FINAL REPORT
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Project title: A new sensor for tracking apple firmness in CA storage.

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Objectives: The specific goal of the research was to determine if the sensor, that measures fruit shrinkage, could track changes in apple firmness while in CA storage conditions.

Explain any deviations from original objectives or schedule: The proposed research was modified to include an investigation of firmness in regular atmosphere (RA). This was done because firmness changes rapidly in RA compared with CA storage providing a rapid assessment of sensors' abilities. Mass loss of apples was tracked during both experiments. Mass loss was also used to predict firmness loss under both storage conditions.

Significant findings:

- The fruit shrinkage sensor can be used to track changes in firmness while in RA and CA storage although the sensor appeared to be reliable in only 3 of 6 trials.
- Mass loss can be used to track changes in firmness while in RA and CA storage.
- Measuring mass loss is better than the fruit shrinkage sensor because an entire fruit or fruits can be measured and potentially is the more reliable approach.
- The rate of firmness loss in the CA storage experiment was independent of apple size.

Results and discussion: Results and discussion are presented for the RA and CA storage experiments preceded by a short introduction and methods.

Apples lose firmness in storage. During storage, apples also lose mass (mainly water) and thus, shrink. We tested the hypotheses that shrinkage and mass loss are correlated with firmness loss in RA and CA storage. Sensors that allow for the estimation of firmness loss while in storage will be useful for the fruit packing industry.

The experiments were conducted in the United States Department of Agriculture controlled atmosphere storage laboratory in Wenatchee, Washington. In the RA experiment, 'Fuji' and 'Delicious' apples were tested under storage conditions of about 95 % relative humidity and about 1-2 °C. Apples were brought into RA conditions on October 16, 2001 and remained in storage for 70 days. Five to 7 apples of each type were taken from storage eight times over 57 days for destructive measurement of firmness. Three apples of each type were repeatedly measured for mass loss eight times over the 57-day period on a scale. Shrinkage was recorded on two 'Delicious' and one 'Fuji' apples using strain gauge sensors (Link et al. 1998) during the 70-day period.

In the CA experiment, 'Delicious' apples of 80, 113, and 125 size classes were tested under conditions of about 95% relative humidity and about 2 °C. Apples were brought into CA conditions on February 11, 2002 and remained in storage for 114 days. Eight apples of each class were taken from storage nine times for destructive measurement of firmness. Five apples of the ‘80’ size and five apples taken from combined ‘113’ and ‘125’ size class lots were repeatedly measured for mass loss nine times on a scale. Shrinkage was recorded on one apple of each size class using strain gauge sensors.

All statistical comparisons are made at the $\alpha = 0.05$ level unless indicated otherwise and error terms are one standard error of the mean.

Results

RA experiment

Firmness loss in 'Delicious' apples over storage time (Fig. 1a) was significant ($P < 0.00001$). The relation between firmness (F) and storage time (t) was linear ($F = 72.76 - 0.248t$, $r^2 = 0.55$). There was no ($P = 0.074$) loss of firmness in 'Fuji' apples over storage time (Fig. 1b). 'Fuji' apples had a mean firmness of 69.06 ± 0.82 N.

Both apple varieties significantly ($P < 0.00001$) lost mass during the storage observation period (Fig. 2). 'Fuji' apples lost mass faster (slope = 0.0342 ± 0.00167 % day^{-1}) than 'Delicious' apples (0.0215 ± 0.00239 % day^{-1}). After 57 days, the predicted mean percent mass loss for 'Fuji' apples was 2.0% and 1.2% for 'Delicious' apples (Fig. 2).

Of the three strain gauge sensors used to measure shrinkage, one apparently failed (data not shown). The relation between shrinkage and sensor observation time was nearly linear for the sensor on the 'Fuji' apple shrinking a total of about 0.70-mm (Fig. 3). In contrast, the relation between shrinkage and sensor observation time was curvilinear for the sensor on the 'Delicious' apple shrinking a total of about 0.28-mm (Fig. 3).

Firmness was significantly ($P < 0.00001$) and negatively correlated ($F = 72.7 - 11.49\overline{\%\Delta m}$, $r^2 = 0.55$) with mean percent mass loss ($\overline{\%\Delta m}$) in 'Delicious' apples (Fig. 4a). There was no ($P = 0.085$) relation between firmness and mean percent mass loss in 'Fuji' apples (Fig. 4b).

Similarly, firmness was significantly ($P < 0.00001$) and negatively correlated ($F = 74.39 - 51.23s$, $r^2 = 0.56$) with shrinkage (s) in 'Delicious' apples (Fig. 5a). There was no ($P = 0.0827$) relation between firmness and shrinkage in 'Fuji' apples (Fig. 5b).

'Delicious' apples were significantly ($P = 0.0005$) less dense (0.741 ± 0.0043 g cm^{-3}) than 'Fuji' apples (0.783 ± 0.0061 g cm^{-3}) and were significantly ($P < 0.00001$) heavier (251.8 ± 1.7 g) than 'Fuji' apples (189.4 ± 1.1 g).

CA experiment

The effect of apple size on firmness dynamics was investigated by comparing, using an F-test, linear regression lines for the relation between firmness and storage time ($F = b_0 + b_1 t$) for small (size 113 and 125 combined) and large (size 80) apples. The curves were significantly different ($F^* = 36.7$, $p < 0.001$). The intercept (b_0), or initial firmness estimate, was significantly greater in small apples (73.7 ± 0.93 N; n = 143) than in large apples (66.1 ± 1.06 N; n = 72). There was no effect of apple size on the rate of firmness loss (b_1), thus data were combined yielding a firmness loss rate of 0.0369 ± 0.0120 N day^{-1} for all apple sizes (Fig. 6). After 114 days, apple firmness decreased 4.21 N.

There was no effect ($F^* = 0.224 < 3.11 = F(.95; 2, 86)$) of apple size on mass loss based on comparing regressions [$\%\Delta m = maxloss * t/(t_{half} + t)$] for the two apple sizes. Thus, the data were combined (Fig. 7, maxloss = 2.54%, t_{half} = 83.6 days).

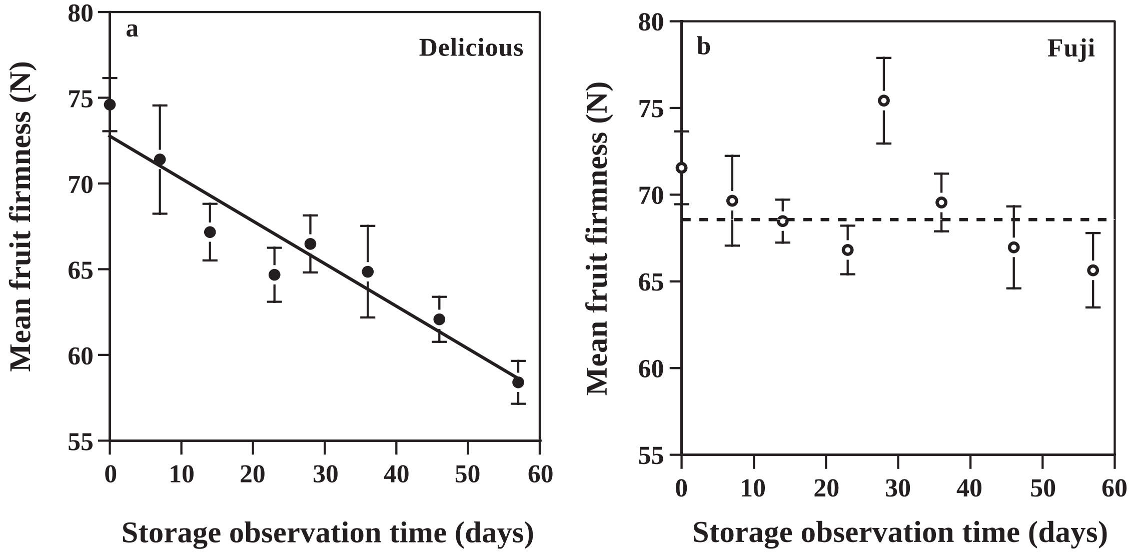

Fig 1. Firmness loss with storage time in 'Delicious' (a) and 'Fuji' (b) apples. Bars are one standard error of the mean.

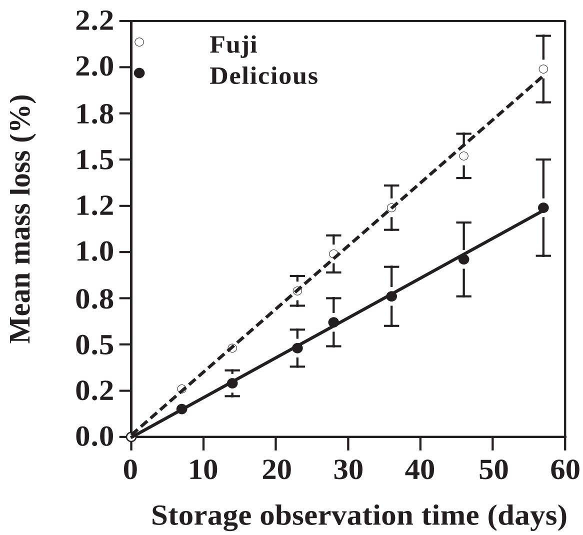

Fig. 2. Percent mass loss with storage time in 'Delicious' and 'Fuji' apples. Bars are one standard error of the mean.

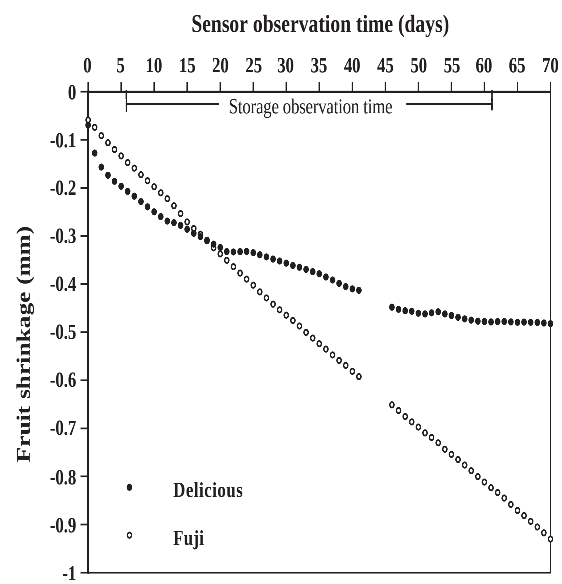

Fig. 3. Shrinkage of 'Delicious' and 'Fuji' apples with storage time.

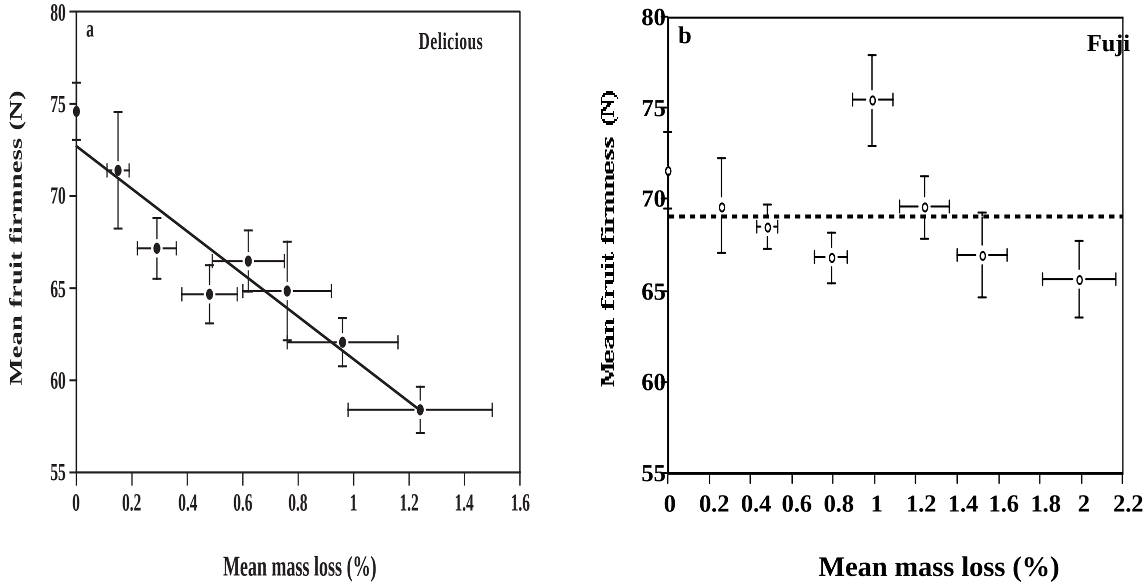

Fig. 4. Relation between mean percent mass loss and mean firmness in 'Delicious' (a) and ‘Fuji’ (b) apples. Bars are one standard error of the mean.

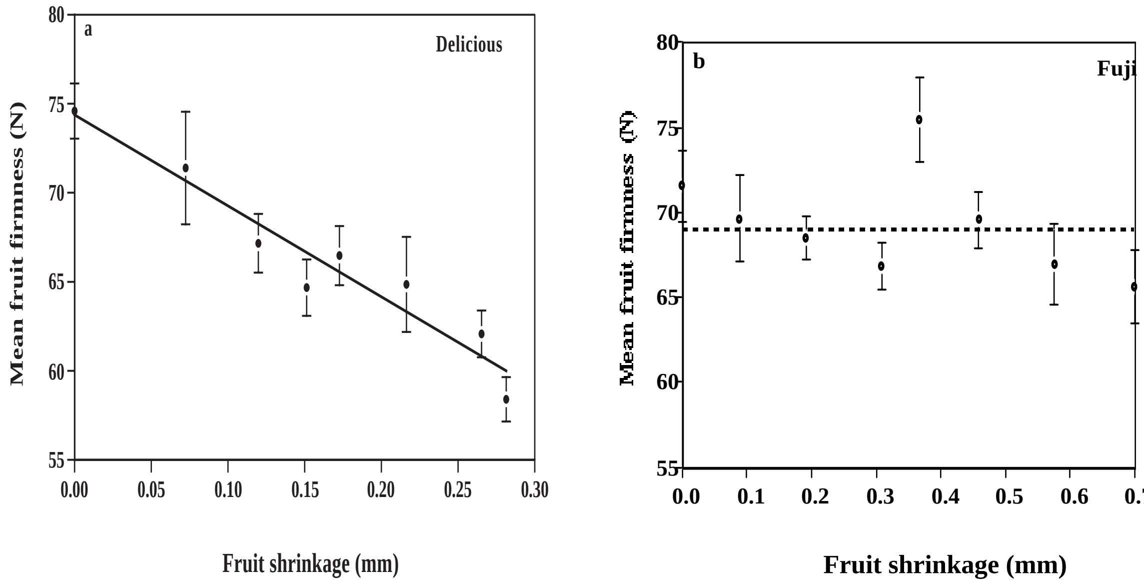

Fig 5. Relation between shrinkage and mean firmness in 'Delicious' (a) and ‘Fuji’ (b) apples. Bars are one standard error of the mean.

Of the three strain gauge sensors used to measure shrinkage, two (Fig. 8; large (80), smallest (125)) apparently produced questionable results. The sensor on the small (113) apple produced a continuous and generally decreasing result and was chosen for correlation with firmness loss data. There is a significant change in each sensor’s response near day 40 (Fig. 8). In this period, the CA storage room failed requiring significant manipulation that may have resulted in the sharp change in the sensor’s response.

Firmness was significantly ($P < 0.0036$) and negatively correlated ($F = 71.6 - 2.86\overline{\%\Delta m}$, $r^2 = 0.04$) with mean percent mass loss ($\overline{\%\Delta m}$) in 'Delicious' apples (Fig. 9). Similarly, firmness was significantly ($P < 0.001$) and negatively correlated ($F = 70.7 – 8.96 s$, $r^2 = 0.05$) with shrinkage (s) in 'Delicious' apples (Fig. 10).

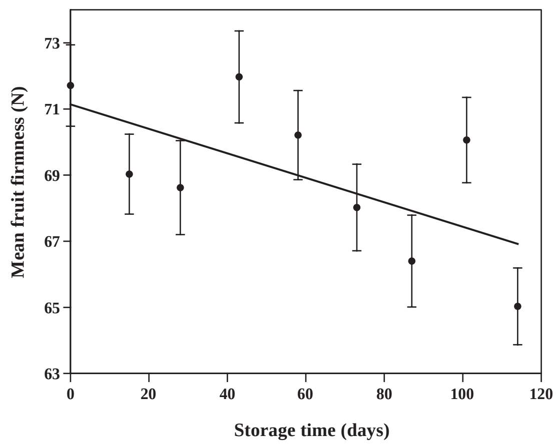

Fig 6. Firmness loss with storage time in 'Delicious' apples. Bars are one standard error of the mean

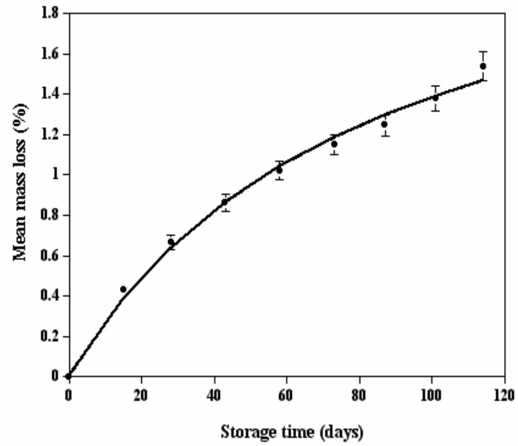

Fig. 7. Relation between mean percent mass loss and storage time in 'Delicious' apples. Bars are one standard error of the mean.

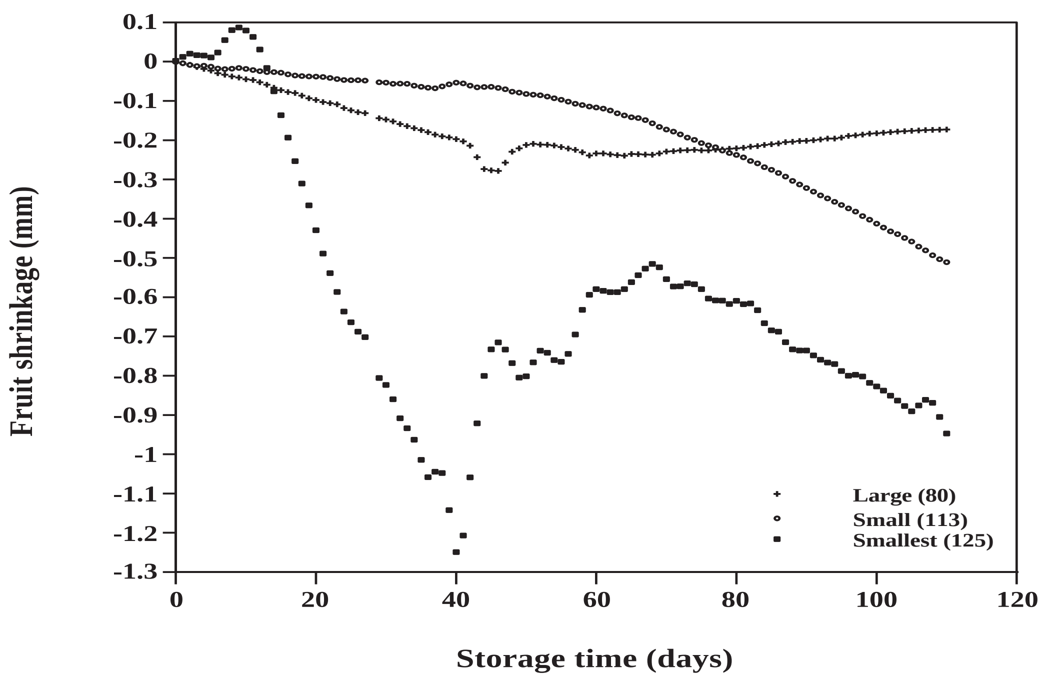

Fig. 8. Shrinkage of 'Delicious' apples with storage time.

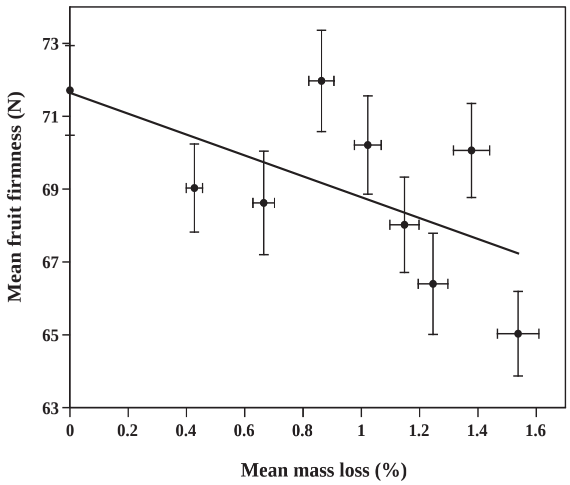

Fig. 9. Relation between mean percent mass loss and mean firmness in 'Delicious' apples. Bars are one standard error of the mean.

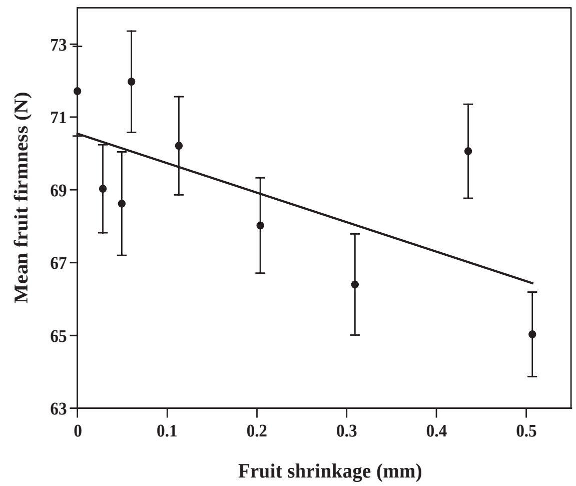

Fig. 10. Relation between shrinkage and mean firmness in 'Delicious' apples. Bars are one standard error of the mean.

Discussion

The main finding of this study was that there is a relationship between mass loss, shrinkage, and firmness in 'Delicious' apples under the conditions of the RA and CA tests. In RA storage, ‘Fuji’ apples did not lose firmness, but lost mass and shrank during the observation period. The rate of firmness loss in the CA storage experiment was independent of apple size.

During storage, most mass loss in apples is water because they are 80-85% water (Pieniazek 1942). At less than 90% relative humidity almost all, mass loss is by transpired water (Maguire et al. 2000). Earlier workers considered mass loss of apples to be equivalent to transpiration because of the relatively small rate of carbon loss (Pieniazek 1944). Under storage conditions of 0°C and 95% relative humidity, Maguire et al. (2000, Fig. 2) predict that about 82% of mass loss in 'Braeburn' apples will be by transpiration and the rest by respiration. In our experiments, it is likely that most of the mass lost was transpired water.

The rate of mass loss in our experiments was similar to that reported by others. Under conditions similar to our RA experiment, 'Jonagold' apples lost mass at a rate of 1.3% per month (De Belie et al. 2000). In our experiment, 'Fuji' apples lost mass at a rate of 1.1% per month and 'Delicious' apples lost mass at a rate of 0.6% per month. In the CA experiment, ‘Delicious’ apples lost nearly 1.5% of their mass over 3.8 months or about 0.4 % per month although the relation was not linear. The lower rate of mass loss in 'Delicious' apples suggests they are less permeable than Fuji apples. Given that fruit transpiration is primarily controlled by the amount of wax on the skin (Pieniazek 1944), it is likely that 'Delicious' apples have more wax than 'Fuji' apples. The lower rate of mass loss in ‘Delicious’ apples in CA versus RA storage may be caused by the lower rate of respiratory CO_2 loss and small potential differences in relative humidity in the two storage conditions. There was no effect of ‘Delicious’ fruit size on percent mass loss over 114 days in CA storage suggesting that, at least for ‘Delicious’ apples under the conditions of the test, the use of mass loss as a predictor of firmness loss can be done independent of apple size. This needs to be confirmed. Lastly, the observation on day 114 in figure 7 suggests an increase in the rate of mass loss relative to the rest of the data. It was noted during the experiment that an apple had been dropped splitting in the skin causing the apple to lose more water and is the cause of the elevated mass loss by day 114.

The shrinkage sensors apparently worked in only half the trials. In the RA experiment, one sensor did not respond (data not shown) as the other two in figure 3. The sensor changed little over the experimental period and showed an apparent increase in apple size near the end. In the CA experiment, two sensors were erratic. The sensor on the large (80) apple may have lost contact with the fruit or the fruit change position during the disturbance near day 40 (Fig. 8). At the end of the experiment, the large (80) apple fell out of its sensor when the apparatus was dissembled. The gradual increase in apparent apple size after day 60 may be a result of little tension on the sensor. The sensor on the smallest (125) apple displayed large and erratic changes over the observation period, but appeared to track shrinkage after about day 70. This particular sensor was an old prototype version of the DEX 100 sensor and may have lost some function after 7 years. The sensor was tightly bound to the apple when the apparatus was dissembled. These sensors may be more reliable if they are more tightly appressed to the fruit even though they would dent the surface, but not break the skin. Variation among fruit and location of the sensor on the fruit may explain variation in sensor response.

In both experiments, shrinkage was reliably measured on three apples. Apples shrink as they lose water (Wilkinson 1965). A 5% mass loss can result in skin wrinkling (Maguire et al. 2000). In the RA experiment, the 'Fuji' apple lost 0.70 mm of the 79.90 mm span between the anvils of the sensor. If we assume the 'Fuji' is a sphere and 79.90 mm is the initial diameter then the 'Fuji' apple lost 2.6% of its volume. If we also assume a 'Delicious' apple is a sphere then a loss of 0.28-mm results in a 1.0% loss of volume. These values are the same magnitude and direction as the measured mass loss of 2.0% in 'Fuji' and 1.2% in 'Delicious' apples. The concordance of these values suggests that dimensional shrinkage in the fruit at its widest point is representative of water loss in the fruit even if they are not true spheres.

In the RA experiment firmness decreased at a constant rate in 'Delicious' apples over the 57-day period dropping to a mean firmness of 58.6 N while 'Fuji' apples remained constant at 69.06 N. These values are lower than the 65.4 N for 'Delicious' and 81.4 N for 'Fuji' apples observed over a 60-day period under similar RA conditions (Drake 1993). The difference may be attributed to higher initial firmness in Drake (1993) because 'Fuji' apples were at a much higher value than in the current study and likely did not change. 'Fuji' apples slowly (1.25 N $month^{-1}$) lose firmness in air storage (Blankenship et al. 1997). The 'Fuji' apples in our study may have significantly lost firmness if the experiment had continued more than 2 months. Firmness loss in 'Red Chief Delicious' apples stored at 4°C over about 55 days was the same (Gussman et al. 1993) as in the current study. Abbott and Liljedahl (1994) observed a loss of about 9 N in 'Delicious' apples (sizes 88 to 113) stored over 85 days at 0°C, which is less than the 15 N loss in our study with larger apples (size 80, 263.6 ± 5.6 g, n=42). Large apples are softer than small apples (Ebel et al. 1993, Blankenship et al. 1997) and may lose firmness more rapidly in RA storage. In the CA experiment, small apples were firmer than large apples and there was no effect of apple size on the loss rate of firmness. In a longer experiment, we may observe an effect of apple size on the rate of firmness loss. If there is no effect of size on the rate of firmness loss then the prediction of firmness using mass loss or shrinkage would be simplified in practice.

The factors that control firmness loss can be related to water content. In peppers, Lurie et al. (1986) observed that control of water loss was sufficient to control firmness. Water stress hastens and possibly triggers the onset of senescence in pepper fruit (Lurie et al. 1986). Apples also lose firmness (Drake 1993) and water (Pieniazek 1944) during storage. Little work has been done, though, to relate mass loss to firmness loss during storage. De Belie et al. (1999) did find a linear decreasing relation between a 'stiffness factor' correlated with firmness (Abbott and Lu 1996) and mass loss. De Belie et al. (1999) found the 'stiffness factor' to be independent of relative humidity (65%, 95%) and, thus of the rate of mass loss. In the current study, the relation between mean percent mass loss and firmness was linear and decreasing in 'Delicious' apples. Based on our preliminary results we suggest that tracking 'Delicious' fruit mass loss during RA and CA storage may allow the prediction of firmness loss. Given that we observed loss of mass in the 'Fuji' apples, it is likely that a predictive relation for firmness will also exist over longer storage times. Senescence processes (Lurie et al. 1986) may require more water loss to become activated in denser 'Fuji' apples than in 'Delicious' apples.

The relation between shrinkage and firmness loss also was linear and decreasing in the 'Delicious' apple. The 'Fuji' apple shrank without firmness loss. The relationships between shrinkage and firmness loss for both apple types were very similar to the relationships between mean percent mass loss and firmness. This concordance is expected because apples shrink as they lose water (Wilkinson 1965). Based on our preliminary results we also can suggest that tracking 'Delicious' fruit shrinkage during RA and CA storage may allow the prediction of firmness loss. It is also likely that a predictive relation between shrinkage and firmness loss will exist in 'Fuji' apples over longer storage times.

Classical approaches for the non-destructive determination of firmness include fruit responses to imposed vibration, mechanical or sonic impulses, impact force analysis, and ultrasonic testing techniques (Muramatsu et al. 1999). These approaches all depend on their correlation with standard destructive measures of firmness such as the Magness-Taylor tester (Magness and Taylor 1925). Our approaches are also dependent on correlation with the Magness-Taylor tester, but are simpler and are based on mass loss (primarily water) that is associated with the physiological processes that control firmness.

The prediction of firmness loss based primarily on water loss can be useful for potential control strategies. Lurie et al. (1986) showed that control of water content in pepper fruit results in control of senescence and firmness. Peppers held at high water content had low levels of water soluble pectins and do not lose firmness (Lurie et al 1986). Water status in fruit is associated with the regulatory control of enzyme activities (Kramer and Boyer 1995) that control senescence. Water stress has been associated with increases in abscisic acid which in turn is associated with ethylene production in many plants and fruits as they senesce (Nooden 1988). Fruit softening is mediated by ethylene production (Mattoo and Aharoni 1988). If apples behave as peppers then careful control of water content, may allow maintenance of firmness, or at least reduce the rate of firmness loss under RA and CA storage conditions.

Conclusion

We have demonstrated two new ways to predict ‘Delicious’ apple firmness under RA and CA storage conditions. The relation between firmness and mass loss, or shrinkage is dependent on apple variety. Other factors that may influence the relationship between firmness and mass loss, or shrinkage include fruit size, initial water content, wax, plus growth, harvest, and storage conditions. Further testing is needed to determine the repeatability of the techniques and their potential for use in practice. Use of mass loss to predict firmness has the advantage because the entire fruit is measured while shrinkage is measured at only two points on a fruit. The shrinkage sensors were also less reliable than repeatedly weighing fruits. Mass loss also can be directly related to water loss.

The next proposed effort is to determine if it is possible to reliably track mass loss in real-time under storage conditions. If it is possible to electronically track mass loss then the technology needed to predict firmness while in storage is reduced to a simple scale. This technology is well understood, inexpensive, and after adequate testing of various sources of apple variation, could be put into practice in the fruit storage industry.

The potential benefit to industry of a technique to predict firmness while in storage would be realized by allowing a manager to pack out fruit of known firmness. Predictive relations for firmness would allow a manager to forecast when a certain lot of apples should be packed out of the storage room. Such information, on a manager’s computer screen upon demand, would allow for more informed decisions on when to pack out lots of apples with consistent and high firmness values.

References

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Budget:
A new sensor for tracking apple firmness in CA storage.
Dr. Steven O. Link

Salary	Steven Link	6,707
Benefits	Steven Link (27%)	1,811
Travel	6 trips to Wenatchee for work	497
Equipment	Sensors and assistance	2,432
Supplies, Services		620
Expenses for Steve Drake's lab		2,000
Miscellaneous	Postage, telephone etc	180
	Total	$14,247