A Handheld, Low-Mass, Impact Instrument to Measure Nondestructive Firmness of Fruit

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Abstract. *A portable, handheld impact firmness sensor was designed for nondestructive measurement of fruit firmness while the fruit remain attached to the tree or for use in other remote locations where the use of a benchtop instrument would be impractical. The instrument design was based on the low-mass, constant velocity, impact-type measurement concept. Validation tests of the handheld sensor using 'Bartlett' pears from orchards in California and Washington showed excellent agreement ($r^2 = 0.92$ and 0.96, respectively) with both ASAE Standard method S368.2 for determining the apparent modulus of intact fruit and the impact firmness scores from a commercial benchtop impact firmness instrument.*

Keywords. *Fruit quality, Nondestructive firmness, Pears, Maturity, Sensing.*

Firmness is one of the more important and commonly utilized measurements of fruit quality. Impact-based nondestructive firmness measurement techniques have been evaluated over a number of years in benchtop settings in many laboratories worldwide, and commercial on-line systems for automated firmness sorting are available (Chen, 1996; Abbott, 1999; Aweta, 2008; Greefa, 2008; Sinclair, 2008). As on-line impact firmness sorters are more widely adopted, many growers and fruit handlers have become interested in a portable, handheld nondestructive firmness instrument that could provide fruit firmness information that is directly comparable with the firmness classification of fruits by on-line devices available for packing lines.

For nearly a century, management decisions related to fruit firmness of pears and other fruits have primarily been based on a destructive test like Magness-Taylor penetrometry (Magness and Taylor, 1925). Nondestructive firmness measurement has the distinct advantage of allowing temporal changes in firmness to be monitored for the management of pre-harvest maturity development and post-harvest ripening of fruits. In addition, it can be used for fruit-by-fruit firmness classification for management decisions related to storage, transportation, and marketing. Nondestructive firmness monitoring can be especially valuable for fast-ripening commodities like pears that can be difficult to manage in the marketing chain.

The concept of impact-type measurements for nondestructive determination of fruit firmness for sorting applications has been studied by a number of researchers (e.g., Rohrbach et al., 1982; Delwiche, 1987). Impact studies have shown that the dynamic response during an impact upon a fruit at a high loading rate can be modeled as a function of the elastic modulus, Poisson's ratio, mass, and radii of curvature of the fruit, the mass and radii of curvature of the impacting object, and their approach velocity at the time of impact. It has been shown that a low mass, on the order of 10 to 20 g, and a high, constant impact velocity (below the impact threshold for fruit damage) offer the best configuration for firmness sensing because the measurement is independent of fruit mass and robust to variation in fruit radius of curvature and fruit motion during measurement (Chen et al., 1985; Chen et al., 1996; García-Ramos et al., 2003). The impact of a low-mass spherically tipped impactor on a fruit can be modeled by the impact of a rigid sphere on an elastic sphere. At high loading rates, the work by Timoshenko and Goodier (1951) on the elastic impact of spheres can be applied to obtain the following relationship for the peak magnitude of the impact force acting on each body:

$$F = \left(\frac{5}{4} \frac{V^2}{n} \right)^{0.6} k^{0.4} \qquad (1)$$

where

V = relative approach velocity of the spheres

$n = \dfrac{m_1 + m_2}{m_1 m_2}$

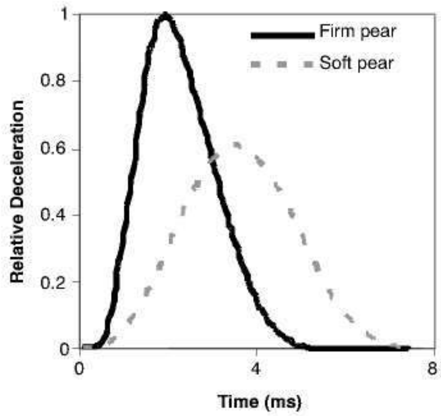

Figure 1. Impact response curves of a low-mass rigid semi-spherical impact arm tip from the handheld sensor on soft and firm 'Bartlett' pears.

$$k = \frac{4}{3}\frac{E}{(1-\mu^2)}r^{0.5}$$

$$r = \frac{R_1 R_2}{R_1 + R_2}$$

m_1 = mass of the impactor
m_2 = mass of the fruit
R_1 = radius of the impactor's spherical tip
R_2 = radius of curvature of the elastic sphere
μ = Poisson's ratio
E = modulus of elasticity of the elastic sphere.

A typical set of impact response curves for a low-mass impact of a rigid sphere on soft and firm 'Bartlett' pears is shown in figure 1. The ratio of the peak acceleration to the time required to reach the peak acceleration (defined as C_1 by Delwiche, 1987) has been used as a firmness index for impact measurements of fruits.

Chen et al (1996) showed that the time required to reach the peak acceleration during impact is:

$$t = 1.47\frac{D_m}{V} \quad (2)$$

where D_m, the maximum deformation during impact, is:

$$D_m = \left(\frac{5}{4}\frac{V^2}{nk}\right)^{0.4} \quad (3)$$

When the impact is implemented using a swing-arm impactor moving in a horizontal plane at the time of impact, the gravitational effect on the impact can be neglected, and the relationship between peak acceleration (A) of the impactor and the elastic modulus (E) of the fruit is:

$$E = \frac{0.54 m_1^{2.5} n^{1.5}}{V^3}\frac{(1-\mu^2)}{r^{0.5}}A^{2.5} \quad (4)$$

The elastic modulus of the fruit can also be expressed as functions of time (eq. 5) and the C_1 ratio A/t (eq. 6):

$$E = \frac{2.46}{nV^{0.5}}\frac{(1-\mu^2)}{r^{0.5}}\left(\frac{1}{t}\right)^{2.5} \quad (5)$$

$$E = \frac{1.15 m_1^{1.25} n^{0.25}}{V^{1.75}}\frac{(1-\mu^2)}{r^{0.5}}\left(\frac{A}{t}\right)^{1.25} \quad (6)$$

The relative importance of fruit size and mass, consistent impact velocity from measurement to measurement, and choice of firmness index can affect the design options used in determining impactor/fruit presentation. García-Ramos et al. (2005) published a review that describes the different existing nondestructive techniques for measuring fruit firmness with benchtop and on-line systems. Impact measurement techniques for fruit firmness have been applied to a number of commodities, including pears (Jarén et al., 1992), peaches (Delwiche, 1987; Valero et al., 2004), and avocados (Correa et al., 1992), among others. Commercial devices have been tested in the laboratory and compared to Magness-Taylor penetrometry readings (e.g., Slaughter et al., 2006) and to acoustic techniques (e.g., De Ketelaere et al., 2006; De Belie et al., 2000; Shmulevich, 1998; Sugiyama et al., 1998).

The American pear industry was one of the pioneering forces in the development of instrumental measurements of fruit firmness, and therefore for the design of penetrometry or "pressure testing" of pears for harvest management (Magness and Taylor, 1925; Murneek, 1921; Allen, 1929). Harvest, packing, and shelf-life thresholds were established on the basis of these penetrometry measurements. Samples of ten pears were tested twice, once on each side, and the average reading was used for management decisions. The need exists for a portable nondestructive instrument that can be used to monitor fruit firmness while the fruit is still on the tree and to allow on-site firmness monitoring in cold storage.

In response to this need, a prototype handheld firmness tester was designed and built for in-orchard sensing of fruit firmness (Chen and Thompson, 2000; fig. 2). The sensor consists of three major components. First, a low-mass impactor, which consists of a semi-spherical impacting tip, is attached to the end of a pivoting arm. Second, a low-mass (~2 g) accelerometer is mounted behind the impacting tip. Third,

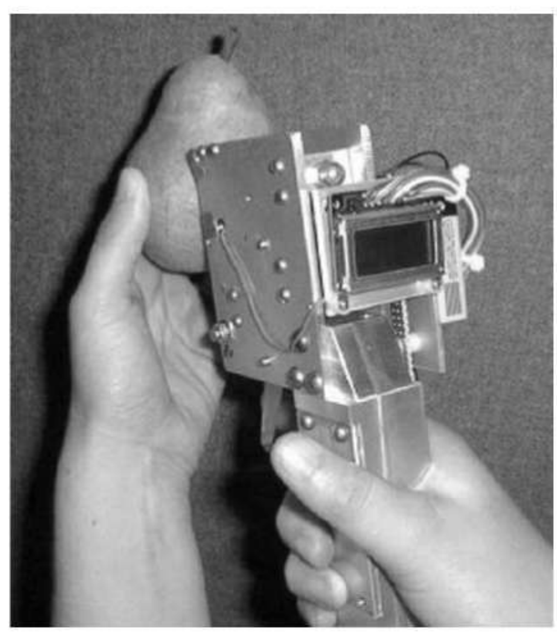

Figure 2. First prototype of the handheld impact firmness sensor (Chen and Thompson, 2000).

a trigger mechanism pulls the impactor against a propulsion spring and releases the impactor such that it impacts each fruit at the same speed each time. A key aspect of the design is that the impactor disengages from the spring prior to impact, so that the impact occurs at a constant velocity. A single-chip microcomputer acquires the impact signal from the accelerometer, processes the data, displays the firmness reading on an LCD screen, and stores the reading for future use. In operation, the operator holds the sensor in a vertical position against the fruit, pulls the trigger, and reads the firmness reading on the display screen. When held vertically, the impact arm travels in a vertical plane and the impact tip strikes the fruit while traveling in a horizontal direction.

Preliminary testing of the handheld prototype was conducted in a 'Bartlett' pear orchard in Courtland, California. Ten sets of measurements were made during late morning on 50 unharvested (i.e., the fruit were still attached to the tree) 'Bartlett' pears on two trees over a one-month period starting late June. A black circle was marked on each fruit in the study to allow repeated measurement of the same spot on each fruit over time. On each test date, ten pears, that were not part of the 50 marked fruit, were picked randomly from the two trees and brought back to the laboratory for testing in the afternoon with a manually operated penetrometer. A nondestructive firmness index based on the peak acceleration was used in the preliminary test. The on-tree results indicated that the average impact firmness reading of the 50 fruits decreased in a curvilinear fashion with time ($r^2 = 0.90$; Chen and Thompson, 2000). A linear decline from 100 N to 60 N ($r^2 = 0.98$; Chen and Thompson, 2000) in the average penetrometer firmness of the ten harvested fruit was observed over the same time period. It was also observed, due to viscoelastic effects, that in a rapid sequence of three impact measurements taken at the same fruit location, the firmness reading obtained from the first impact was about 5% lower than that obtained from the third impact at the same spot (data not shown). A second preliminary test of the handheld prototype using 20 'Bartlett' pears showed a strong linear relationship ($r^2 = 0.93$; Chen and Thompson, 2000) to the impact firmness determined with an on-line impact firmness system. However, preliminary testing with a rubber reference ball revealed that the original design, using a pivot arm that was mechanically unbalanced with respect to its center of rotation, had a strong gravitational effect on the impact sensor. To minimize the error due to gravity, the original prototype had to be positioned in a consistent vertical orientation during operation.

Objective

The objectives of this research were:

- To develop an improved handheld impact firmness sensor based on the original concept of Chen and Thompson (2000) in order to minimize gravitational effects upon the low-mass constant velocity impact measurement.
- To evaluate the performance of the improved sensor by comparison with ASAE standard method S368.2 (*ASAE Standards*, 2003) for apparent modulus using nondestructive measurement by spherical indention (Chen et al., 1996) and to the firmness score determined by a commercial benchtop impact-type fruit firmness sensor.

'Bartlett' pears were selected as the test commodity because firmness is an important index of maturity for 'Bartlett' pear and because they ripen quickly and the management of ripening pears can be a challenge in the marketing chain.

Materials and Methods

The design of the improved handheld impact firmness sensor is shown in figure 3. The impacting tip (1 in fig. 3) had a semi-spherical tip with a radius of curvature of 0.8 cm. An accelerometer (2 in fig. 3; BBN model 501, total mass 1.8 g) was mounted directly behind the impact tip. The impacting tip and accelerometer were mounted to the top of the pivoting arm (3 in fig. 3). The impacting arm, accelerometer, and pivoting arm assembly was mechanically counterbalanced (static only). Upon actuation, the trigger mechanism (6 in fig. 3) caused the pivoting arm to rotate clockwise, deflecting the propulsion spring (5 in fig. 3) until the motion of the pivoting arm was halted by a mechanical stop (4 in fig. 3). The pivoting arm would then be released, allowing it to travel in a counterclockwise direction until the impacting tip struck the fruit (not shown). The pivoting arm would lose contact with the propulsion spring prior to impact so that the impacting tip was traveling at a constant velocity at the time of impact.

The acceleration signal was conditioned for amplification and noise reduction (by passing the signal through an active second-order low-pass filter with a cutoff frequency of 200 Hz) before digitizing (12-bit resolution). The peak acceleration, the time to reach the peak acceleration, the slope of the acceleration curve at the point of inflection, and the length of time that the pivoting arm traveled at a constant velocity were extracted from the impact acceleration curve and stored for future analysis.

The performance of the handheld impact sensor was evaluated for possible effects of device orientation in order to determine if the new design had successfully eliminated the

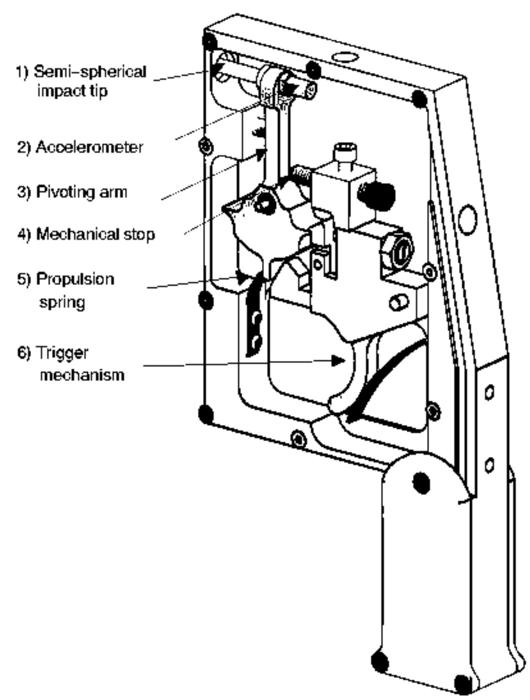

Figure 3. Illustration of the improved prototype showing the redesigned, mechanically counterbalanced impact arm (signal conditioning circuitry, microprocessor, and display not shown for clarity).

gravitational sensitivity of the previous design. A series of impact tests was conducted using a randomized complete block statistical design with five orientation treatments and three replicate impact measurements on six rubber samples of varying hardness. In addition to the control orientation (the normal orientation shown in fig. 3, with the pivoting arm rotating in the vertical plane and the impact tip traveling horizontally at impact), the handheld impact sensor was orientated at +30° and -30° of roll (tilted 30° to the right or left, both at 0° of pitch) and at 45° and 90° of pitch (tilting forward, both at 0° of roll). The rubber samples consisted of three cubical samples with Shore A hardnesses (ASTM, 2005) ranging from 31 to 64 and three spherical samples with Shore A hardnesses ranging from 38 to 64.

The apparent modulus of elasticity (E) for each rubber sample was determined by compression using the spherical indention method described by Chen et al. (1996). The diameter of the spherical indenter used in the compression test was 9.5 mm (R_1 = 4.75 mm), and the loading rate was 5 mm s^{-1}. The apparent modulus for each rubber sample was calculated according to ASAE Standard S368.2 for compression testing (*ASAE Standards,* 2003). The original formula for general spherical contact can be simplified considering that the spherical indenter possesses a much smaller radius of curvature than the fruit and is expressed as:

$$E = \frac{3}{4}\frac{F\left(1-\mu^2\right)}{D^{1.5}R_1^{0.5}} \qquad (7)$$

where

D = deformation applied (1.5 mm) and when

$R_2 >> R_1, \Rightarrow \frac{R_1 + R_2}{R_1 R_2} \approx \frac{1}{R_1}$ and

μ = 0.49 was selected (as suggested by Fridley et al., 1968). Chen et al. (1996) showed that these assumptions result in a small error (about 1.3%) in E.

Multiple linear regression analyses were conducted using Proc Reg (SAS, 2004) in order to evaluate handheld impact models for apparent modulus based on equations 4 through 6. Models were also evaluated for predicting apparent modulus using the traditional A, A/t, and $1/t$ relationships.

An analysis of variance test was conducted using Proc GLM (SAS, 2004) to determine if any of the orientations had significantly (0.05 level) different firmness readings. Fisher's protected least significant difference (LSD) test was conducted on the average firmness measurements for all statistically significant orientations.

'Bartlett' pears were harvested during the normal commercial harvesting period from three commercial orchards located in the California "River" and "Lake" pear-growing districts and the Yakima growing area in Washington State. The fruit were transported to the UC Davis campus for testing. Upon arrival, 18 pears were selected at random for immediate testing. The remaining pears were stored at 20°C and 95% relative humidity. Californian pears were first exposed to a 100 ppm ethylene atmosphere at 20°C for 60 h to facilitate ripening prior to testing. Each day, over a six- to seven-day period, sets of 18 pears were removed from storage for testing.

The firmness of each pear was measured six times with each of three methods: using the improved handheld impact firmness sensor, a commercial benchtop impact firmness sensor (Sinclair IQ interim benchtop model SIQFT-B), and a 9.5 mm diameter spherical indenter attached to a universal testing machine (Guss Fruit Texture Analyzer, FTA GS-14). Each measurement was made three times on each side of the fruit, spaced approximately 2.5 cm apart in an equilateral triangle pattern centered about the widest part of the pear. Discolored, damaged, or sunburned regions were avoided during measurement. The nondestructive nature of the impact tests allowed the measurements to be made in the same locations on each fruit. Spherical indention tests were conducted after the impact tests. A loading rate of 5 mm s^{-1} was used in the spherical indention tests where the compressive force required for a 1.5 mm indention was recorded.

The apparent modulus of elasticity (E) for each intact pear was determined using the same compression test method with a 9.5 mm diameter spherical indenter described for the rubber samples. The spherical indention test may only be considered nondestructive in hard pears. The average value for each pear was determined, and the fruit were then randomly segregated into calibration and validation sets, with one-third of the fruit (120 pears) in the calibration set and two-thirds (240 pears) in the validation set. The calibration set was used for model development, and the fruit from the validation set were reserved for model testing. Multiple linear regression analyses were conducted using Proc Reg (SAS, 2004) in order to evaluate firmness models for the handheld impact sensor based on the traditional A, A/t, and $1/t$ relationships and equations 4 through 6 and to compare with the performance of the other two measurement methods.

Results and Discussion

Model performance for predicting apparent modulus of the rubber samples using the handheld impact firmness sensor is summarized in table 1. Regression analysis indicated that models based on $1/t$ were superior to those based on A or A/t. While the best results were obtained using $1/t$ (r^2 = 0.993, SEC = 0.12 MPa), the model based on equation 5 using $(1/t)^{2.5}$ performed similarly (r^2 = 0.990, SEC = 0.15 MPa). Model performance was not improved by including impact arm velocity or A or A/t terms in the $1/t$ models. Good results were also obtained for the model based on equation 6 using $(A/t)^{1.25}$ and the traditional A/t model. The main cause for the decrease in performance of models based on A/t was due to poor ability to predict the apparent modulus of hard samples.

Predicted apparent modulus values from the $1/t$ regression model were used to evaluate the results from the handheld impact sensor orientation tests. Analysis of variance indicated that the new design for the handheld impact sensor was insensitive (α = 0.05) to changes in pitch. However, a small but significant (α = 0.05) effect of ±30° of roll was observed. The $1/t$ values for the handheld sensor increased by an average of 1% when the device was tilted 30° to the left

Table 1. Handheld impact model performance for predicting apparent elastic modulus of rubber samples.

Model Parameters	R^2	SEC (MPa)
$1/t$	0.993	0.12
$(1/t)^{2.5}$	0.990	0.15
$(A/t)^{1.25}$	0.935	0.37
A/t	0.931	0.38
$A^{2.5}$	0.720	0.77
A	0.696	0.80

or right when compared to the neutral position. The values for +30° of roll were not significantly different from those of -30° of roll. The differences between the insensitivity to pitch and the small sensitivity to roll may be due to the fact that the impact arm rotates in the pitch direction. Changes in roll may result in a small side load on the impact arm's bearing that results in small changes in the bearing's coefficient of friction that affect the impact response.

In contrast to the tests on rubber samples (which were conducted by a single operator in a single afternoon), the handheld impact firmness tests on pears were conducted by two operators over a ten-week period. It was observed during the pear tests that the operator could affect the rotation speed of the impact arm by varying the trigger speed of the handheld sensor. Impact arm travel time was added as a separate independent term to the traditional A, A/t, and $1/t$ relationships and equations 4 through 6 as a potential parameter for model development for predicting apparent modulus.

The general ranking of parameters for the handheld impact sensor, in terms of their ability to predict the average apparent modulus for the whole pear, was similar to that observed for the models developed for the rubber samples. The model based on equation 5 using $(1/t)^{2.5}$ gave the best performance upon validation, with a coefficient of determination of $r^2 = 0.890$ and a standard error of validation of SEV = 0.38 MPa (fig. 4). The model based on $1/t$ gave nearly the same performance. The validation performances of other handheld impact models are summarized in table 2.

In contrast to the models developed for the rubber samples, a small but significant ($\alpha = 0.01$) improvement was observed when multiple parameters were used in the model

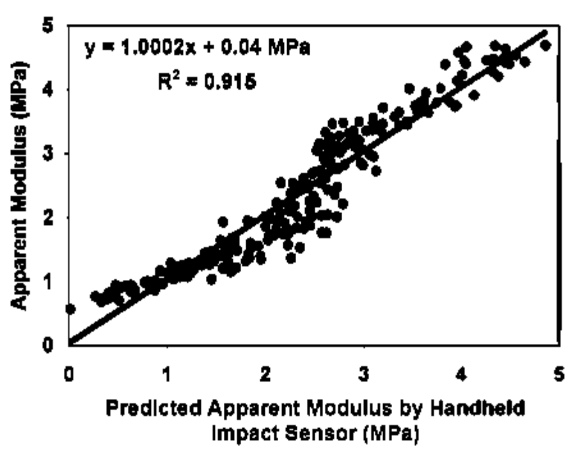

Figure 4. Validation results for the handheld impact firmness model using $(1/t)^{2.5}$ and $(A/t)^{1.25}$ terms to predict whole-pear apparent modulus.

Table 2. Validation performance of handheld impact models for predicting the apparent elastic modulus of whole pears.

Model Parameters	R^2	SEV (MPa)
$(1/t)^{2.5}$	0.890	0.38
$1/t$	0.878	0.40
$(A/t)^{1.25}$	0.781	0.53
A/t	0.775	0.54
A	0.505	0.80
$A^{2.5}$	0.477	0.82
$(1/t)^{2.5}$ and $(A/t)^{1.25}$	0.915	0.33
A and A/t	0.920	0.32

for pears. A model with both $(1/t)^{2.5}$ and $(A/t)^{1.25}$ terms had a coefficient of determination of $r^2 = 0.915$ for the validation dataset with a standard error of validation of SEV = 0.33 MPa. A model with both A and A/t terms had a similar level of performance, with a coefficient of determination of $r^2 = 0.920$ for the validation dataset and a standard error of validation of SEV = 0.32 MPa. In general, impact arm velocity was a significant ($\alpha = 0.05$) factor in most models, but the increase in model performance was quite small (0.01 to 0.02 MPa reduction in SEV) when it was included in the model. The results obtained for the handheld impact sensor were comparable to those obtained when using a commercial benchtop impact firmness instrument to predict the average apparent modulus of whole pears. The coefficient of determination between the commercial benchtop impact firmness values and the apparent modulus by spherical indention was $r^2 = 0.910$ for the validation dataset with a standard error of validation of SEV = 0.34 MPa.

The relationships between both impact methods (handheld and commercial benchtop) and the apparent modulus by spherical indention showed a sharp drop in apparent modulus between 3 and 2.5 MPa with two distinct linear relationships for firm and soft pears, as shown in figure 4. Model performance improved for both impact methods when separate linear regression models were developed for firm and soft pears. The level of improvement was particularly beneficial for soft fruit. For example, the SEV dropped from 0.38 MPa to 0.18 MPa when separate handheld sensor models for firm and soft fruit were developed using both $(1/t)^{2.5}$ and $(A/t)^{1.25}$ terms. While no discoloration or other visual signs of bruising were observed during testing, some tissue softening could be detected by touch on soft fruit after spherical indention measurements, which may indicate that the spherical indention of 1.5 mm was not completely nondestructive for soft fruit. This effect may partially explain the existence of the two linear relationships observed, one for firm pears and another for soft pears.

The ability of the handheld impact sensor to predict the average firmness score per pear determined by using a commercial benchtop impact firmness instrument was slightly superior to the results obtained when predicting the average apparent modulus of the fruit. As observed for the models developed for apparent modulus of rubber samples or pears, the performances of the traditional $1/t$, A/t, and A models were nearly the same as those based on equations 4 through 6 when predicting the benchtop impact firmness scores. The model based on $1/t$ gave the best performance upon validation, with a coefficient of determination of $r^2 = 0.916$ and a standard error of validation of SEV = 2.93 SiQ units. The validation performances of other handheld impact models are summarized in table 3. A strong and statistically significant ($\alpha = 0.01$) improvement in model performance was observed when two parameters were used to predict the benchtop impact firmness scores. For example, a model with both $1/t$ and A/t terms had a coefficient of determination of $r^2 = 0.963$ for the validation dataset with a standard error of validation of SEV = 1.94 SiQ units (fig. 5). As with models developed for apparent modulus, impact arm velocity was a significant ($\alpha = 0.05$) factor in most models. However, the model improvement due to including the impact arm velocity in the model was not as strong as was observed by creating a model containing two of the traditional impact firmness

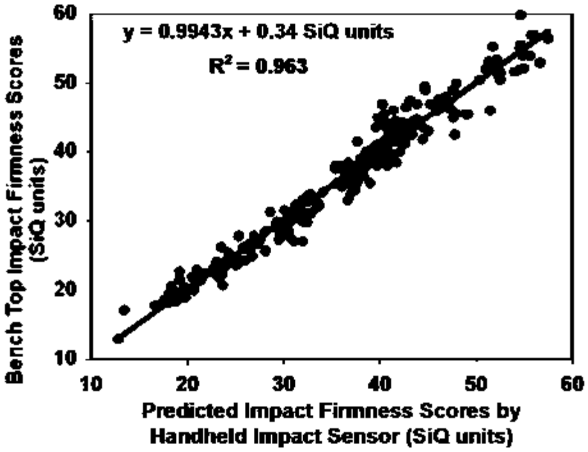

Figure 5. Validation results for the handheld impact firmness model using $1/t$ and A/t terms to predict whole pear firmness as determined by a commercial benchtop impact firmness instrument.

Table 3. Validation performance of handheld impact models for predicting the impact firmness score for a commercial benchtop instrument for whole pears.

Model Parameters	R^2	SEV (SiQ units)
$1/t$	0.916	2.9
$(1/t)^{2.5}$	0.901	3.2
A/t	0.872	3.6
$(A/t)^{1.25}$	0.872	3.6
A	0.623	6.2
$A^{2.5}$	0.584	6.5
$1/t$ and A/t	0.963	1.94

parameters or those from equations 4 through 6 in the model. Construction of models with more than two parameters did not show a meaningful improvement in performance.

The level of agreement between the predicted values for the handheld impact sensor using both $(1/t)^{2.5}$ and $(A/t)^{1.25}$ terms and apparent modulus by spherical indention and impact firmness from the commercial benchtop instrument were evaluated in relation to the number of measurements taken per fruit:

- The coefficient of determination values for the validation dataset based on the average of 1, 2, 4, and 6 measurements per fruit for apparent modulus predicted by the handheld sensor were 0.860, 0.889, 0.906, and 0.915, respectively.
- In comparison, the coefficient of determination values for the validation dataset based on the average of 1, 2, 4, and 6 measurements per fruit for the benchtop impact firmness scores predicted by the handheld sensor were 0.891, 0.928, 0.952, and 0.965, respectively.
- The coefficient of determination values for the validation dataset based on the average of 1, 2, 4, and 6 measurements per fruit for apparent modulus predicted by the benchtop impact firmness sensor were 0.835, 0.893, 0.905, and 0.910, respectively.

In all three cases, there was a substantial improvement in the level of agreement between these methods when the average of four measurements per fruit was taken when compared to a single measurement per fruit.

Conclusions

A second-generation handheld impact firmness sensor was designed for nondestructive measurement of fruit firmness while the fruit remain attached to the tree or for use in other remote locations where the use of a benchtop instrument would be impractical. The sensor was based on the low-mass, constant impact velocity concept originally developed by Chen et al. (1985). The device incorporated a mechanically counterbalanced (about the center of rotation) impact arm in order to minimize gravitational effects on the measurement, which can be problematic in handheld firmness applications of this type. The improved design was robust to orientation changes in pitch; however, a small effect (~1%) due to orientation changes in roll was observed. The handheld sensor showed excellent agreement (r^2 = 0.92 and 0.96, respectively) with both the ASAE Standard method S368.2 for determining the apparent modulus of intact fruit as well as the impact firmness scores from a commercial benchtop impact firmness instrument.

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