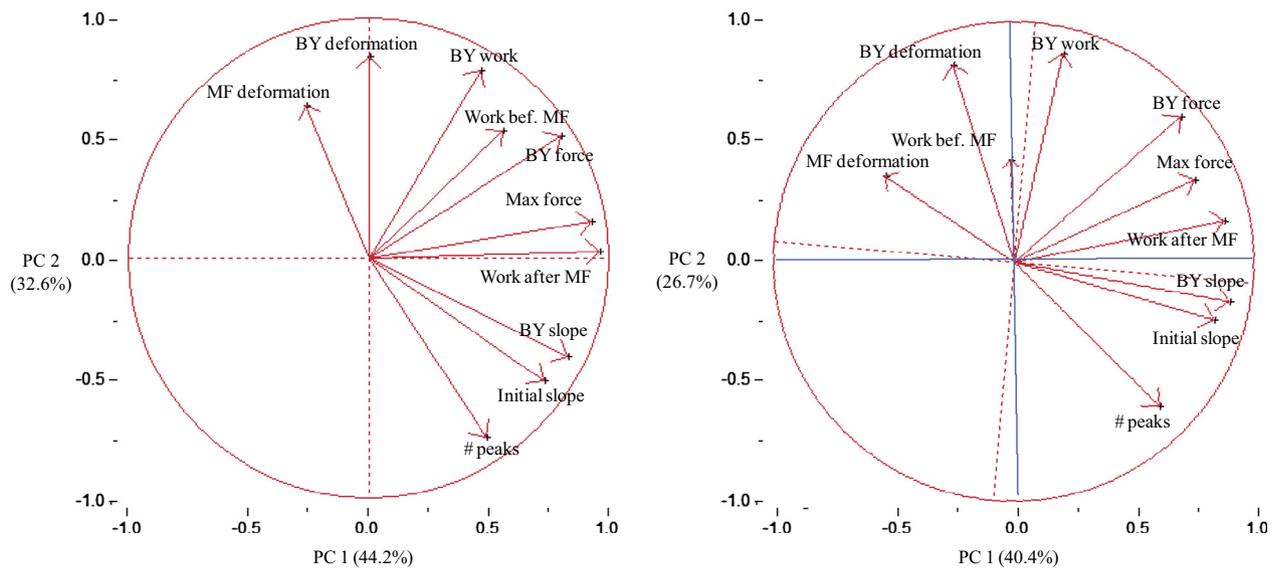


Fig. 5. PCA loadings of puncture test measurements on principle components (PC) 1 and 2 for Magness–Taylor solid (A) and hollow probes (B). (B) Has been rotated 2 factors by the Varimax rotation method. MF = maximum force; BY = bioyield.

The initial slope parameter, as measured with the Magness–Taylor solid probe, determined that Amarillo was statistically less stiff than the other cultivars. Imagination and RWT8225 were the stiffest cultivars. In contrast, analysis of initial slope using the hollow probe determined more overlap, and thus less distinction, between statistical groups in terms of their stiffness properties and the cultivar rankings differed. Imagination and Amarillo were the least stiff, and Distinction and RWT8225 the most stiff, however there was overlap between Amarillo, Petite Perfection and RWT8225. Petite Perfection was not distinguished from either group. The hollow probe results for initial slope were ranked more closely to the maximum force rankings than the initial slope results using the Magness–Taylor solid probe. These apparent contradictions in tissue texture measurements between cultivars are likely due to the interaction between the different types of loading (compression vs. shear) of the two probe designs and differences in the internal tissue structures between the cultivars. Future work is needed to fully understand the complex interaction between cultivar, tissue mechanics and type of loading.

Both the Magness–Taylor and hollow probes significantly distinguished the stiffness of the locule tissue from that of the heart and placenta tissues. The equivalent performance of the two probes in differentiating tissue types using these two parameters suggests that the compressive and/or shear strength of the heart and placental tissues are more similar to each other while the locule tissue is different.

In comparisons between the three different tissues, use of the hollow probe for the maximum force parameter resulted in more discriminating power between the three tissue types than the current standard Magness–Taylor solid probe. The hollow probe discriminated the tissues into three separate, statistically significant groups. The Magness–Taylor only distinguished placenta tissue from the locule and heart tissues. The ability of the hollow probe to distinguish all three tissue types using the maximum force measurement suggests significant differences in the shear properties of the heart, placenta, and locule tissue. This indicates it may not be representative to measure just the maximum force of the heart tissue, as is the industry standard practice. Additional sampling of the placenta and locule tissue may provide additional information that better represents the fruit flesh.

The differences in performance of the solid and hollow probes for each mechanical property attribute indicate each probe is capturing different material properties. The anatomy of the tissues differs by cultivar. Therefore, coupled with the different types of loading of the two probe designs, one parameter may be more indicative than another, depending on the anatomy. The larger spread of values of the initial slope parameter measured by the Magness–Taylor probe indicates the means were more distinct, indicating better sensitivity. Each statistical group contained two cultivars with the Magness–Taylor, as opposed to three cultivars with the hollow probe.

In puncture tests performed on tomato, [Jackman and Stanley \(1992\)](#) found the initial tissue deformation arose from the stretching of its middle lamellar pectin, allowing the rearrangement of cells. Additionally, the compaction of interstitial air spaces provided little resistance to the applied force. In onion, [Gonzalez et al. \(2010\)](#) found strong positive correlations between cell viability and initial slope, indicating cell viability and therefore membrane intactness were related to this mechanical property parameter. Thus tissues having more cells with intact membranes are stiffer, providing more resistance to an applied force and resulting in higher initial slope values. The initial slope results determined on watermelon raise the question of the significance of cell membrane and cell wall integrity and cell arrangement for tissue mechanical properties. The application of cell imaging methods would help determine the extent that cellular arrangement and cell wall or membrane integrity contribute to stiffness in different watermelon cultivars.

Regarding the number of peaks parameter, the Magness–Taylor solid probe and the hollow probe displayed a number of differences. First, the solid probe was only able to separate the cultivars into two statistically different groups, while the hollow probe was able to separate them into three groups. Furthermore, the mean number of peaks measured by the solid probe was statistically lower than that of the hollow probe (Tukey–Kramer HSD at $\alpha = 0.05$, $Q_{\max} = 3.18$). For example, the mean for Amarillo was 14 peaks with the solid probe, and 27 with the hollow probe. This indicates a larger number of tissue failure events were detected using the hollow probe.

[Gonzalez et al. \(2010\)](#) observed a strong positive correlation between percent viable onion cells and number of peaks, suggesting that peaks arise from the puncture probe traveling through different intact cell layers. In watermelon, the greater number of peaks measured with the hollow probe suggests the compactness of the probe ($11.6 \text{ mm}^2/\text{mm}^2$) and the cell dimensions and arrangement in watermelon tissue enable the rupture of more cells through shear. In comparison, the compactness of the Magness–Taylor solid probe is only $1 \text{ mm}^2/\text{mm}^2$ even though the two probes have similar contact areas.

Overall, comparison of the Magness–Taylor and hollow probe puncture test parameters by Tukey–Kramer HSD revealed that the hollow probe was superior to the Magness–Taylor solid probe at distinguishing both tissue types, though not cultivars, using the mean maximum force parameter of the sample. This is a promising finding because it is also the most field applicable parameter to

measure, being fast and easy to replicate. This is a good reason to further explore the relationship between shear force and mechanical properties in watermelon, and perhaps other commodities. For these reasons, the hollow probe was included in the next phase of experiments.

3.2. Comparison of Magness–Taylor, hollow and snowflake probes in classification of watermelon mechanical property regions

The performance of the snowflake, hollow, and Magness–Taylor probes in distinguishing the watermelon cultivar and tissue type using individual puncture probe measurements was evaluated using discriminant analysis. A two-factor multivariate discriminant function based upon the maximum force and number of peaks parameters from [Fig. 4](#) provided equivalent classification performance to more complex models and superior performance to univariate models.

The two-factor (maximum force and number of peaks) multivariate discriminant function for the Magness–Taylor solid puncture probe misclassified the watermelon cultivar/tissue type texture regions for 42% of the total probe measurements. Heart_{Fascination} tissue was most often misclassified as either Petite Perfection or placental tissue ([Table 2](#)). The hollow and snowflake probes performed better at this task, misclassifying only 32% and 34% of measurements, respectively. Overall, the hollow probe showed improved classification for both Heart_{Fascination} and Placenta_{Fascination}, which come from cultivar Fascination, known for high firmness. The snowflake probe demonstrated improvement in classifying Heart_{Fascination}, though not Placenta_{Fascination}. This suggests the sensitivity threshold of the new probes may work better with organoleptically firmer fruit. Testing a wider range of fruits may help support this. Thus, while the hollow and snowflake probes demonstrated improved performance over the industry standard Magness–Taylor solid probe, the two new probes were not significantly different.

Based on work by [Bourne \(1966, 1975\)](#), it was hypothesized that an optimal probe compactness exists that emphasizes mechanical property differences in watermelon. The compactness value for the hollow probe (compactness = $11.6 \text{ mm}^2/\text{mm}^2$) is 11 times larger, or less compact, than the Magness–Taylor solid probe (compactness = $1 \text{ mm}^2/\text{mm}^2$). Meanwhile, the snowflake probe compactness value (compactness = $25.2 \text{ mm}^2/\text{mm}^2$) is only 2.5 times larger than that of the hollow probe. Though the snowflake probe is 25 times larger than the Magness–Taylor, there is a non-lin-

Table 2

Predicted classification by Quadratic Bayesian discriminant analysis of tissue regions from Magness–Taylor solid, UC Davis hollow, and snowflake puncture probe measurements. Correct classification levels are shown in bold type along the diagonal, with counts above and percentages in parentheses.

Probe	Predicted Classifications			
	Heart _{Fascination}	Heart _{Petite Perfection}	Placenta _{Fascination}	Placenta _{Petite Perfection}
<i>Solid</i>				
Heart _{Fascination}	6 (32%)	7 (37%)	4 (21%)	2 (11%)
Heart _{Petite Perfection}	2 (10%)	17 (85%)	0 (0%)	1 (5%)
Placenta _{Fascination}	4 (13%)	0 (0%)	18 (60%)	8 (27%)
Placenta _{Petite Perfection}	1 (3%)	0 (0%)	13 (43%)	16 (53%)
<i>Hollow</i>				
Heart _{Fascination}	13 (65%)	4 (20%)	3 (15%)	0 (0%)
Heart _{Petite Perfection}	1 (5%)	14 (70%)	2 (10%)	3 (15%)
Placenta _{Fascination}	3 (10%)	4 (13%)	19 (63%)	4 (13%)
Placenta _{Petite Perfection}	0 (0%)	3 (11%)	4 (15%)	20 (74%)
<i>Snowflake</i>				
Heart _{Fascination}	14 (70%)	4 (20%)	1 (5%)	1 (5%)
Heart _{Petite Perfection}	0 (0%)	16 (80%)	2 (10%)	2 (10%)
Placenta _{Fascination}	1 (3%)	9 (30%)	14 (47%)	6 (20%)
Placenta _{Petite Perfection}	0 (0%)	4 (14%)	4 (14%)	21 (72%)

ear decrease in advantage to increased compactness. There appears to be an upper limit to the value of increasing the shear over the compression component of the probe for texture testing of watermelon. Thus the difference between the Magness–Taylor and hollow probe is larger than between the hollow and snowflake probes, which appear to be in agreement with the results. Additionally, the biggest gain was in more accurately distinguishing Heart_{Fascination}. This may be attributed to increased sensitivity arising from the interaction between tissue mechanics and the type of loading applied, though further work is required to fully understand this complex relationship.

The Heart_{Fascination} ellipses of the canonical analysis plots (not shown) are smaller for the hollow and snowflake probes than for the Magness–Taylor probe, indicating increased sensitivity for the mechanical characteristics of the cultivar Fascination. While these results reveal some impact from differences in compactness, there does not appear to be a clear advantage to increasing compactness value beyond that of the hollow probe design. A further advantage of the hollow probe design is that it is much simpler to manufacture than either the Magness–Taylor or the snowflake probes. Readers are referred to Abbott (1999) for a complete description of the exact shape and dimensions of the Magness–Taylor probe. Abbott reports that one problem with the Magness–Taylor test is that some studies have incorrectly reported measurements under the generic term Magness–Taylor for puncture tests using a hemispherically tipped or other non-standard probe shape. This type of problem is unlikely to occur with the hollow probe since the front face of the probe is flat.

4. Conclusions

An increased shear hollow probe design for puncture tests exhibited superior performance in quantifying watermelon tissue mechanical properties when compared to the industry standard Magness–Taylor probe. The hollow probe was better than the Magness–Taylor probe at distinguishing tissue types using the maximum force parameter, statistically separating tissue types better than other parameters. The contrasts in probe performance when comparing various tissue measurements across cultivars suggests a complex relationship between cultivar, tissue mechanics, and type of loading.

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