Comparison of Four Nondestructive Sensors for Firmness Assessment of Apples

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Abstract
Nondestructive firmness measurement is critical to assuring postharvest quality and marketability of apples. In this research, two in-house developed sensors (bioyield and spectral scattering) and two commercial sensors (acoustic and visible and shortwave near-infrared (Vis-SWNIR) spectroscopy), were evaluated for assessing the firmness of apples. Spectral scattering measurements were taken from the fruit moving online, while firmness measurements using the other three sensors were made in a stationary condition. The destructive Magness-Taylor (MT) penetrometric test was also conducted to provide reference firmness measurements, against which the four sensors were evaluated. A total of 6,535 'Delicious', 'Golden Delicious', and 'Jonagold' apples harvested in 2009 and 2010 were tested. For spectral scattering and Vis-SWNIR techniques, firmness prediction models were developed using partial least squares methods and then validated with independent samples. The correlation of spectral scattering with MT firmness for the three apple varieties for the two harvest years varied between 0.849-0.940, and similar results were obtained with Vis-SWNIR (R=0.849-0.924). Acoustic and bioyield measurements had considerably lower correlations with MT firmness, with R=0.589-0.871 and 0.608-0.852, respectively. This research demonstrated that spectral scattering and Vis-SWNIR were generally superior to acoustic and bioyield techniques in assessing MT firmness, but they require calibration models, which adds complexity in practical uses.

Key words: Acoustic, Bioyield, Firmness, Spectral Scattering, Visible and Near-infrared.

1. Introduction
Firmness is an important quality attribute in determining the maturity and postharvest quality of apples and how the harvested fruit should be handled and marketed. Extensive research has been reported on the development of nondestructive firmness measurement techniques (Ruiz-Altisent et al., 2010). In the past 15 years, a number of sensing techniques have been developed for assessing the firmness of apple and other fruit. Among them are acoustic, bioyield, visible and shortwave near-infrared (Vis-SWNIR) spectroscopy, and spectral scattering. Since firmness reflects the complex structural and mechanical properties of apple fruit, which are affected by such factors as variety, harvest season, climate or growth location, etc., it is not surprising that different firmness measurement results have been reported for different sensors (Zude et al., 2006). So far no study has been reported of comparing mechanical sensors like acoustic and bioyield and optical techniques including Vis-SWNIR and spectral scattering for firmness evaluation of apples and other fruits. It is thus desirable and also necessary to evaluate and compare these sensors for firmness measurement. Such study would enable us to gain a better understanding about the merits and shortcomings of each sensor and may offer a new approach, such as sensor fusion, for more accurate and robust assessment of fruit firmness.

This paper reports on the evaluation of four nondestructive sensors for firmness measurement for three varieties of apple harvested in two seasons. Two in-house built sensors (i.e., bioyield and spectral scattering) and two commercial sensors (i.e., acoustic and Vis-SWNIR) were used in the study. The spectral scattering sensor was evaluated on apples
moving on the line, while the remaining three sensors were tested on apples in a stationary condition.

2. Materials and Methods

2.1. Experimental Procedure

'Delicious' (D), 'Golden Delicious' (GD) and 'Jonagold' (JG) apples were harvested from an orchard of Michigan State University's Clarksville Horticultural Experiment Station in Clarksville, Michigan, USA in 2009 and 2010. The harvest for each year was carried out in six consecutive weeks in order to have a wider range of physiological conditions for the studied varieties. One day after each harvest, a set of about 100 apples for each variety were tested, and the rest apples were stored in refrigerated air at 0 °C. One week after the last harvest, tests for the stored apples were begun. The stored apples for 2009 were tested once a week for the first six weeks and then every two weeks for up to eight weeks. The experiment was completed in five months for 1191, 1176, and 928 apples of D, GD and JG, respectively. Stored apples for 2010 were tested once a week for the first four weeks and then every two weeks for up to six weeks. A total of 1153 fruit for D, 1146 for GD and 1141 for JG were tested in the 2010 experiment.

Four nondestructive sensing techniques (i.e., acoustic, bioyield, Vis-SWNIR and spectral scattering) were used for measuring the firmness of apples (Fig. 1). Spectral scattering measurements were carried out in an online setting, while measurements using the other three sensors were made when fruit were in a stationary condition. All measurements were made from the same equatorial area of each test fruit. Acoustic firmness measurements were made in triplicate for each fruit, using a tabletop acoustic firmness sensor (Model DTF V0.0.0.105, AWETA, Nootdor, Netherlands) (Fig. 1a). The sensor recorded the weight and resonant frequency of the acoustic vibration generated by gently tapping the fruit on the equatorial area, from which an acoustic firmness index was calculated (van der Gaag, 2006).

Bioyield (BY) firmness was measured using an in-house built tabletop BY sensor (Lu and Tipper, 2009) (Fig. 1b). This sensor consisted of a digital force gauge with a specially-designed probe (6.4 mm diameter) with a rubber tip for better detection of bioyield point, a motor-driven stand and a control box. The loading speed for BY-force measurements was set to 0.37 mm/s and the measurement was completed when the BY point had been
detected. The BY point was defined as the first point on the force-deformation curve, where a drop in force was equal to or greater than 0.01 N.

Vis-SWNIR spectra were acquired from the fruit, using a miniature Vis-SWNIR spectrometer (S4000, Ocean Optics, Dunedin, FL, USA) operated in interactance mode for 460-1,100 nm (Mendoza et al., 2011) (Fig. 1c). The light was delivered to the fruit through a 26-mm diameter ring guide. Mounted in the center of the light guide was a beam collimator for collecting the light that had reemerged from the fruit in 10 mm diameter area. A buffering zone of about 8 mm was established between the illumination area and the detection area on the fruit to ensure that the detecting probe only collected the light that has interacted with the flesh tissue.

Spectral scattering images were acquired, using a prototype online hyperspectral scattering system (Mendoza et al., 2011) (Fig. 1d). The test apples were moving on a 2.4 m conveyor at a speed of 82 mm/s (~ one fruit for two seconds). The hyperspectral imaging system consisted of a back-illuminated electron-multiplying CCD camera (Model PhotonMAX: 1024B Air-Cooled, Princeton Instruments, Trenton, NJ, USA), an imaging spectrograph (ImSpector V10E, Spectral Imaging Ltd., Oulu, Finland), a quartz tungsten halogen light source, and a point light beam of 1.5 mm in size. It had an effective spectral region of 500-1,090 nm with 1.65 nm nominal spectral resolution.

After completion of the nondestructive tests, destructive Magness-Taylor (MT) firmness measurements were taken from the same equatorial area of each fruit, where nondestructive measurements had been made. MT measurements were carried out using a texture analyzer (model TA.XT2i, Stable Micro Systems, Inc., Surrey, U.K.) with a steel probe of 11 mm diameter for a penetration depth of 9 mm at a loading speed of 2 mm/s. Maximum force recorded on the force/displacement curve was used as the measure of fruit firmness.

2.2. Data Analysis

Acoustic firmness index (FI) and bioyield force were directly collected by the instruments and used in further analysis. For Vis-SWNIR and spectral scattering techniques, they are indirect methods and hence need calibration models relating spectral/image features to MT firmness measurements. For the Vis-SWNIR data, the dark-subtracted spectra were corrected by reference spectra acquired from a Teflon disk, from which first derivative spectra were obtained. For the spectral scattering images, mean reflectance spectra were first obtained for the spectral range of 450–1,050 nm and a total spatial distance of 20 mm (Lu, 2007). Multi-resolution wavelet transform method based on both discrete and continuous one-dimensional decompositions were then applied to the mean reflectance spectra. Moreover, image features were extracted from each preprocessed scattering image, which was split (in left and right sides of the scattering image with respect to the light incident point), averaged (pixel by pixel), cropped, and standardized. Two types of image processing methods were tested on these images: statistical texture analysis and multi-resolution wavelet transform for two-dimensional decompositions (Mendoza et al., 2011). Extracted from each scattering image were 392 scattering features (i.e., 121 for mean reflectance, 48 for 1-D discrete wavelet transform, 121 for 1-D continuous wavelet transform, 24 for 2-D discrete wavelet transform, and 78 for 2-D continuous wavelet transform which included texture image features extracted from each 2-D decomposition).

After the completion of processing the Vis-SWNIR and spectral scattering data, partial least squares (PLS) method was applied to develop calibration models for firmness. The features data were auto-scaled by first subtracting the mean and then dividing by the standard deviation. Prior to the model development, each set of apples were first sorted for firmness; the sorted samples were then split into two groups systematically (70% samples for calibration and the remaining 30% samples for validation or test), so that each group covered the entire range of MT firmness. To statistically compare the performance of Vis-SWNIR and spectral scattering systems, PLS calibration and validation were run for 10 times for each sensing technique. For each new run starting from the 2nd run, 1/7 of the samples (or 10% of
the total calibration and validation samples) in the calibration set for the previous run were taken out randomly and replaced with the equal number of test or validation samples that were also randomly taken out from the previous validation set. These taken-out calibration samples then became a part of the new validation set of samples. Hence, there were 1/3 new samples for the validation set for each new run. Mean values for number of latent variables or factors, correlation coefficient and standard error for the calibration and validation data sets (i.e., $R_{cal}$, $R_{pred}$, SEC, and SEP) were calculated as measures of the model performance. The SEPs for Vis-SWNIR and spectral scattering were tested using the t-test at the 0.05 level to determine if there was a significant difference between the two sensing systems. Statistical tests were not applied to the acoustic and bioyield firmness results because there was only one measurement (or the average of three measurements for the acoustic test) for each fruit.

3. Results and Discussion

The MT firmness measurement results for 2009 and 2010 are summarized in Table 1. Apples for each variety had relatively large variations in MT firmness. Overall, Jonagold had the largest standard deviations in both years, while the mean and standard deviation for D and GD were relatively close.

**TABLE 1:** Statistical summary of Magness-Taylor (MT) firmness measurements (N) for three varieties of apples for 2009 and 2010

<table>
<thead>
<tr>
<th>Year</th>
<th>Delicious</th>
<th>Golden Delicious</th>
<th>Jonagold</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2009</td>
<td>2010</td>
<td>2009</td>
</tr>
<tr>
<td>No. Samples</td>
<td>1091</td>
<td>1153</td>
<td>1076</td>
</tr>
<tr>
<td>Mean</td>
<td>56.7</td>
<td>68.8</td>
<td>57.4</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>15.8</td>
<td>17.5</td>
<td>15.7</td>
</tr>
</tbody>
</table>

Correlation analysis showed that both acoustic and bioyield measurements correlated with MT firmness for the three varieties in both harvest years. The results in Table 2 showed that the two sensors overall had similar performance; the acoustic sensor performed better in three cases than the bioyield sensor, while the opposite was true for the bioyield sensor in the remaining three cases. Acoustic measurements are related to the global mechanical properties of apples and are affected by fruit shape, while bioyield measurements reflect the mechanical properties of local tissues. The general shape for the three varieties of apple

**TABLE 2:** Comparison the four nondestructive sensors, in terms of correlation coefficient (R) and standard error (SE), with Magness-Taylor (MT) firmness measurement for ‘Delicious’, ‘Golden Delicious’, and ‘Jonagold’ apples for 2009 and 2010*

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Delicious</th>
<th>Golden Delicious</th>
<th>Jonagold</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2009</td>
<td>2010</td>
<td>2009</td>
</tr>
<tr>
<td>Acoustic</td>
<td>0.747</td>
<td>10.32</td>
<td>0.796</td>
</tr>
<tr>
<td>Bioyield</td>
<td>0.608</td>
<td>12.63</td>
<td>0.852</td>
</tr>
<tr>
<td>Vis-SWNIR</td>
<td>0.865</td>
<td>8.04a</td>
<td>0.852</td>
</tr>
<tr>
<td>Scattering</td>
<td>0.849</td>
<td>8.42b</td>
<td>0.888</td>
</tr>
</tbody>
</table>

* Simple regression was performed for acoustic and bioyield measurements with MT firmness. For Vis-SWNIR and spectral scattering, the results shown in the table are the means of 10 runs for the test or prediction set of samples that were not used in the calibration models. The superscripted letters for the SEs in the table indicate if there were significant differences between the Vis-SWNIR and spectral scattering techniques by the t-test at $p=0.05$. 
were quite different; D apples were elongated and conical along the stem-calyx direction, while JG apples were round and GD apples were conical. JG apples had the largest range of sizes for both harvest seasons. These factors altogether would have complicated the performance of these two sensors in measuring MT firmness. In addition, variations in MT firmness correlation for the same varieties were observed for the two harvest years. This has showed the complexity or difficulty of assessing MT firmness using nondestructive techniques.

Compared to acoustic and bioyield measurements, Vis-SWNIR and spectral scattering had consistently higher correlation coefficients for predicting MT firmness for all three varieties for both harvest years, except for Vis-SWNIR for Delicious in 2010 (Table 2). The correlations ranged between 0.849 and 0.924 for Vis-SWNIR and between 0.849-0.940 for spectral scattering. The t-test for the standard error of prediction between the two optical techniques showed that spectral scattering was significantly better than Vis-SWNIR in four of the six cases (i.e., three varieties x two harvest years). Figure 2 shows the firmness prediction results obtained with spectral scattering for one run, while the results with Vis-SWNIR for one run are given in Fig. 3. It should be noticed that the spectral scattering test was conducted...
under an online condition, while the Vis-SWNIR test was carried out in a stationary condition. For the same sensing system, it would be more difficult to achieve the same firmness prediction results in an online condition than in a stationary condition. These results showed that spectral scattering is promising for online sorting and grading of apples firmness.

4. Conclusions

This research evaluated the four nondestructive sensors in terms of their correlation with Magness-Taylor (MT) firmness measurement for ‘Delicious’, ‘Golden Delicious’, and ‘Jonagold’ apples for two harvest years. The acoustic and bioyield sensors had similar correlations with MT firmness (R=0.589-0.871 and R=0.608-0.852, respectively), which varied greatly with harvest year and between varieties. On the other hand, spectral scattering and visible and shortwave near-infrared (Vis-SWNIR) spectroscopy also had similar prediction results for MT firmness (R=0.849-0.940 and R=0.849-0.924, respectively), and they were consistently better in predicting MT firmness of the three apple varieties than the acoustic and bioyield sensors. Spectral scattering is promising for sorting and grading apples for firmness, since the test was conducted under an online situation. Both spectral scattering and Vis-SWNIR depend on calibration models and require complex data analyses, and it is thus more challenging to implement them in practical applications. Since the four sensors are based on different measurement principles, they can be complementary in firmness measurement. Hence a sensor fusion approach could be advantageous to achieve superior firmness prediction results.

References list