A PORTABLE DEVICE FOR THE BIOYIELD DETECTION TO MEASURE APPLE FIRMNESS

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ABSTRACT. The bioyield phenomenon occurs to the apple fruit when it is subjected to compressive loading (i.e., compression or puncture), which causes cell failure without disintegrating the macro tissue structure. Force at the bioyield point is useful for nondestructive evaluation of fruit firmness. A portable device, which consisted of an off-shelf force meter, an actuation driver, and control unit, was developed for detecting bioyield force from apples. Experiments were performed on ‘Golden Delicious’ and ‘Red Delicious’ apples to determine the correlation between bioyield force measurement and the standard Magness-Taylor (MT) firmness test, evaluate the sensitivity of bioyield measurement to changes in firmness over time, and quantify firmness variation over the fruit. Bioyield force correlated with MT force with $R^2$ values of 0.835, 0.654, and 0.751 for ‘Golden Delicious,’ ‘Red Delicious,’ and the pooled data, respectively. Bioyield force was as sensitive to firmness change over time as MT force ($R^2 = 0.990$) for apples that underwent accelerated softening. The bottom section (the calyx end) of the apple was significantly firmer than the middle and top sections of the fruit. Moreover, the south face or sunny side of the apple was significantly firmer than the north face or shady side of the fruit. Hence, two bioyield measurements should be performed at opposing sides of an apple around the equator to obtain the average firmness value for the fruit. The bioyield device is useful for measuring the firmness of apples in the orchard and during postharvest handling, and for monitoring fruit conditions during storage.

Keywords. Apple, Fruit, Firmness, Bioyield, Nondestructive sensing.

Firmness is a textural attribute of apple fruit, and it is of key importance in determining consumer satisfaction. Firmness also serves as an important physiological indicator in determining the best time to harvest a crop of apples. The ability to monitor the firmness of apples during postharvest handling and storage would enable packinghouse operators to provide more consistent and better quality fruit for the consumer.

The Magness-Taylor (MT) firmness test is the current industry standard method to measure firmness. This test records the amount of force required to penetrate the fruit flesh to a specific depth using a cylindrical probe as a measure of fruit firmness. The MT firmness device, invented in 1920s, has served the apple industry’s needs for several decades. Because MT testing is destructive, it is only suitable for sampling a small number of fruit to obtain average firmness information from a large lot of fruit. The technique cannot meet increasing consumer demand for high quality and consistent fruit because a great variation in fruit firmness exists in a lot of fruit.

To measure or monitor the firmness of individual apples for the fresh market, a device must be capable of measuring the firmness nondestructively. Hence, researchers have pursued the development of nondestructive firmness measurement techniques over the past decades (Abbott et al., 1997). Several mechanical devices and methods (such as quasi-static force/deformation, impact, and sonic) were developed (Delwiche et al., 1989; Prussia et al., 1994; Abbott et al., 1995; Sugiyama et al., 1998; Sugiyama, 2001; Garcia-Ramos et al., 2003; Shmulevich et al., 2003). However since these methods measure different mechanical characteristics or properties in comparison to MT, their performance against this standard test has not been satisfactory, especially for firm fruit such as apple. Abbott et al. (1995) reported low correlation ($R^2 < 0.35$) between sonic measurement and MT firmness for ‘Red Delicious’ apples. Shmulevich et al. (2003) showed that both impact and sonic methods correlated with the MT test poorly ($R^2 < 0.36$) for ‘Golden Delicious,’ ‘Granny Smith,’ and ‘Starking Delicious’ apples. More recently, researchers also explored other non-mechanical methods, such as near-infrared spectroscopy and spectral scattering, for nondestructive evaluation of fruit firmness (Lammertyn et al., 1998; Lu, 2004, 2007). While these optical techniques look promising for online sorting and grading for fruit firmness, considerable technical difficulties still exist. They are not ready for use as a low-cost portable device for firmness measurement and monitoring in the orchard and at the packinghouse, due to high instrumental cost and the reliance on complicated calibration procedures at the present.

Engineers have long questioned the merit or need of using MT firmness measurement as the standard to evaluate the performance of a new nondestructive technique, because it is so challenging to achieve good correlation between a
nondestructive method and the standard MT firmness test. But the end users (i.e., fruit growers, packers, and inspectors) would be reluctant to adopt a new nondestructive method that correlates poorly with the MT tester.

Lu et al. (2006) investigated a method of using a mechanical probe with a soft tip to improve the measurement of bioyield force for evaluation of apple firmness nondestructively. Bioyield is a mechanical phenomenon that takes place in many plant products when they are subjected to compressive loading, including compression and puncture. Bioyield measurement involves detecting a sudden drop in force while displacement continues to increase in a test. This drop in force indicates cell failure without disintegrating the macro tissue structure. Lu et al. (2006) applied the Hertz contact theory to evaluate the interaction of a rubber tip with an apple to improve the accuracy and sensitivity of measuring the point at which bioyield occurs. The research provided guidelines for the design of a bioyield probe including the diameter, thickness, and elasticity of the rubber tip, to measure the bioyield point effectively.

The measurement of bioyield has several benefits. First, a properly designed instrument utilizing bioyield may leave a small indentation on the surface of the apple, but would be well within the confines of the USDA grading standards definition of injury. Second, since the bioyield measurement would not degrade the fruit, the method could be useful for measuring the maturity of apples on the tree and for monitoring the firmness change in individual fruit after harvest. Finally, because the bioyield test measures the strength of the cellular tissue, it has shown to correlate with the MT test better than other nondestructive mechanical tests in measuring the firmness of apples (Lu et al., 2005, 2006). Hence, the bioyield measurement technique could replace or co-exist with MT as a testing standard.

The objectives of the research were therefore to:

- Design and build a low-cost, portable device to automatically detect and measure the bioyield point/force from apples;
- Determine the correlation between bioyield and MT measurements for apples stored in air refrigeration and controlled atmosphere conditions;
- Compare bioyield measurements with MT firmness measurements to determine their sensitivity to the physiological change in apples with time; and
- Evaluate firmness variation across the surface of the apple to determine an appropriate bioyield firmness measurement procedure.

**MATERIALS AND METHODS**

**DESIGN OF THE BIOYIELD DEVICE**

A bioyield device should be nondestructive to the fruit, low in cost, and easy to operate. Moreover, it should be portable and rugged for automated measurement, analysis, and storage of measured data. Based on these criteria, a bioyield device was built (fig. 1), which consisted of force meter, actuation drive, control unit, and software.

A commercial force meter (IMADA DPS-11R, Imada, Inc., Northbrook, Ill.) was used to measure force up to 49.0 N with a resolution of 0.01 N. Attached to the force meter is a removable probe. The probe consists of two parts, the steel threaded shaft and a rubber tip. Using the design guidelines from the work conducted by Ababneh (2002), a rubber tip of 6.35-mm (0.25-in.) diameter and 3.18-mm (0.125-in.) thickness provided optimal bioyield detection results. In addition, Ababneh (2002) suggested that the elastic modulus of the rubber should not exceed twice that of the apple. A tip design meeting these criteria would minimize the budging effect, reduce stress concentrations, and improve surface contact when the rubber tip is in compression against the apple fruit. This would effectively improve the accuracy and sensitivity in detection of the bioyield point (Lu et al., 2006). Six rubber tipped probes of the same dimensions (6.35-mm diameter and 3.18-mm thickness) but with the elastic modulus ranging between 3.14 and 23.55 MPa were compared. After evaluation of each rubber tipped probe (Tipper, 2006), the final design selection consisted of the number 50 polyurethane rubber tipped probe, which had an elastic modulus of 4.79 MPa. The range of the elastic modulus values reported for ‘Golden Delicious’ and ‘Red Delicious’ apples was between 3.35 and 9.10 MPa (Mohsenin, 1986). Ababneh (2002) used the elastic modulus of 4.01 MPa for the model apple in the finite element simulation of the bioyield test. In view of these requirements, this particular probe tip design seemed appropriate.

The actuation drive serves two main purposes. First, it provides a constant rate of displacement by actuating the apple vertically at a user-configured fixed speed. Second, the rack and pinion housing acts as a structural support arm for the force meter and as a connection block for the gearbox and motor assembly. A “cup,” mounted to the top of the rack gear, holds the apple while testing. The device performs a bioyield test at a speed of 3.65 mm/min. ASAE Standard S368.4 (ASAE Standards, 2000) recommends a testing speed of 10 mm/min or less to observe the bioyield point of an apple.
The control unit is responsible for controlling the stepper motor, monitoring the force meter readings, communicating with the computer, storing test data, and displaying information on the liquid crystal display.

The software was specifically written using StampDAQ (Parallax Inc., Rocklin, Calif.), LabView software (National Instruments, Austin, Tex.), and MS Excel (Microsoft Corp., Redmond, Wash.). The software consists of three programs that are used to control and monitor the device, record bioyield test data, and perform data analysis. The first program builds menus and settings to control the device. The second program is responsible for operating the bioyield test to detect the bioyield point. The StampDAQ software forms the basis for real-time data acquisition between the bioyield instrument and a computer. The bioyield point is detected when a drop in force is greater than 0.01 N. The third program performs postprocessing analysis to obtain bioyield test results (i.e., force and displacement at the bioyield point) and statistical information. A detailed description of the software programs and functions is given in Tipper (2006). Figure 2 demonstrates the bioyield data on the LabView program after completion of parsing and processing.

**BIOYIELD TESTS OF FRUIT FIRMNESS**

**Fruit Samples**

‘Golden Delicious’ and ‘Red Delicious’ apples were harvested from an orchard at Michigan State University’s Horticultural Teaching and Research Center in Holt, Michigan in the fall of 2004. These apples were either stored in air refrigeration condition at 0°C or in controlled atmosphere (at 0°C with 2% O2 and 3% CO2) storage condition prior to the testing. Only those apples with the size or maximum equatorial diameter between 70 and 83 mm (2.75 and 3.25 in.) were used in the experiment.

All tests were conducted at room temperature (~22°C). In addition, all apples remained at room temperature for a period of at least 12 h before testing started. This ensured the apple temperature reached equilibrium with the testing environment after removal from storage.

**Calibration of the Bioyield Probe**

All bioyield tests started with rubber tip calibration. This calibration step recorded the force/displacement curve of the rubber tip by compressing the rubber-tipped probe against the rigid, flat steel surface (i.e., the holding platform mounted onto the top of the rack gear, as shown in fig. 1) using the same testing parameters that would be used for the apple test. This procedure served for two purposes: first, the force/displacement data for the rubber tip was used to reconstruct the actual force/displacement response curve for each test apple. During the bioyield test for an apple fruit, the displacement recorded is the combined deformation of the rubber tip and the apple sample. With the knowledge of the force/displacement response of the rubber tip, we can reconstruct the force/displacement response curve for each test apple by subtracting the displacement of the rubber tip obtained in the calibration test from the one obtained in the apple test for each force level. The software had a built-in function to automatically perform these calculations and display the actual force/displacement for the apple on the computer screen (fig. 2). Second, this calibration procedure would enable us to ascertain if the rubber tip still performed as expected at the time of the testing since temperature, humidity, and wear could affect the rubber tip’s property and hence its performance.

**Comparison of Bioyield and MT Measurements**

Six hundred fifty ‘Red Delicious’ apples and 650 ‘Golden Delicious’ apples were used in the experiment to compare bioyield measurements with the results of MT tests. On a given date, 100 apples were tested. The experiment had been performed over a 36-day period, so that a large range of firmness for the test samples would be obtained.

For each test apple, two bioyield measurements and one MT measurement were taken. The location of each bioyield measurement was approximately 45 degrees from the predetermined MT test location as shown in figure 3. All tests were conducted on the equator, located on the largest...
diameter of the fruit. The two bioyield measurements were averaged to represent the bioyield value for the test apple, and the average bioyield values were then used in subsequent analysis.

**Comparison between Bioyield and MT over Time**

Two hundred sixty-four ‘Golden Delicious’ apples were used in this experiment to determine if bioyield measurements were as sensitive to firmness changes over time as MT measurements. The apple samples were placed in plastic buckets covered with a lid and plastic bag to prevent excessive moisture loss; they were kept at room temperature (~22°C) to accelerate the softening process from the start of the experiment.

On each test date, 33 apples were randomly selected. Bioyield and MT measurements were taken from the two opposite sides of the equator of the apple. The two bioyield measurements and two MT measurements were averaged, and the average firmness values were used in further analysis.

**Bioyield Location Study**

The apple fruit is inhomogeneous and anisotropic in the cellular structure; its mechanical properties vary with location and/or direction within the fruit (Abbott and Lu, 1996). This experiment was designed to quantify bioyield firmness variations on the face of the fruit, so that an appropriate test procedure can be recommended to ensure accurate, consistent firmness measurements for each fruit. The MT firmness test was not performed in the experiment due to its destructive nature.

The firmness location study consisted of 12 bioyield measurements on 50 ‘Golden Delicious’ apples. The measurement sections (top/middle/bottom) and directions (north/east/south/west) of each test were designated in a coordinate system shown in figure 4. The south direction designated the “sunny” or blush side of the apple (if distinguishable).

The bioyield firmness data obtained from the bioyield location study were analyzed using two-factor ANOVA (i.e., Analysis of Variance) to determine if there were significant variations in firmness due to face section, face direction, and/or interactions between the two factors. In performing ANOVA, the bioyield data were treated to be normally distributed, in view of the measured bioyield data (Tipper, 2006). ANOVA was performed with fruit section and face direction. Further statistical analyses were performed to quantify firmness variations with section and direction. A significance level of 0.05 was used to determine the effect of these factors.

**RESULTS AND DISCUSSION**

**COMPARISON BETWEEN BIOYIELD AND MT MEASUREMENTS**

The bioyield device provided information on the force, displacement, slope of the force-deformation curve, and area contained within the force-deformation curve. It was found that bioyield force correlated best with MT force, while other parameters (i.e., bioyield displacement, slope, area under force/displacement curve, and drop in force after bioyield detection) yielded minimal to no correlation with MT force (results are not presented here). Hence the following discussion is only focused on bioyield force as the primary measured parameter of firmness.

An $R^2$ value of 0.751 and the standard error of 7.10 N were obtained for the pooled data of ‘Red Delicious’ and ‘Golden Delicious’ apples (fig. 5). Further regression analysis between MT and bioyield measurements for each apple variety yielded $R^2$ values of 0.835 and 0.654 and the standard error of 5.37 N and 8.42 N for ‘Golden Delicious’ and ‘Red Delicious’, respectively (fig. 6). Better correlation for ‘Golden Delicious’ than for ‘Red Delicious’ is in agreement with the results reported in Lu et al. (2005). ‘Red Delicious’ apples are less round and more irregular in shape compared to ‘Golden Delicious.’ This morphological difference may have caused ‘Red Delicious’ apples to be more variable in the mechanical properties within the same fruit, thus contributing to lower correlation.

Ababneh (2002) reported an $R^2$ value of 0.845 when MT measurements from one side of the apples correlated with those from the opposite side of the same apples. In view of this, the correlation results between bioyield and MT measurements are quite impressive, especially for ‘Golden Delicious’ apples. The correlation results from this study are much better than those ($R^2 < 0.36$) reported in Abbott et al. (1995) and Shmulevich et al. (2003), when the sonic and
impact methods were compared with the MT tests. The results from this experiment were also better than the results of previous work reported in Lu et al. (2005). Several differences may account for the increase in accuracy. The bioyield device actuated at 3.65 mm/min versus the previous instrument at 22.2 mm/min. Better rubber tip design used in this device may have also contributed to the improved correlation.

Better correlation between bioyield force and MT force is not surprising. Both firmness measurement techniques apply quasi-static loading to the fruit and measure the failure strength of the apple tissue. The bioyield test measures a peak force at the time when an initial cellular rupture in the apple tissue occurs, while the MT test measures maximum force during the puncture of an apple in which the macroscopic tissue failure occurs.

**Comparison between Bioyield and MT over time**

Figure 7 compares the MT force with bioyield force for the average of each group consisting of 33 samples (66 test locations per measurement type) over a time period of 30 days. The $R^2$ value between MT force and bioyield force was 0.990. The results show that bioyield measurements were as sensitive to physiological changes as MT force for apples that underwent an accelerated softening process. The ability to monitor fruit conditions during postharvest storage is critical to maintaining and delivering high quality apples. The excellent correlation between MT force and bioyield force over time demonstrates that the bioyield test can provide reliable measurement and/or monitoring of fruit firmness changes during storage, which will be especially valuable for commercial application.

**Bioyield Location Study**

There was a significant difference in the firmness of the fruit between sections (top/middle/bottom) ($P = 0.000$) and between directions (north/east/south/west) ($P = 0.043$) (table 1). Since variations due to factor interactions were not significant ($P = 0.994$), further discussion is focused on main factors (i.e., section and orientation).
As shown in table 2, the bottom section of the fruit was firmer when compared to the top and middle sections. However, the difference in firmness between top and middle sections was not significant (P = 0.114). This finding is in agreement with results from the study on the variation of elastic modulus in apples performed by Abbott and Lu (1996).

Further statistical analyses showed that the south face (sunny or blush side) of the apples was significantly firmer than the north face (P = 0.019) (table 2). The south face of an apple receives the most sunlight exposure, which may account for the difference in firmness when compared with the north side of the fruit. The east and west sides receive lesser doses of sunlight, resulting in a moderate firmness. The mean of bioyield measurements (26.07 N) for the north and south sides of the apple fruit was not significantly different from that (26.01 N) for the east and west sides (P = 0.882). Hence, the average of the two measurements from opposing sides of the fruit may provide a more consistent and reliable quantification of the fruit’s firmness.

### DISCUSSION

An examination of a few test apples after the bioyield test showed that the bioyield tests induced small bruises (approximately 6.4 mm in diameter and 2 mm in depth), which are much smaller than the USDA definition of injury caused by bruising for apples (USDA Agricultural Marketing Service, 2002). Additional testing could help quantify the bruise dimensions and determine if the bruise would lead to any long-term or value-degrading effects. During the experiment, it was found difficult to determine the location of a bioyield test on several apples both visually and by touch. Hence, the device achieved the goal of nondestructive measurements.

The excellent correlation between bioyield and MT tests in the time study (fig. 7) demonstrates that the bioyield test can be used to monitor changes in firmness. However, further research is needed to determine if such correlation still exists when the outer layer tissue of the apple has more significant moisture loss compared to inner layers. Unlike MT measurements, bioyield test can only measure the firmness of cellular structure near the skin.

The bioyield location study provided important information on using an appropriate procedure to perform bioyield measurements. Since the bottom section of an apple is significantly firmer than the middle and top sections, this study reaffirmed the conventional procedure of performing firmness measurements around the equator of an apple. Moreover, since the south side of an apple is significantly firmer than the north side of the fruit and the average of bioyield measurements for the south and north sides was not significantly different from the average for the east and west sides of the fruit, an average of bioyield measurements from opposing sides of an apple would provide better quantification of the firmness of each apple fruit.

### CONCLUSIONS

A portable device was designed for bioyield force detection to measure apple fruit firmness. The device causes minimum damage to the fruit and does not degrade it after testing. The device design features include accurate control of loading speed, automated detection and recording of bioyield point, and ease of operation. Moreover, the device is portable and relatively low in cost (<$1,000), and it can operate stand-alone or via computer, thus making it suitable for use in both field and laboratory environments.

The bioyield tester provided good firmness measurement for apples as it showed better correlation with the standard MT test (R² = 0.835 and 0.654 for ‘Golden Delicious’ and ‘Red Delicious,’ respectively), compared to such nondestructive methods as sonic and impact (Abbott et al., 1995; Shmulevich et al., 2003). The bioyield test was as sensitive to physiological changes in apples as the MT test; an excellent correlation (R² = 0.990) between the two methods was obtained for ‘Golden Delicious’ apples that underwent accelerated softening. Hence the device will be useful for monitoring firmness changes during harvest and postharvest storage.

Significant variations in firmness were observed over the apple fruit. The bottom section of an apple was significantly firmer than the middle and top sections of the fruit, while the south (or sunny) side of the fruit was firmer than the north side. Hence an appropriate firmness measurement procedure should consist of two bioyield measurements from opposite sides of an apple at the equatorial region to obtain an average firmness value for the fruit.

### REFERENCES


