Comparison of Devices for Measuring Cherry Fruit Firmness

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Abstract. The performance of three relatively new nondestructive cherry firmness devices and a penetrometer were evaluated and compared with the firmness testing performance of an Instron Universal Testing Machine. The inherent variability of the nondestructive devices was estimated by repeated measurement of a uniform, symmetrical, and resilient rubber ball. Analysis of residuals from correlations between each device and the Instron from firmness testing on common samples of sweet cherries (*Prunus avium* L.) confirmed the relative variability of the nondestructive devices, and estimated measurement reliability of the penetrometer. Subjective firmness sensing by compression of cherries between the fingers of human evaluators proved to be less reliable than the devices tested. Sweet cherry firmness correlated reasonably well with skin color, with the strength of the correlations from each device agreeing with device ranking in terms of firmness measurement reliability. Firmness correlated poorly with soluble solids, titratable acidity, and specific gravity; soluble solids correlated well with specific gravity; and skin color correlated reasonably well with both soluble solids and specific gravity. Fruit surface pit volume, induced by a specific impact force from a ball bearing, correlated relatively well with fruit firmness measured by the penetrometer, but poorly or inconsistently with measurements from the remaining firmness devices.

Firmness is an important attribute of sweet cherries and is often used to assess fruit quality. Cherry firmness affects fruit shelf life, consumer acceptance, and possibly susceptibility to both mechanical damage and infection by rot organisms (Brown and Bourne, 1988). Fruit firmness sensing by compressing the fruit between one's fingers continues to be a common method for assessing firmness among producers, packers, and inspectors for lack of a better standardized, convenient, and cost-effective method. With increased emphasis on fruit quality, the recent development of new cherry firmness measuring devices has provided alternative methods of evaluating this parameter. Objective measurement of cherry firmness would reduce biases and inaccuracies associated with sensing firmness by compression of the fruit between fingers. Such devices may also provide information relating the importance of firmness with respect to other cherry maturity and quality characteristics.

The objectives of this study were to evaluate four firmness devices that are either available commercially, or have commercial potential for assessing cherry fruit firmness. Evaluation of the devices occurred with respect to a research based firmness-testing instrument with proven reliability (Instron), and to firmness sensing using human fingers. It was also the aim of this study to examine relationship strengths between fruit firmness as measured by each type of firmness sensor, and fruit maturity and quality indices, including surface pitting.

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Materials and Methods

Firmness devices. Three relatively new nondestructive firmness devices considered to have real or potential commercial application for the sweet cherry industry were evaluated. The three devices were Momentum Transfer Generator or MTG (Washington State Univ., Pullman), FirmTech1 (BioWorks, Stillwater, Okla.), and the unofficially named Low Mass Impactor (Univ. of California, Davis). A fourth device, the UC Firmness Tester (Western Industrial Supply Co., San Francisco), incorporating an Ametek penetrometer (Ametek, Hatfield, Pa.) commonly utilized for measuring firmness of many fruits, was also evaluated. These devices were evaluated against a fifth device, the Instron Universal Testing Machine model 1122 (Instron Corp., Canton, Mass.), which is widely accepted as a reliable firmness-testing instrument for biological materials.

The MTG evaluates firmness using the transfer of momentum from an impacting fruit onto a disc fastened to the spring-supported coil of an audio speaker. The corresponding coil movement generates a voltage-time signal in the form of a dampened sinusoidal wave. The initial slope of the sinusoid, determined by the instrument electronics, is interpreted as a firmness index (Younce and Davis, 1995). Cherry fruit are dropped ≈ 60 mm by a release mechanism to impact the fruit cheek on the speaker disc. Individual cherry firmness, sample mean firmness, and sample standard deviation of firmness are displayed on a computer interfaced with the instrument and can be saved to a file.

The FirmTech1 measures firmness using the force-deformation response from a cherry fruit compressed across the cheeks (Armstrong

et al., 1995). Cherries are positioned into shallow indentures on a turntable that automatically rotates and aligns each fruit periodically under a small load cell attached to a linear stepper motor. In this study, a predetermined force of 200 g (medium of a range of forces offered by the device) was progressively applied to the fruit cheek by a flat plate attached to the load cell. The rate at which the force increases with respect to fruit deformation is defined as firmness. For a sample of cherries, the mean, maximum, minimum, standard deviation, and frequency distribution of firmness are presented through an interfaced computer. Firmness of individual cherries in the sample is saved to a file.

The Low Mass Impactor involved impacting a small spherical, low-mass object onto the fruit cheek, and evaluating the acceleration response of the rebounded mass (Chen and Ruiz-Altisent, 1996). A small accelerometer mounted behind the mass supplies an interfaced computer with the impact response signal, from which the slope of the initial acceleration curve with respect to time is used as a firmness index. Results of each test are displayed on the computer, and successive tests can be appended to a single data file.

The UC Firmness Tester is a fruit destructive device that incorporates a penetrometer as the force-sensing component. The penetrometer is mounted on a retractable frame from which a lever fixed to the frame is used to depress the penetrometer tip (3-mm diameter) into the cherry flesh. The maximum force applied to the fruit is defined as fruit firmness and occurs momentarily prior to collapse of the flesh beneath the penetrometer tip. A gauge on the penetrometer is used to record fruit firmness.

The Instron is a research tool developed to determine firmness and strength of materials, and has been used for measuring firmness of many fruits (Bourne, 1982). In this study, a nondestructive 1-mm compression was applied by a ball bearing (9-mm diameter) secured to the load cell and descending at 20 mm·min⁻¹ to a sweet cherry balancing on three adjoining ball bearings (9-mm diameter) fixed to a plate. Fruit cheek contact with the four ball bearings during a compression cycle was minimal, reducing the influence of fruit diameter or surface irregularities on firmness measurements. The slope of the resulting, highly linear force-deformation curve was equated to cherry firmness.

To test for instrument variability, 12 consecutive firmness measurements were conducted with each device on a uniform, symmetrical, and resilient rubber ball (27-mm diameter) of typical mature sweet cherry firmness. The penetrometer could not be tested on the rubber ball due to its destructive mode of action.

Fruit evaluation. 'Bing' sweet cherries were harvested on five occasions, and sourced from either one of two commercial properties in San Joaquin County, Calif., between 15 and 29 May 1996 (commercial harvesting period). The fruit were from mature trees on 'Mahaleb' rootstock and were grown under standard com-

mercial conditions. At each harvest, ≈ 10 kg of fruit were harvested from the mid- to outer canopy area of several trees, up to a height of ≈ 2 m. Emphasis was on acquiring fruit of mixed maturity with a full range of fruit firmness. Following each harvest, cherries were transported to the laboratory and sorted to remove blemished and misshapen fruit. They were then divided into six groups of 100 fruit each for the first harvest, and six groups of 50 fruit each for subsequent harvests. Each group was assigned for measurement by one of the five firmness devices, while the sixth group was subjected to firmness measurement by all five devices.

Firmness measurements were conducted after fruit temperature had equilibrated in a controlled environment of 20°C . The order in which the nondestructive devices were used to measure firmness on the common group of cherries subjected to measurement by all devices was rotated across the five harvests. Penetrometer firmness was always conducted last as this is a destructive measurement. Following firmness measurements from the four nondestructive devices, each cherry was evaluated for specific gravity (relationship of fruit stemless mass and volume) as detailed by Mohsenin (1986) and skin color using a Minolta chromameter model CR-200 (Minolta Corp., Ramsey, N.J.). Each cherry was then impacted on one cheek by a smooth metal ball (3-mm diameter) fixed to a nail (4.1 g mass) and dropped from a height of 100 mm. Fruit were held for ≈ 24 h in cold storage (0°C) to allow pits to develop and then removed to equilibrate to 20°C for penetrometer firmness measurement and pit size determination. A small section of skin was removed from the opposite cheek from that with the surface pit, as a site for the penetrometer test. Surface pit diameter and depth were determined from cross-sections of the pits, observed under a dissecting microscope fitted with an ocular micrometer. Based on the dimensions of each pit, volume was estimated based on a sphere cap calculation. Individual fruit were then juiced to evaluate total soluble solids content (Abbe Refractometer, Buffalo, N.Y.) and acidity (titration to pH 8.2 with 0.1 N NaOH).

On three occasions, an additional sample of 50 cherries was used to compare firmness measured by each nondestructive device with firmness subjectively determined by compression of the fruit between human fingers. Firmness sensing using fingers was undertaken by one individual using a soft and a hard rubber ball representing the range of a five-point scale used in rating for firmness.

Results and Discussion

Instrument limitations associated with resolution or inaccuracy were evident from multiple firmness measurements made on the rubber ball. Evidence of the ball's resilient properties were apparent from testing with the Instron (Fig. 1), where mean firmness variability from 12 measurements was only 0.28%. Noting that some variability would exist due to the Instron device, we concluded that in

these tests firmness variability of the rubber ball must be $<0.28\%$, and for the purposes of this study considered negligible. Measurements from the remaining nondestructive devices, which exhibited larger relative firmness variability, can be interpreted as being largely attributed to device measurement variability or error (Fig. 1). Successive testing on the rubber ball revealed that the Instron was the most precise instrument, followed by the FirmTech1, Low Mass Impactor, and MTG.

Evaluation of device accuracy was also possible by comparing firmness measurements from each instrument on a common sample of cherries from each harvest. This was possible, as minor cherry fruit deformation (occurring in this study by compression or impactation) is nondestructive, and may not affect subsequent firmness tests on the same fruit (Lustig and Bernstein, 1987). Researchers have utilized this approach to compare devices for measuring firmness of cherries (Brown, 1988; Kenworthy and Silsby, 1974; Younce and Davis, 1995), and of other soft fruits (Chen and Ruiz-Altisent, 1996; Lesage and Destain, 1996). In this study, cherry deformation of 1 mm using the Instron was considered nondestructive based on results by Lidster and Tung (1979). They observed that compressing sweet cherries by 4 mm between smooth flat plates at a low loading rate allowed the cherry structure

to temporarily distort and flow without cell rupture in all but 7.2% of fruit compressed.

Firmness measurements from each of the devices, when correlated with Instron measurements on the same sample of fruit, would reflect residuals resulting from: 1) variability or error of measurement associated with the cherry firmness devices themselves; 2) any relative firmness inconsistency from the individual fruit at positions around their circumference; and 3) measurement of firmness variability associated with fruit contact area inconsistency with the firmness devices, either due to irregularities in fruit size or shape (considered negligible for the Instron because of the minimal fruit contact area with the ball bearings). Variability of firmness due to Instron measurement would be expressed through correlations with all the remaining devices, thereby causing no relative effect. The correlation between each device and the Instron for all harvests was significant ($P < 0.001$). Relative strength of the correlations between the Instron and the remaining devices was consistent between the fruit from the two orchards, and between early- and late-season fruit (data not shown). Therefore, the firmness residuals of the regressed correlation from each harvest were combined across all five harvests for each device, totaling 300 firmness measurements. Results of these correlations are pre-

Fig. 1. Variability of 12 firmness measurements and average measurement variability (a.v.) of the nondestructive devices on a resilient, symmetrical rubber ball of typical mature cherry size and firmness.

sented in histograms detailing the frequency of the firmness residual values (Fig. 2). Fruit firmness inconsistency around the circumference of the fruit, measurement variability due to device/fruit contact area inconsistency, and measurement variability due to device resolution or error featured standard deviations of residuals of 9.5%, 12.9%, 13.4%, and 15.3% for the FirmTech1, Low Mass Impactor, MTG, and penetrometer, respectively. Assuming firmness inconsistency around the circumfer-

ence of the fruit to be randomly distributed within measurements from all devices with comparative equality, the differences between histograms given in Fig. 2 would reflect the relative variability of firmness measurement by each device due to inaccuracy and fruit contact area inconsistencies. These differences proportionally agree with the device precision assessment given by the mean errors illustrated in Fig. 1.

The penetrometer was less accurate at mea-

suring firmness than were the FirmTech1, Low Mass Impactor, and MTG (Fig. 2). Skin removal at the penetrometer measurement site eliminated the influence of skin strength on the firmness measurement. Brown (1988) found that sour cherry firmness measured by nondestructive compression of the fruit between plates using an Instron failed to correlate significantly with firmness measured by puncture force of a small diameter probe tip through the skin. In addition, Brown and Bourne (1988) suggested that firmness measured by puncture testing through the flesh, as opposed to the skin, may give a better perception of total sweet cherry firmness. Operator inaccuracies are associated with the penetrometer measurement, which may arise from the speed, angle, depth, or acceleration used to push the probe into the fruit (Harker et al., 1996). In this study, measurements were conducted by the same, experienced individual in order to minimize operator variability. The mean and variability of fruit firmness measured by the devices for each harvest are presented in Table 1.

Estimation of cherry firmness using a compression force between human fingers was evaluated for accuracy by correlating the firmness rating against previous Instron measurements on the same fruit, and using the residuals analysis as detailed above. The correlation from each sample was significant ($P < 0.001$). Assuming Instron measurement variability or error to be negligible, the revealed residuals would result from firmness inconsistency of the individual fruit around their circumference, inconsistency in finger/fruit contact area, and human error in sensing firmness. Standard deviation of the residuals of the correlations from the combined samples was 16.3%, a greater variability than the devices used in this study (Fig. 2). However, this result would be expected to vary depending on the skill and experience of the individual conducting such an evaluation. Inconsistent results were apparent when fruit firmness, estimated by compression between fingers, was correlated with the remaining firmness devices (data not shown). No particular device consistently showed an improved correlation with finger firmness sensing over remaining devices.

Skin color, soluble solids content, titratable acidity, and, to a lesser extent, fruit specific gravity are other maturity indices of cherry, which, in addition to firmness, are considered important harvest or postharvest factors. Sample size at each harvest for the correlations between fruit firmness, as mea-

Fig. 2. Firmness variability expressed by residuals of correlations between each firmness device, including firmness sensed by compressing fruit between fingers, and the Instron on common samples of fruit, with standard deviations (sd) given. Differences between histograms represent firmness variability due to measurement inaccuracy and or fruit/sensor contact area inconsistencies.

Table 1. Mean and sd (in parentheses) of 'Bing' cherry fruit measurements of skin hue, total soluble solids (SS), titratable acidity (TA), specific gravity (SG), and firmness as measured by each of the firmness devices.

Orchard	Harvest	Firmness					Skin hue (°) ^y	SS (%)	TA (%)	SG
		Instron (N·mm ⁻¹)	Firm-Tech1 (g·mm ⁻¹)	Low Mass Impactor	MTG ^z	Penetro- meter (g)				
1	1	1.03 (0.18)	239 (31)	743 (125)	860 (91)	222 (39)	21.4 (3.7)	18.0 (1.5)	1.12 (0.10)	1.052 (0.009)
	3	1.14 (0.19)	251 (37)	772 (128)	827 (101)	228 (38)	18.3 (4.5)	17.5 (2.3)	0.91 (0.10)	1.050 (0.012)
	5	0.91 (0.22)	225 (35)	711 (124)	809 (91)	212 (41)	15.1 (4.3)	18.8 (1.9)	0.98 (0.10)	1.056 (0.012)
2	2	0.97 (0.24)	242 (51)	752 (171)	852 (124)	220 (44)	20.7 (3.9)	14.5 (1.7)	0.89 (0.09)	1.036 (0.010)
	4	0.91 (0.21)	219 (48)	701 (137)	782 (99)	210 (42)	18.0 (4.4)	15.1 (1.7)	0.94 (0.08)	1.039 (0.011)

^zMomentum Transfer Generator.

^yAngle attributed to colors classed as red (0°), yellow (90°), green (180°), blue (270°), or an intermediate between any adjacent pair of these colors.

sured by each device, and these other maturity indices was doubled. This was possible by combining maturity index and firmness measurements from each device on the common sample of cherries, with maturity index and firmness measurements from each device on their own exclusive sample of cherries.

Cherry skin lightness and hue color was equally correlated with fruit firmness. The strength of lightness (data not shown) or hue color relationships with firmness varied dramatically between harvests (Table 2), generally reflected by the distribution of fruit color and firmness from each harvest (Table 1). A large distribution of maturity expressed wide firmness and color qualities, which mathematically correlated more closely than narrower distributions of maturity. Various studies have failed to detect a significant correlation between cherry firmness and skin color, although in those studies, color was determined by subjective evaluation, and firmness may have been measured by less accurate devices (Brown, 1988; Facticeau and Rowe, 1979; Lidster et al., 1978; Proebsting and Murphey, 1987). In this study, the relative relationship trends of firmness from each device with skin hue color within each harvest were not always consistent (i.e., Instron firmness measurement did not always correlate best with skin color) (Table 2). However, the mean correlation coefficients (r) across harvests (omitting harvest one, which had exceptionally poor correlations due to narrow fruit maturity distribution) ranged between 0.62 and 0.40 for the Instron and penetrometer, respectively (Table 2). Contending with the added variability of fruit skin color, such correlations did reveal the extent of precision of the devices relative to each other. Ranking of color/firmness correlations for each device agreed with the ranking of device precision for the rubber ball, and device fruit firmness evaluations from correlations with the Instron.

Relationships between fruit firmness and fruit soluble solids content, titratable acidity, and specific gravity were generally poor or indistinguishable (Table 2). No trend or pattern was observable for firmness and soluble solids correlations between firmness devices within harvests. Fruit specific gravity showed a poor relationship with firmness, although the trend indicated that specific gravity increased as fruit firmness decreased. Fruit titratable acidity established an improved correlation with firmness, although the relationships were still relatively poor. Discrimination between performance of each device relative to titratable acidity was not apparent due to poor correlations. Mean r across the five harvests was ≈ 0.30 for each device. The mean and variability of total soluble solids, specific gravity, and titratable acidity measured at each harvest are presented in Table 1.

Analysis of the associations between cherry skin color, soluble solids, titratable acidity, and specific gravity was possible with larger sample sizes for each harvest. As firmness was not a variable for this evaluation, measurements from cherry samples used exclusively for each of the five devices, and the sample

subjected to measurement by all devices, from each harvest could be combined. A strong positive correlation ($P < 0.001$) was found between fruit soluble solids content and specific gravity for each harvest (Table 3). Correlation coefficients varied between 0.74 and 0.87, averaging 0.79. Soluble solids content correlated reasonably well with fruit skin hue

color (Table 3), consistent with findings from other studies (Drake and Fellman, 1987; Facticeau and Rowe, 1979; Proebsting and Murphey, 1987), with a mean r across all harvests of 0.56 ($P < 0.001$). Specific gravity and skin color also correlated reasonably well; mean r across harvests was 0.60 ($P < 0.001$). Titratable acidity featured poorer associations

Table 2. Relationship of 'Bing' cherry skin hue, total soluble solids (SS), titratable acidity (TA), specific gravity (SG), and mechanically induced surface pitting with fruit firmness measured by the Instron, FirmTech1, Low Mass Impactor (LMI), Momentum Transfer Generator (MTG), and penetrometer.

	Harvest	Correlation coefficients				
		Instron	FirmTech1	LMI	MTG	Penetrometer
Skin hue ($^{\circ}$) ^a	1 ^y	0.16*	0.17*	0.14*	0.15*	0.21**
	2	0.54***	0.42***	0.61***	0.47***	0.54***
	3	0.49***	0.34***	0.19	0.17	0.14
	4	0.71***	0.63***	0.67***	0.52***	0.43***
	5	0.74***	0.60***	0.41***	0.49***	0.48***
	Mean (2-5)	0.62	0.50	0.47	0.41	0.40
SS (%)	1	0.31***	0.33***	0.39***	0.27***	0.13
	2	0.19	0.21*	0.11	0.08	0.12
	3	0.00	0.13	0.25*	0.13	0.30*
	4	-0.11	-0.14	-0.03	-0.06	0.12
	5	-0.21*	0.02	0.22*	0.09	0.02
TA (%)	1	0.33***	0.35***	0.29***	0.32***	0.26***
	2	0.20*	0.04	0.17	0.19	0.19
	3	-0.08	0.22*	0.24*	0.11	0.34***
	4	0.20*	0.19	0.21*	0.23*	0.29**
	5	0.50***	0.51***	0.58***	0.61***	0.41***
SG	1	0.18*	0.11	0.27***	0.18*	0.12
	2	-0.32**	-0.30**	-0.35***	-0.33***	-0.25*
	3	-0.21*	-0.13	0.13	0.04	0.13
	4	-0.38***	-0.37***	-0.28**	-0.21*	-0.01
	5	-0.47***	-0.21*	-0.04	-0.12	-0.13
Pitting vol (mm ³)	1	0.17*	0.26***	0.36***	0.35***	0.54***
	2	0.53***	0.38***	0.30**	0.34***	0.65***
	3	0.34***	0.29**	0.27**	0.30**	0.55***
	4	0.31**	0.28**	0.34***	0.03	0.54***
	5	0.73***	0.49***	0.38***	0.46***	0.65***
	Mean (1-5)	0.42	0.34	0.33	0.30	0.59

^aAngle attributed to colors classed as red (0°), yellow (90°), green (180°), blue (270°), or an intermediate between any adjacent pair of these colors.

^ySample size: harvest 1, 200; harvests 2-5, 100.

*, **, ***Significant at $P \leq 0.05$, 0.01, or 0.001, respectively. All other values nonsignificant at $P \leq 0.05$.

Table 3. Relationship between skin hue, total soluble solids (SS), titratable acidity (TA), and specific gravity (SG) of 'Bing' cherry fruits.

	Harvest	Correlation coefficients		
		SS (%)	TA (%)	SG
Skin hue ($^{\circ}$) ^a	1 ^y	-0.58***	-0.03	-0.53***
	2	-0.47***	0.16**	-0.55***
	3	-0.63***	-0.38***	-0.72***
	4	-0.50***	-0.02	-0.46***
	5	-0.61***	0.20**	-0.74***
SS (%)	1		0.39***	0.74***
	2		0.18**	0.76***
	3		0.66***	0.87***
	4		0.19**	0.75***
	5		0.37***	0.85***
TA (%)	1			0.27***
	2			0.15*
	3			0.59***
	4			0.08
	5			0.10

^aAngle attributed to colors classed as red (0°), yellow (90°), green (180°), blue (270°), or an intermediate between any adjacent pair of these colors.

^ySample size: harvest 1, 600; harvests 2-5, 300.

*, **, ***Significant at $P \leq 0.05$, 0.01, or 0.001, respectively. All other values nonsignificant at $P \leq 0.05$.

with fruit soluble solids, skin color, and specific gravity (Table 3).

Sweet cherry surface pitting, a disorder caused by impact bruising, has been related to fruit firmness (Facteau, 1982). In this study reasonably good, consistent relationships were found between firmness, measured by the penetrometer, and mechanically induced surface pit volume (Table 2). Lidster and Tung (1979) commented that mature sweet cherry, although more susceptible to bruising due to permanent cell distortion, is less susceptible to incidences of surface pitting, as cells are more resistant to rupture upon impact. This agrees with findings from our study where firmer cherries were found to be more susceptible to surface pit damage when impacted by a small spherical object. Poor or inconsistent relationships, although still significant, were evident with the remaining more accurate firmness measurement devices (Table 2). The strength of the correlations of pit size with each firmness device, when averaged across harvests, remained consistent with the ranking of device precision and accuracy (Figs. 1 and 2), with the penetrometer correlation with pit volume being the anomaly (Table 2). The reason for this result is uncertain, yet speculation suggests that measurement of flesh firmness without the influence of the skin (which occurred only with the penetrometer) may have been important. Alternatively, bioyield force (point of fruit cell rupture and collapse) may bear some relation to surface pit development. Further study is required in order to understand the relationship between cherry firmness and surface pitting.

Evaluation of each firmness device based on 1) the rubber ball test for measurement accuracy or consistency, 2) cherry firmness as correlated with Instron-measured cherry firmness, 3) skin color correlations with cherry firmness, and 4) surface pit damage correlations with cherry firmness (with the penetrometer being the anomaly), demonstrates that the FirmTech1 measured fruit firmness most accurately, followed by the Low Mass Impactor, MTG, penetrometer, and compression test using human fingers. With respect to ease of operation and speed of sample firmness testing, the commercial or potentially commercial devices were ranked from most to least desirable in the following order: FirmTech1, MTG, Low Mass Impactor, and penetrometer.

Literature Cited

- Armstrong, P.R., G.K. Brown, and E.J. Timm. 1995. Nondestructive firmness measurement of soft fruit for comparative studies and quality control. Amer. Soc. Agr. Eng. Paper No. 95-6172.
- Bourne, M.C. 1982. Food texture and viscosity: Concept and measurement. Academic, New York.
- Brown, S.K. 1988. Assessment of fruit firmness in selected sour cherry genotypes. HortScience 23:882-884.
- Brown, S.K. and M.C. Bourne. 1988. Assessment of components of fruit firmness in selected sweet cherry genotypes. HortScience 23:902-904.
- Chen, P. and M. Ruiz-Altisent. 1996. A low-mass impact sensor for high-speed firmness sensing of fruits. Paper no. 96F-003, AgEng96, Madrid, Spain.
- Drake, S.R. and J.K. Fellman. 1987. Indicators of maturity and storage quality of 'Rainer' sweet cherry. HortScience 22:283-285.
- Facteau, T.J. 1982. Relationship of soluble solids, alcohol-insoluble solids, fruit calcium, and pectin levels to firmness and surface pitting in 'Lambert' sweet cherry fruit. J. Amer. Soc. Hort. Sci. 107:151-154.
- Facteau, T.J. and K.E. Rowe. 1979. Factors associated with surface pitting of sweet cherry. J. Amer. Soc. Hort. Sci. 104:706-710.
- Harker, F.R., J.H. Maindonald, and P.J. Jackson. 1996. Penetrometer measurement of apple and kiwifruit firmness: Operator and instrument differences. J. Amer. Soc. Hort. Sci. 121:927-936.
- Kenworthy, A.L. and L. Silsby. 1974. Red tart cherry fruit quality: Measuring fruit firmness objectively. Michigan State Univ. Agr. Expt. Sta. Res. Rpt. 253.
- Lesage, P. and M.F. Destain. 1996. Measurement of tomato firmness by using a nondestructive mechanical sensor. Postharvest Biol. Tech. 8:45-55.
- Lidster, P.D., S.W. Porritt, M.A. Tung, and P.W. Voisey. 1978. A texture measurement technique for sweet cherries. HortScience 13:536-538.
- Lidster, P.D. and M.A. Tung. 1979. Identification of deformation parameters and fruit response to mechanical damage in sweet cherry. J. Amer. Soc. Hort. Sci. 104:808-811.
- Lustig, I. and Z. Bernstein. 1987. An improved firmness tester for juicy fruit. HortScience 22:653-655.
- Mohsenin, N.N. 1986. Physical properties of plant and animal materials. 2nd ed. Gordon and Breach, New York.
- Proebsting, E.L., Jr., and A.S. Murphey. 1987. Variability of fruit quality characteristics with sweet cherry trees in central Washington. HortScience 22:227-230.
- Younce, F.L. and D.C. Davis. 1995. A dynamic sensor for cherry firmness. Trans. Amer. Soc. Agr. Eng. 38:1467-1476.