A LOW-MASS IMPACT SENSOR FOR HIGH-SPEED FIRMNESS SENSING OF FRUITS

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Background:

Results of previous studies conducted by different researchers have shown that impact techniques can be used to evaluate firmness of fruits (Delwiche et al., 1989; Delwiche et al., 1996; Jarén et al., 1992). A common technique used is to drop the fruit on a force sensor and measure the force as a function of time (McGlone and Schaare, 1993; Nahir et al., 1986; and Younce and Davis, 1995). A firmness index is then determined from impact parameters extracted from the force-time data. A problem inherent in this technique is that the impact force is also a function of the mass and radius of curvature of the fruit. Therefore, a large variation in these two parameters will affect the accuracy in firmness measurement. Other shortcomings of this technique are that the speed is limited by the free-fall speed of the fruit and the impact location on the fruit is difficult to control. A different approach is to impact the fruit with a small spherical impactor of known mass and radius of curvature and measure the acceleration of the impactor (Chen et al., 1996; and Jarén et al., 1992). The advantage of this method is that the measured impact-acceleration response is independent of the fruit mass and is less sensitive to the variation in the radius of curvature of the fruit. Moreover, results of our recent study (Chen et al., 1996), based on both theoretical analysis and experimental evaluation, indicate that using a low-mass impactor can result in the following additional desirable features:

1. It increases the strength of the measured acceleration signal, facilitating easier detection and maximizing signal-to-noise ratio.
2. It increases both the magnitude of the calculated firmness index and the rate of change of firmness index with respect to fruit firmness (i.e., the firmness index is sensitive to the change in fruit firmness).
3. It minimizes the error due to movement of the fruit during the impact.
4. It minimizes fruit damage caused by the impact.
5. It facilitates high speed sensing.

It is evident that a low-mass impact sensor can be a viable firmness sensor for fruits.

Objectives:

The objectives of this project were to:

- Develop a low-mass impact sensor for high-speed firmness sensing of fruits.
- Evaluate the performance of the sensor.

Design of the impact sensor

Results of our previous study indicate that an impact sensor should have low mass, high-speed impact, constant impacting speed, and good structure integrity. Based on these findings, we designed and fabricated an experimental low-mass impact sensor for high-speed sensing of fruit firmness. The impactor consists of a semi-spherical impacting tip attached to the end (near the center of percussion) of a pivoting arm. A small accelerometer is mounted behind the impacting tip. Impact is done by swinging the impactor to collide with the fruit. The pre-amplified signal from the accelerometer is transmitted through the pivot to a computer where the signal is analyzed and firmness index determined. Preliminary tests indicated that such a sensor could detect fruit firmness at a speed of five fruits per second (maximum speed of the existing conveyor in our lab). The sensor is simple and compact in size. The entire unit (sensor, actuators, and frame) occupies a space of about 4"x6"x8". The sensor provides a strong signal with high signal-to-noise ratio.

Experimental Procedures

Two basic tests were made to evaluate the performance of the impact sensor:

1. Test with a rubber ball (lacrosse ball) to evaluate the consistency and repeatability of the sensor.

Impact on fixed and free ball. The result of our previous study based on theoretical analysis of elastic impact indicated that when the impacting mass is small compared to the impacted (fruit) mass, the peak acceleration, A, and the firmness index A/t, where t is the time required to reach A, should not be sensitive to whether the fruit is fixed or free to move. A test was conducted to experimentally verify this result. Some impacts were made while the rubber ball was resting on a flat surface (free to move) and some were made while the ball was held by a clamp (fixed).

Impacts at different distances. The impact sensor was designed to impact each fruit with the same impacting velocity. Therefore the impacting velocity should not be affected by how far the impacting arm swings before it hits the fruit. A test was made to evaluate the effect of the swing distance on the output of the sensor. In this test, impacts were made while the impact surface of the rubber ball was set at 8, 11, 14, 17, 20 and 23 mm away from the impacting tip when the impactor is in the cocked position. Eight impacts were made for each position. Four impacts were made when the ball was free to move, and the other four impacts were made when the ball was fixed. The total number of 48 impacts were made in random order.

2. Comparison of fruit firmness measurements obtained with the impact sensor and those obtained with a universal testing machine.

Impact and penetrometer tests were made on kiwifruits and peaches. The following measurements were made on each fruit: First, two impacts were made on opposite sides of the fruit while it was positioned at 10 mm from the impacting tip (in the ready position). The acceleration history during the impact was recorded and stored in a computer. Then penetrometer measurements were made at about 1 cm from the impact locations after a 2-mm layer of peel was removed. A 7.9 mm diameter cylindrical plunger, mounted on a load cell of an Instron universal testing machine, was moved at a rate of 60 mm/min until it penetrated 8 mm into the fruit. The force-deformation data were recorded and saved. Three firmness parameters were obtained from each impact test. They were the maximum acceleration, A , the ratio A/t (where t is the time required to reach A), and the slope (change in acceleration with respect to time) of the impact curve near 0.5t (Fig. 1). These impact firmness parameters were compared with the following firmness parameters obtained from the penetrometer measurement: the maximum force, F, which is the penetrometer reading, and the force-deformation firmness, which is the slope (change in force with respect to deformation) of the force-deformation curve at mid point between the initial point and F (Fig. 2).

Kiwifruits. A total of twenty-one kiwi fruits (three groups of seven fruits each) were used in this test. Seven fruits were harvested and ripened in room temperature for 10 days; the second group of seven fruits were picked and ripened for 4 days, and the third group consisted of newly picked fruits. The test was conducted on November 10, 1995.

Peaches. Fay Alberta peaches were used for this experiment. Tests were conducted at two to three days intervals from July 18 to August 11, 1996. On each test day, about 10 fruit were picked from the university experimental orchard in Davis, California, and 7 fruits were selected for the tests (except on July 18, when 10 fruits were tested). A total of 80 peaches were tested.

Results

The result of the 48 impacts (24 on free and 24 on fixed ball) made at six different distances is shown in Fig. 3. The maximum acceleration, A, remained practically unchanged throughout the 48 impacts. The value of A/t was found to vary more than expected. It was later observed that, because the acceleration signal was converted by an 8-bit A/D converter, the value of maximum acceleration, A, occurred several times over a range of time. Since the computer program was written to detect A the first time it occurs, the value of t can vary up to 10% for two similar impacts. For this reason the slope of the impact curve was considered a better firmness parameter than the ratio of A/t.

The results of fruit firmness measurements were evaluated by comparing the firmness parameters obtained with the impact sensor to those obtained with the penetrometer test. Tables 1 and 2 shows the coefficients of determination between different pairs of firmness parameters for kiwifruits and peaches, respectively. The impact parameters correlate better with the force-deformation firmness than with the penetrometer reading. This was expected because the penetrometer reading represents the flesh strength and is not a good measure of firmness. The best correlation ($R^2 = 0.924$ for kiwifruits and 0.867 for peaches) was between the slope of the impact curve and the force-deformation firmness. Examples of plots showing the relationships between the firmness parameters obtained with the two methods are shown in Figures 4 and 5 for kiwifruits and Figures 6 to 9 for peaches. Figure 6 shows that the maximum acceleration drops rapidly as the penetrometer reading is drops below 10 N, indicating that the impact sensor is more sensitive to firmness change in soft fruits than is the penetrometer. When extremely soft fruits (those with Amax values below 8 m/s^3) were analyzed separately (Fig. 7), the r^2 value for the rest of the fruits increases from 0.791 to 0.827.

Conclusion

A low-mass impact sensor for high-speed firmness sensing of fruits was built and tested. Results of tests with a rubber ball indicated that the impact measurement was not sensitive to the distance between the impactor and the impacting surface of the sample within the range of 8 to 23 mm, and was not sensitive to how the sample was held. Tests with kiwifruits and peaches show good correlation between firmness readings based on impact and those obtained with the penetrometer. The best correlation was between the slope of the impact curve (at mid-point) and the force-deformation firmness. Preliminary test showed that the sensor could sense fruit firmness at a speed of 5 fruits/s.

Acknowledgment

The authors would like to thank Dr. Sayedahmad Shafii, Post Graduate Researcher, for the final design and fabrication of the impact sensor and to Ms. Yenny Tjan, Graduate Assistant, for conducting the impact experiment.

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Table 1. The values of coefficient of determination (R^2) between impact firmness parameters and penetrometer test parameters for kiwifruits.

	Penetrometer reading, N	Force-deformation firmness, N/mm
A, m/s^2	0.848	0.885
A/t, m/s^3	0.809	0.875
Slope, m/s^3	0.876	0.924

Table 2. The values of coefficient of determination (R^2) between impact firmness parameters and penetrometer test parameters for peaches.

	Penetrometer reading, N	Force-deformation firmness, N/mm
A, m/s^2	0.791	0.854
A/t m/s^3	0.810	0.848
Slope, m/s^3	0.821	0.867

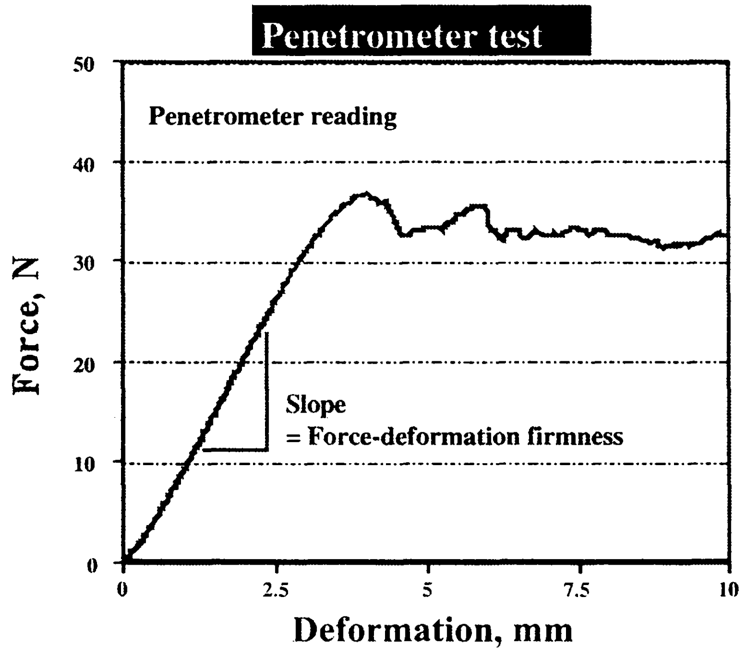

Figure 1 A typical force-deformation curve of a penetrometer test, showing the penetrometer reading and the force-deformation firmness use in the analysis

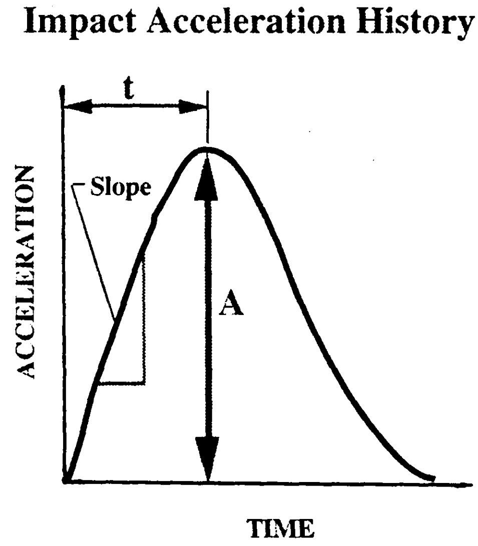

Figure 2 An impact curve showing the maximum acceleration, A, time, t, required to reach A, and the slope used as one of the firmness indexes.

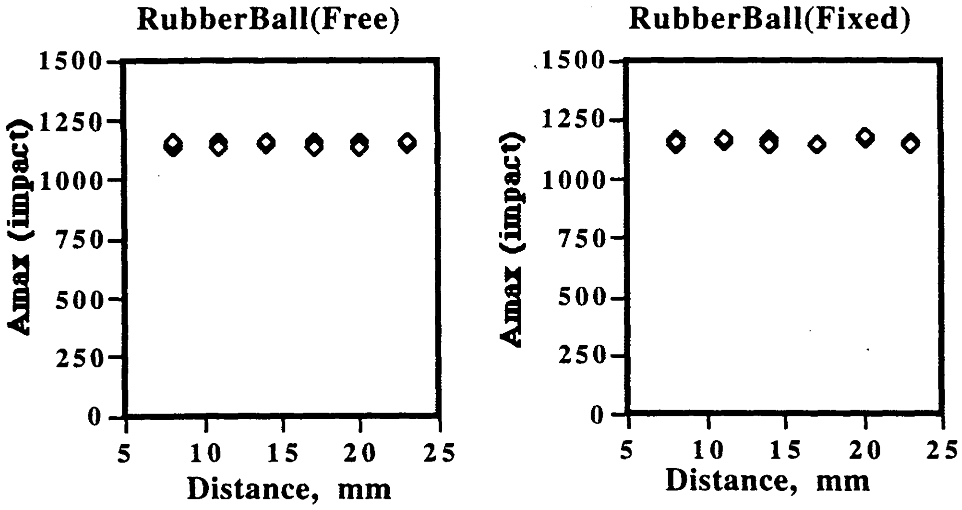

Figure 3 Comparison of maximum acceleration values obtained when the rubber ball was set at different distances from the impactor and when the ball was allowed to move freely (left) and fixed (right).

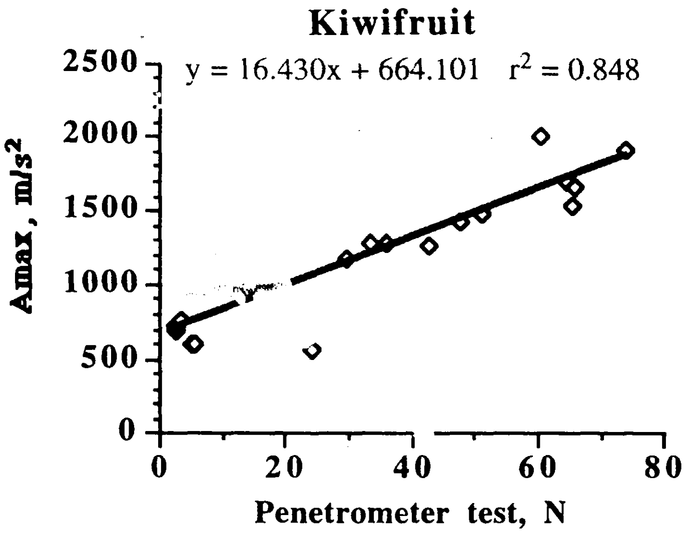

Figure 4 Relationship between maximum acceleration and penetrometer reading for kiwifruit.

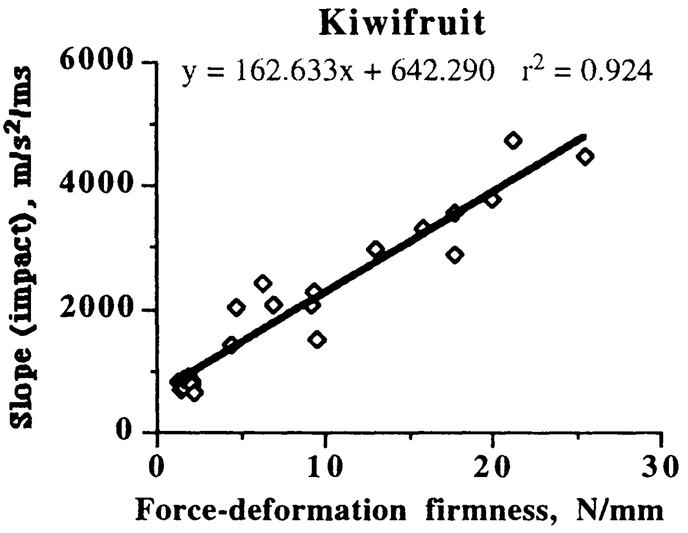

Figure 5 Relationship between slope of impact curve and penetrometer reading for kiwifruit.

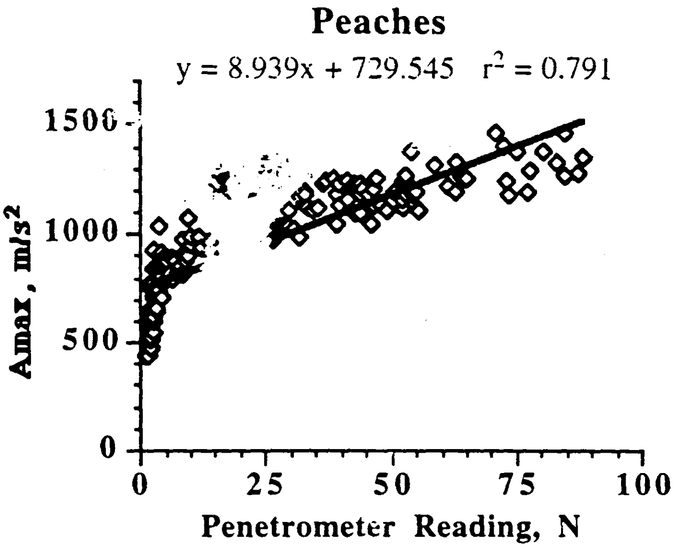

Figure 6 Relationship between maximum acceleration and penetrometer reading for Fay Alberta peaches.

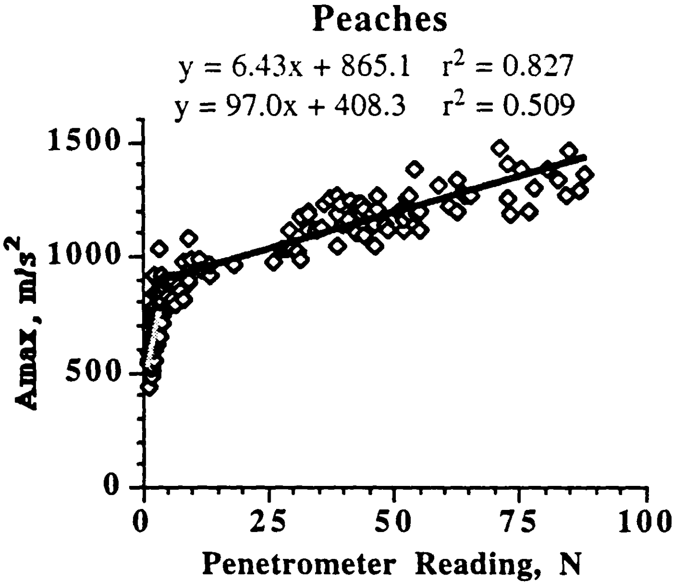

Figure 7 Relationship between maximum acceleration and penetrometer reading for Fay Alberta peaches when extremely soft fruits were evaluated separately.

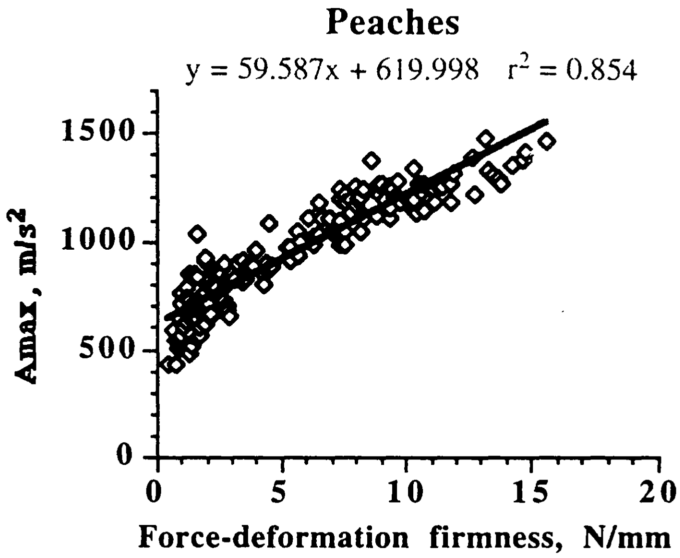

Figure 8 Relationship between maximum acceleration and force-deformation firmness for Fay Alberta peaches.

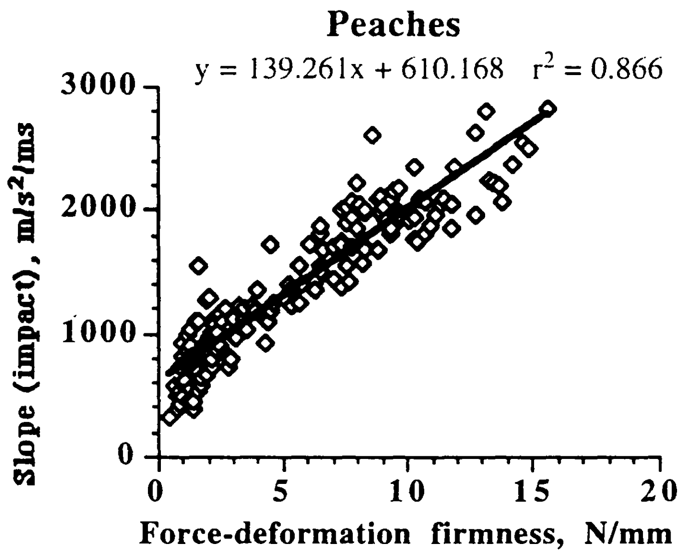

Figure 9 Relationship between slope of impact curve and force-deformation firmness for Fay Alberta peaches.