Reprinted from Vol. 109(2), March 1984
Journal of the American Society for Horticultural Science
Alexandria, VA 22314

J. Amer. Soc. Hort. Sci. 109(2):221–228. 1984.

Sensory and Instrument Measurement of Apple Texture

Judith A. Abbott, Alley E. Watada, and David R. Massie
Horticultural Science Institute, U.S. Department of Agriculture, ARS, Beltsville Agricultural Research Center, Beltsville, MD 20705

Additional index words. *Malus domestica*, maturity, storage, quality, mechanical properties, firmness

Abstract. **The relationships among selected sensory textural attributes and data from modified Instron texture profile analysis (force/deformation curves obtained in compression of tissue cylinders) were examined for 'Golden Delicious', 'Rome Beauty', 'York Imperial', 'Redspur Delicious', and 'Miller Sturdy Spur Delicious' apples (*Malus domestica* Borkh.). Sensory crispness, hardness, and toughness were closely related to each other and to Instron texture profile forces at breakpoint (yield), failure, and 75% compression and to work energy in compression and rebound. Correlations of sensory attributes with the best single Instron texture profile variables were similar to those with Magness-Taylor penetration force (measured on an Instron); however, combinations of several texture profile variables in regression equations generally improved prediction of sensory attributes. Experimental Instron texture profile variables, especially force near midcompression, or the experimental variations on the customary variables, such as mean forces around failure and around full compression, were selected for prediction equations more frequently than the customary variables.**

The relative importance of texture as a quality attribute varies among types of fresh fruits and is greatest for firm, fleshy fruits such as apples and pears (8). Texture, as a general term, is often used to encompass both sensory reactions and mechanical responses of the food material to applied forces. Most horticultural studies of texture have related mechanical measurements to fruit maturity or to resistance to mechanical injury. Few studies have been undertaken to correlate mechanical properties with sensory attributes of fresh fruits and vegetables. Most sensory evaluations of apples reported in the literature are based on hedonic terms and scales (relating to pleasure or acceptability) rather than on intensities of defined attributes and so they cannot be used to determine the mechanical properties involved in sensory evaluation of specific textural attributes.

Williams and Carter (20) developed a vocabulary and method

Received for publication 13 Apr. 1983. Reference to a specific brand or firm name does not constitute endorsement by the USDA over others of a similar nature not mentioned. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

for evaluating all sensory aspects of quality of 'Cox's Orange Pippin' apples, including defects and appearance, texture, and flavor. The textural terms selected were hardness, toughness, crispness, and flouriness (presumably equivalent to mealiness).

The term "firmness" may be preferable to "hardness" in describing food texture so as not to conflict with mechanical engineering definitions (14); however, Boyd and Sherman (6) report that consumers' use of the term hardness does not correspond with the usage by material scientists but agrees with the definition of the General Foods sensory texture profile (10), i.e., force required to compress a solid substance between molar teeth. Sensory toughness is manifested by high, persistent resistance to breakdown on mastication (15) and should relate to rupture energy in mechanical tests (14). Although it has been proposed (18, 19) that crispness is an acoustical phenomenon, crispness often has been related to mechanical characteristics. For example, in sensory analysis of almonds (16), crispness tended to follow sensory hardness or fracturability, depending on the panelist.

Instrument texture profiles of many foodstuffs have been made using General Foods texturometers or Instron universal testing instruments (7); however, systematic comparisons of instrument texture profile variables with sensory attributes of apples have not been published. The mechanically measured properties most often used to define textural characteristics are force, deformation, and elasticity. Apparent elasticity is the rate of change of force with respect to deformation, often calculated as slope from the initial straight portion of a compression force/deformation curve. The point at which to determine slope and the method of measuring slope are subject to many interpretations (14). Finney (11) has recommended that "firmness" of fruits and vegetables be defined as elasticity measured under small-deformation conditions (not to exceed 1% and where no yielding occurs). Bourne (5) defines small-deformation for foods as less than 25% absolute deformation or less than 50% of the rupture deformation, whichever is less. Bourne (4) characterized "crispness' as resistance to deformation under load up to the point of sudden fracture and suggested that this characteristic can be measured by elasticity. In the General Foods texture profile, crispness is associated with fracturability, the force at failure or rupture. The yield point is a point on the force/deformation curve prior to the point of maximum force at which there is an increase in deformation with a decrease or no change in force (13). The yield point in apples is often a sharp drop in the curve and is an indication of initial cell rupture. Szczesniak and Smith (17) interpreted the yield point on General Foods texture profile curves as crispness in their study of strawberries. Brennan et al. (9) reported high correlations between sensory crispness scores of apples and shear press maximum force ($r = 0.91$), General Foods Texturometer hardness ($r = 0.87$), and Instron texture profile fracturability ($r = 0.86$).

This study was undertaken to compare, on the same apples, measurements of sensory textural attributes, Magness-Taylor firmness, and texture profile variables, including experimental variables and variations of the customary variables.

Materials and Methods

Horticultural conditions. The cultivars used—'Golden Delicious' (Goldens), 'Rome Beauty' (Romes), 'York Imperial' (Yorks), and 2 strains of Delicious, 'Redspur' (Redspurs) and 'Miller Sturdy Spur' (Millers)—were selected for diverse flavor and texture characteristics. All 5 cultivars were tested the first year; only Goldens and Yorks were tested the 2nd year. Each was harvested from a commercial orchard in Maryland, Pennsylvania, or Virginia over at least a 2-week period centered on the growers' estimated optimum commercial harvest dates for long-term, conventional refrigerated storage. For each cultivar, about 200 apples (70- to 85-mm-diameter) were picked from the same 4 trees on each harvest date. The apples were sorted, treated with ethoxyquin, air-dried for 2 to 3 hr, and placed in pulp trays in apple cartons lined with perforated polyethylene bags. Fruit were stored in air at 0°C and 95% relative humidity at Beltsville for about 0, 10, and 20 weeks. Fruit were analyzed immediately after removal from storage or after ripening for 1 week at 20°.

Experimental arrangement. In the first season, the design for each of 5 cultivars was 4 harvests × 3 storage durations × 2 ripening periods. One lot of 10 apples was examined immediately after removal from storage (no ripening) and 2 lots were examined after 1 wk of ripening. Instrument measurement values were averaged over the 10 apples per lot for all statistics reported herein; therefore, $n = 36$, except Yorks were harvested only 3 times so $n = 27$. In the 2nd season, the design for each of 2 cultivars was 3 harvests × 3 storage durations × 2 ripening periods × 2 days of testing × 2 panels × 2 apples per session; thus, $n = 144$ for each cultivar.

Mechanical measurements. Magness-Taylor and modified texture profile tests were made on an Instron Model TM interfaced to a Nova computer (Data General Corp.) for controlling the Instron and for directly collecting all data (1, 2). Tests were performed at a crosshead speed of 25.4 mm/min.

The Magness-Taylor (MT) tests were made as previously described (3) with an 11.1-mm MT probe mounted in the Instron. The Instron/computer was programmed to allow the MT probe to penetrate 7.94 mm after contact and to determine and record the maximum force and the deformation at that force. The mean of MT tests on the blush and opposite sides was calculated and then labelled FMTI and DMTI for force and deformation, respectively.

For texture profiles, a radial specimen was removed midway between the MT test sites, using a 15.0-mm-diameter cork borer mounted in a manual drill press. The section was inserted skin-end first into a device which removed a 2.5-mm slice including the skin and cut a 10.0-mm-thick specimen. The Instron/computer was programmed to tare the load cell on command, then to lower the compression plate mounted on the Instron crosshead, detect contact with the specimen, compress the specimen to 2.5 mm thick, then to reverse the crosshead and move the compression plate upward, constantly reading the load cell output (force) (2). The computer recorded a force value every 0.0254 mm; each record contained 295 force values for compression and 105 for rebound. Fig. 1 illustrates a specimen compressed beyond failure. The customary Instron texture profile variables measurable on the first compression/rebound cycle and several variations and experimental variables (1, 2) were measured on each curve (Fig. 2, Table 1). Acronyms for the texture profile variables are defined in Table 1.

Sensory analysis. Panelists were technical and nontechnical personnel of the USDA Beltsville Agricultural Research Center, selected for at least normal acuity in both texture and flavor perception and ability to verbalize and quantify sensory information, as indicated by their ability to describe 30 natural and synthetic odors, ability to rank series of food standards, and general agreement with other panelists during training sessions. After screening and training, 17 persons participated in panels the first season and 14 the 2nd season. Twelve sessions during the first season were devoted to training panelists and developing

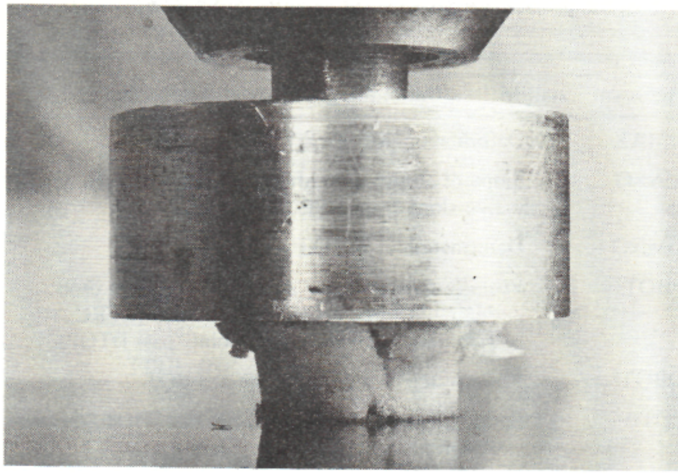

Fig. 1. Apple specimen compressed beyond failure in Instron texture profile.

the flavor and texture terms used; 8 training sessions were held during the 2nd session. During training, panelists were given the food samples anchoring the various scales of the General Foods sensory texture profile (10). Apples of several cultivars and a wide range of maturities were sampled and described qualitatively and/or quantitatively.

Crispness was the characteristic of primary interest and one for which adequate definition does not exist. A working definition for crispness in apples was developed by the panel: a buildup of pressure is sensed, then an abrupt drop in pressure as the tissue breaks or shatters. The tissue splits cleanly and audibly along a plane ahead of the teeth, seeming to break rather than being cut. Crispness can persist through several chews; therefore, it was analyzed over the initial bite and first 5 chews.

Hardness was defined as the force required to compress or crush the tissue between the molars (10) during the first few chews. Toughness was defined as the force required to cut the tissue with the teeth and was related to the amount of residual material left after several chews.

Testing was done under normal room light. Since the apple skin was removed for mechanical tests, panelists peeled the apple wedges before evaluating texture. Panelists were instructed to place the peeled wedge between their incisors with the core edge up for the initial bite so that biting was along a radial axis, since this was the orientation for the instrument tests.

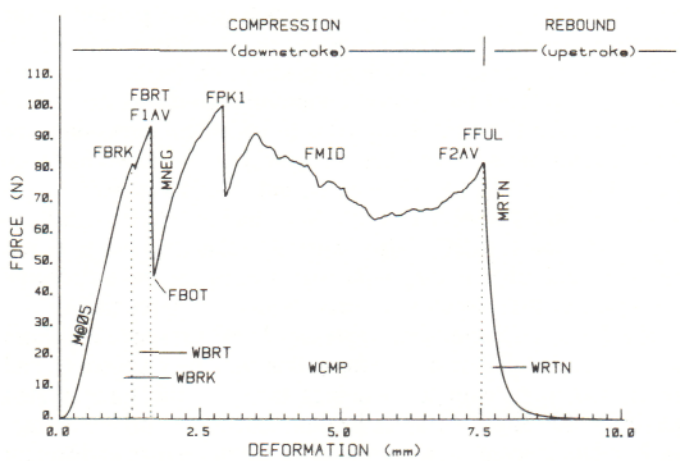

Fig. 2. Selected variables on Instron texture profile curve of 'Golden Delicious' apple tissue.

Two experimental arrangements were used for sensory evaluations: 10-apple composites were evaluated during the first season and individual apples during the 2nd season. In the first season, 3 wedges from each of 10 apples were combined in a bowl and each panelist took 3 random wedges. At least 6 trained panelists evaluated both texture and flavor of 1 to 4 composite samples at each session. Intensities of CRISP, HARD, TOUGH, MEALY, and JUICY were rated using category scales, 0 = not detectable to 7 = extremely strong. Two pools of 7 panelists were formed in the 2nd season and parallel panel sessions were conducted with 4 panelists evaluating the texture of 2 apples (and flavor of 2 other apples, not reported here) at each session. Each apple was cut into 8 wedges and each panelist was given one wedge; wedges where instrument tests were made were discarded. Intensities of CRISP, HARD, TOUGH, MEALY, SPONGY, and JUICY were rated on unstructured, 100-point scales (lines 100-mm-long, labelled LOW and HIGH at the ends); scores were distances in mm from the LOW end.

Statistical analyses. Horticultural variables were analyzed by fitting orthogonal polynomials (12). Variations in sensory data due to differences in scaling by individual panelists were minimized by standardizing scores to $\bar{x} = 0$ and $s = 1$ within each panelist each year, over all horticultural variables (12). Panel means were then calculated and used for all further analyses.

Relationships among measurement variables were studied using standard correlation, regression, and principal component factor analyses (12). Coefficients of determination are symbolized by r^2 for simple regressions, by R^2 for multiple regressions where there could be ≥ 1 variable in the model, and by R^2 in table headings where both simple and multiple regressions are summarized.

Factor analysis is a data reduction tool which groups related variables into factors (sets of highly correlated variables), each factor representing a pattern in the matrix of simple correlations among all variables. The first factor generally accounts for the majority of the variation in the data and usually represents the general relationship among the variables. Each successive factor represents more specific relationships. The coefficient of the factor, called a loading, may be interpreted as a correlation coefficient relating a particular variable to the given factor. If one or more variables load highly on the given factor, then the factor may be interpreted as representing an underlying principle measured by those variables. A variable which loads highly on more than one factor is said to be complex, i.e., is related to several factors.

Results and Discussion

Horticultural variables. Cultivars differed significantly in most of the variables measured and so they were further analyzed separately. Harvests, storage durations, and ripening significantly affected essentially all measurement variables; most interactions were significant. General condition and variability of the cultivars are indicated by the values for selected variables in Table 2. Typical changes in texture profile curves during storage are illustrated in Fig. 3.

Measurement variables. Correlations among CRISP, HARD, and TOUGH were high and positive, indicating that panelists perceived these variables to be closely related (Table 3). Relationships of MEALY, JUICY, and SPONGY to CRISP, HARD, and TOUGH were inconsistent and differed among cultivars and among panelists. Millers, Redspurs, and Yorks generally had lower correlations among various textural measurements (e.g., Yorks in Table 3) than did Goldens and Romes, probably because

Table 1. Names or acronyms[z] for Instron texture profile variables extracted from compression force/deformation curve, progressing from contact through reversal to termination (see Fig. 2).

Acronym	Definition and derivation of acronym
Contact	Contact threshold (force > 0.11 N)
M@05	Slope at 0.5 mm, a measure of elasticity (apparent E = M@05/128.46 mm^2)
MBRK	Maximum slope to breakpoint, maximum slope between contact and zero derivative, a measure of elasticity (apparent E = MBRK/128.46 mm^2)
DMBK	Deformation at MBRK
FBRK	Force at breakpoint (first break in curve), "yield force" (14), force where slope first drops below 0.5 MBRK
DBRK	Breakpoint, "yield point" (14), deformation at FBRK
WBRK	Work to breakpoint, area under curve to DBRK
FFRC	Force at "fracturability" (7), failure or rupture; maximum force at zero derivative
DFRC	Deformation to FFRC
WFRC	Work to fracture, area under curve to DFRC
FTOP[y]	*Visually selected* rupture force, force at top of abrupt drop in curve
DTOP[y]	*Visually selected* rupture deformation, D at FTOP
F1AV	Average force of first major peak, mean force DBRK to (DBRK + 1.0 mm)
MSDV	SD of the slope from DBRK to (DBRK + 1.0 mm), measure of abruptness of rupture
FMAX	Maximum force in first 5.0 mm, usually identical with FFRC, intended for comparison with maximum force in Magness-Taylor measurement
DMAX	Deformation at FMAX
MNEG	Slope of abrupt drop after rupture, maximum negative slope from DFRC to 7.5 mm
DMNG	Deformation at MNEG
FBOT[y]	*Visually selected* force at bottom of abrupt drop, minimum force between DFRC and (DFRC + 0.76 mm) (within 30 data points past DTOP)
DBOT[y]	*Visually selected* deformation at FBOT
FDTB[y]	Force difference between FTOP and FBOT, measure of abruptness and extent of failure
DDTB[y]	Deformation difference between DTOP and DBOT, measure of abruptness of failure
FMID	Mean force midway between DBRK and 7.5 mm for a distance of 1.0 mm
F2AV	Average force of final peak, mean force from 6.5 to 7.5 mm
FFUL	Force at full compression, texture profile "hardness" (7), force at crosshead reversal or 7.5 mm
7.5 mm	Crosshead reversal, "full" compression of 75% initial sample height
WCMP	Work to compress, area under curve to 7.5 mm
MRTN	Maximum slope during crosshead return stroke, maximum slope of rebound curve
DMRN	Deformation at MRTN (distance past crosshead reversal + 7.5 mm)
WRTN	Work returned on rebound, area under curve from 7.5 mm to 10.1 mm
10.1 mm	Termination

[z]Acronyms for the texture profile variables are 4-character words, e.g., FBRK or DFRC. The first letter defines the type of measurement represented: F = force; D = deformation; W = work energy or area under the curve; and M = slope. The remaining 3 characters identify which F, D, W, or M; e.g., BRK for breakpoint and FRC for fracturability. All slopes (M) were determined as the first derivative at data point i by the formula $M_i = [0.5(F_{i+3} + F_{i+2}) - 0.5(F_{i-3} + F_{i-2})]/0.127$ mm, where F_i represents the force at data point i and 0.127 mm is the deformation over which the slope is calculated.

[y]Variables measured only 2nd season.

these 3 cultivars tended to vary less than Goldens and Romes (Table 2).

Correlations between sensory values and force at each of the 400 individual data points making up each Instron texture profile curve were nonsignificant (data not shown), indicating that force values at specified deformations were not meaningful and confirming the need to use defined mechanical events such as yield or failure.

Correlations among the instrumental texture profile variables were generally high (data not given). This was expected since all of those variables were measured on single compression tests of individual specimens and several of the variables were merely variations in the way specific features of the compression curve were measured. The intercorrelation of texture profile variables is reflected in the factor analysis results, with most variables loading highly on a single factor.

Factor analysis solutions differed among cultivars in details (numbers of factors and loading values), but were similar in patterns. Factor 1 accounted for a much greater portion of the variance than did succeeding factors in all cultivars (Table 4). Based on the variables with high loadings on factor 1, factor 1 seems to represent the general underlying structural strength of the tissue. All instrument variables in which compression force was an element (acronyms beginning with F, W, or M) had high loadings on factor 1. CRISP, HARD, and TOUGH related strongly to factor 1 and MEALY and SPONGY had relatively high loadings on factor 1. JUICY also generally related to factor 1; juiciness would relate to turgor pressure and turgor should account for a part of the overall structural strength of apple tissue.

The basic characteristics represented by subsequent factors were not clear (Table 5). Deformation variables generally had lower and more complex loadings than did the force-related variables. Based on variables loading moderately highly on factor 2, factor 2 seems to represent different properties in different cultivars and in different seasons. Factor 2 in Goldens relates to deformation at breakpoint the first year but to the deformation

Table 2. Minimum and maximum values of selected variables, by cultivar.

Variable	Composites[z]					Individuals[y]	
	Goldens	Millers	Redspurs	Romes	Yorks	Goldens	Yorks
n[z,y]	36	36	36	36	27	140	144
FFRC (N)							
Min	35.6	48.2	43.4	46.8	55.5	34.8	43.4
Max	90.0	97.2	92.5	121.5	81.2	106.9	138.9
FMID (N)							
Min	18.7	28.8	28.1	11.3	50.8	15.8	36.1
Max	80.0	80.8	70.8	92.7	98.6	112.0	149.5
FFUL (N)							
Min	21.8	43.7	36.2	35.6	52.1	20.2	42.0
Max	96.2	107.1	92.5	115.6	128.1	107.3	183.3
WCMP (Nmm)							
Min	135.7	226.5	209.8	143.6	349.9	133.6	268.2
Max	517.0	546.4	501.5	616.8	645.4	651.8	972.6
FMTI (N)							
Min	25.9	41.8	37.4	40.6	44.9	26.6	50.4
Max	67.7	78.3	69.8	84.5	86.7	88.6	131.9
HARD, raw[x]							
Min	1.5	3.0	2.3	1.7	3.7	3.9	23.5
Max	5.0	5.1	5.1	5.5	5.7	75.0	88.0
HARD, standardized[w]							
Min	−1.5	−0.5	−0.8	−1.4	0.1	−1.6	−0.7
Max	0.8	1.0	1.0	1.4	1.4	1.2	1.9

[z]First year, used means of 10 apples for instrument variables and 10-apple composites for sensory variables.
[y]Second year, used values for individual apples.
[x]Means of raw scores for 10-apple composites scored 0–7 by 6–10 panelists or means of raw scores for individual apples scored 0–100 by 4 panelists; higher scores indicate stronger intensity.
[w]Means of scores in x above, averaged after they were standardized to $\overline{x} = 0$ and $s = 1$ within each panelist.

at failure the 2nd season. Factor 2 relates to both deformation and force at failure in 2nd-season Yorks. Subsequent factors generally were based on single variables which differed among cultivars, with the exception that factor 3 in 2nd-season Yorks contained several variables related to the extent of failure of the tissue.

Regression of sensory attributes on instrument measurements. The ultimate test of the validity of instrument measurements for estimating quality must be their success in predicting sensory measurements on the same samples. It must be possible to estimate one or more of the sensory variables using the instrument variables in regression equations (Table 6). The sensory texture of Goldens and Romes could be estimated relatively well and, with the exception of SPONGY, using more than one variable in the regression equation did not substantially improve prediction. None of the sensory variables could be satisfactorily predicted for Millers, Redspurs, or Yorks (R^2 values were <0.80). These 3 cultivars changed less during storage than did Goldens

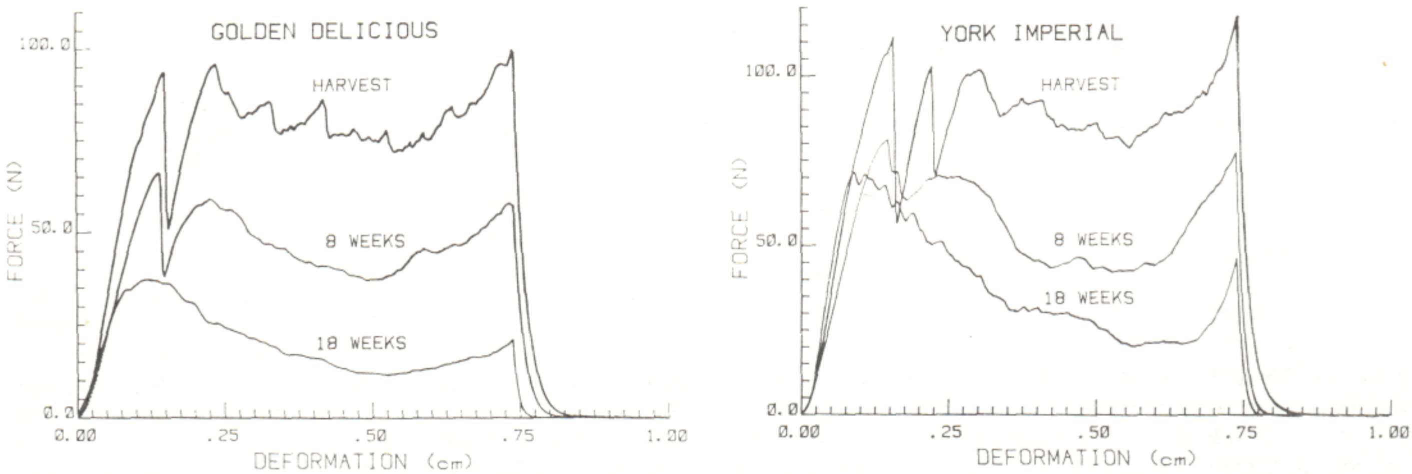

Fig. 3. Instron texture profile curves of representative individual 'Golden Delicious' and 'York Imperial' apples after each storage period (no ripening).

Table 3. Correlation coefficients (r) among sensory textural attributes for first season Goldens, Romes, and Yorks.

Cultivar	Variable	Variable: CRISP	HARD	TOUGH	MEALY	SPONGY	JUICY
Goldens	CRISP	1.00[z]	0.94	0.88	−0.73	0.57	0.81
	HARD		1.00	0.93	−0.66	0.61	0.69
	TOUGH			1.00	−0.70	0.70	0.62
Romes	CRISP	1.00	0.96	0.95	−0.92	0.62	0.94
	HARD		1.00	0.95	−0.90	0.62	0.94
	TOUGH			1.00	−0.88	0.63	0.91
Yorks	CRISP	1.00	0.84	0.53**	−0.45*	NS	0.66
	HARD		1.00	0.62	−0.52**	0.38*	0.54*
	TOUGH			1.00	NS	0.44*	NS

[z]Significance is assumed to be $P \leq 0.1\%$ unless indicated: * = $P \leq 5\%$, ** = $P \leq 1\%$, or NS = nonsignificant.

Table 4. Percentage of variance accounted for by significant factors in principal component analyses.

Factor no.	Composites (%): Goldens	Millers	Redspurs	Romes	Yorks	Individuals (%): Goldens	Yorks
1	76.8	63.4	60.0	84.3	65.5	65.3	41.8
2	8.8	13.3	12.5	5.3	7.1	7.2	13.8
3	---	6.5	7.3	---	4.9	5.0	7.5
4	---	3.7	3.9	---	4.1	3.0	6.0
5	---	3.0	3.8	---	3.8	2.6	5.1
6	---	---	3.1	---	---	2.4	4.0
7	---	---	---	---	---	---	2.8
8	---	---	---	---	---	---	2.5
Residuals	10.3	10.1	9.4	10.4	14.6	14.5	16.5

Table 5. Summary of variables loading highly on principal component factors other than factor 1 (loadings of 0.80 to 1.00); variables in parentheses had loadings of 0.50–0.79.

Factor	Composites: Goldens	Millers	Redspurs	Romes	Yorks	Individuals: Goldens	Yorks
2	DMBK	DMBK	(DMBK)			(DBOT)	DBOT
	(DBRK)	(DFRC)	(DFRC)		(DFRC)	(DFRC)	DFRC
		(DMTB)	(DMAX)			(DTOP)	DTOP
			(CRISP)		(CRISP)	(DMNG)	WFRC
			(HARD)		(JUICY)		(FFRC)
			(MEALY)				(FTOP)
							(FBOT)
3	(DMTB)	(JUICY)	(DMTB)			(DBRK)	(DMNG)
							(MNEG)
							(MSTD)
							(FBOT)
							(FDTB)
4		(DMAX)			SPONGY	(DDTB)	
5			(DMAX)		(DMTB)		
6			(DMRN)			(DDTB)	

or Romes (Table 2), but there were significant changes in both sensory scores and instrument measurements. Any single Instron texture profile variable could account for only about half of the variation in CRISP, HARD, or TOUGH scores and even less in MEALY, SPONGY, or JUICY. Combinations of several Instron texture profile variables substantially improved the estimations of some sensory variables, such as MEALY for Redspur. The sensory textural characteristics of Yorks apparently were not measured adequately.

Magness-Taylor firmness (FMTI) did not successfully estimate the intensities of most characteristics for Millers, Redspurs, or Yorks (Table 5). FMTI was an acceptable predictor of CRISP,

Table 6. Coefficients of determination for sensory variables vs. FMTI, best single texture profile variable, and best stepwise multiple regression model based on texture profile variables.[z]

Attribute	Composites										Individuals			
	Goldens		Millers		Redspurs		Romes		Yorks		Goldens		Yorks	
	R^2	Variable	R^2	Variable	R^2	Variable	R^2	Variable	R^2	Variable	R^2	Variable	R^2	Variable
CRISP														
FMTI	0.85		0.52		0.43		0.86		0.33		0.80		0.35	
Single[y]	0.85	WRTN	0.58	FMID	0.57	FMID	0.91	FMID	0.48	F1AV	0.82	F2AV	0.49	F2AV
Multiple[x]	0.85	WRTN	0.70	FMID	0.73	FMID	0.93	FMID	0.48	F1AV	0.82	F2AV	0.50	F2AV
				DMBK		MBRK		F1AV						DMAX
				MRTN				FBRK						
HARD														
FMTI	0.83		0.53		0.42		0.88		0.50		0.77		0.48	
Single	0.87	WRTN	0.58	WCMP	0.57	FMID	0.91	WCMP	0.51	FFRC	0.80	F2AV	0.54	F2AV
Multiple	0.90	WRTN	0.58	WCMP	0.73	FMID	0.93	WCMP	0.51	FFRC	0.80	F2AV	0.54	F2AV
		FFUL				M@05		FMAX						
								DBRK						
TOUGH														
FMTI	0.88		0.63		0.50		0.85		0.41		0.73		0.50	
Single	0.93	FBRK	0.67	MRTN	0.62	FMID	0.89	FMID	0.47	MRTN	0.77	F2AV	0.52	F2AV
Multiple	0.93	FBRK	0.67	MRTN	0.74	FMID	0.90	FMID	0.47	MRTN	0.77	F2AV	0.54	F2AV
						MBRK		M@O5						FMID
						DMRN								
MEALY														
FMTI	0.50		0.37		0.22**		0.77		0.22*		0.59		0.27	
Single	0.52	F1AV	0.42	WCMP	0.37	FMID	0.80	WCMP	0.26**	MSDV	0.68	WCMP	0.31	
Multiple	0.52	F1AV	0.53	WCMP	0.74	FMID	0.83	WCMP	0.26**	MSDV	0.68	WCMP	0.31	F2AV
				FMAX		MBRK		DMRN						
						DFRC								
						F1AV								
SPONGY														
FMTI	0.44		0.38		0.18*		0.35		0.34		---		---	
Single	0.50	FBRK	0.42	MRTN	0.30	DBRK	0.38	FMID	0.45	WCMP	---		---	
Multiple	0.63	FBRK	0.42	MRTN	0.40	DBRK	0.58	FMID	0.72	WCMP	---		---	
		MSDV				DMAX		FFUL		MSDV				
								F1AV		DMBK				
JUICY														
FMTI	0.63		0.34		0.44		0.89		0.16*		0.38		NS	
Single	0.78	M@05	0.38	FMID	0.47	FMID	0.91	WCMP	0.19*	F1AV	0.50	F2AV	0.17*	WRTN
Multiple	0.94	M@05	0.38	FMID	0.47	FMID	0.93	WCMP	0.19*	F1AV	0.62	F2AV	0.28**	WRTN
		DMAX						DFRC				WBRK		FMAX
		MRTN										WCMP		M@05
		DMBK										FMAX		MBRK
		DFRC										FTOP		
		FMID												

[z]Significance of regression model is assumed to be P ≤ 0.1% unless indicated: * = P ≤ 5% and ** = P ≤ 1%. P to enter and to stay = 5% for individual steps of stepwise multiple regression.
[y]Best single Instron texture profile variable.
[x]Best stepwise multiple regression model using Instron texture profile variables, listed in sequence of selection.

HARD, and TOUGH for Goldens and Romes. The r^2 value for FMTI was comparable in most cases to the r^2 for the best single Instron texture profile variable (Table 6).

It was implied in the panel's working definition of crispness that crispness was associated with events in the first compression peak of the texture profile curve, specifically with the force required for failure of the tissue and with the abruptness of the failure. Others have related crispness to initial slope of the curve (elasticity) and to force at yield or at failure (7). Therefore, the correlations between CRISP and mechanical events during compression through failure (first peak variables) were examined closely. The variables selected in stepwise regression analyses of CRISP on Instron texture profile variables are summarized in Table 6. The instrument variable which correlated most highly with CRISP differed among cultivars but was most frequently FMID, which probably best measures overall strength. The equations for CRISP for Goldens did not include any peak 1 variables. Of the variables selected for Romes, F1AV and FBRK relate to peak 1 but are variables not ordinarily measured in texture profile analyses. Crispness could not be estimated as well for the remaining cultivars, but the first variable selected was FMID for both Millers and Redspurs. Best Instron texture profile regression models included MBRK for Redspurs and DMBK for Millers, maximum initial slope and its location, respectively; neither is measured ordinarily in texture profile analyses. F1AV was the only significant variable for composite Yorks and F2AV and DMAX were selected for individual Yorks; however, the R^2 values were extremely low in both instances.

Similarly, the Instron texture profile variables most highly correlated with hardness were examined. Force at maximum compression customarily is defined as hardness in texture profile analyses (7). FFUL was selected as the 2nd variable for composite Goldens but neither FFUL nor F2AV was selected for any other cultivar in the first year; F2AV but not FFUL was selected for both culitvars in the 2nd year.

Bourne (5) attributed the lack of a reliable measure of apple texture to high fruit-to-fruit variability, substantial differences among seasons, only moderate softening during storage, and the tendency of attributes to change in different directions and at different rates. The direct comparison of sensory and instrument measurements on the same apples, as described herein, should eliminate variation among fruit and among seasons as causes of failure; however, universal measurements of apple textural attributes were not obtained.

Three possible causes of failure to obtain universal measures of apple texture are failure of the sensory panels to quantify properly the individual sensory attributes, failure of the instrument variables to measure directly the attributes sensed by the panelists, and too narrow a range of possible sensory or instrument values. Failure of the panelists cannot be assumed since satisfactory results were obtained with Goldens in both seasons and with Romes. Lack of relationship between the mechanical properties measured instrumentally and the properties measured by the panelists cannot be ruled out as the source of difficulty. However, this seems improbable because of the success with Goldens and Romes, because both instrument and sensory tests were destructive compressive tests, and because many aspects of the mechanical failure were examined. The problem probably lies in the narrow range of values for the cultivars which were perceived to change less than Goldens and Romes.

Conclusions

Regression of sensory scores on instrument variables could be used to develop prediction equations to estimate sensory textural attributes in those cultivars where the ranges of sensory scores and instrument values were broad. The best single Instron texture profile variable was similar to Magness-Taylor firmness in predicting sensory scores; however, the Instron texture profile variable selected as best differed among cultivars and between years within cultivars. Using combinations of several Instron texture profile variables frequently improved prediction (maximum models in stepwise regression usually contained only 1 or 2 variables but some contained as many as 6 variables). Therefore, when prediction of the sensory textural characteristics of apples is important, as in evaluating effects of preharvest or postharvest treatments on quality, it is recommended that a combination of several variables from a multivariable mechanical measurement such as the Instron texture profile described herein be used instead of a single variable test such as the Magness-Taylor firmness test.

Literature Cited

1. Abbott, J.A. 1982. Sensory and mechanical measurement of fresh apple texture. PhD Thesis, University of Maryland, College Park.
2. Abbott, J.A., D.R. Massie, and A.E. Watada. 1983. Using a computer with an Instron for horticultural texture measurements. J. Texture Studies 13:413–422.
3. Abbott, J.A., A.E. Watada, and D.R. Massie. 1976. Effe-gi, Magness-Taylor, and Instron fruit pressure testing devices for apples, peaches, and nectarines. J. Amer. Soc. Hort. Sci. 101(6):698–700.
4. Bourne, M.C. 1966. Measurement of texture. Frontiers in Food Res. 1:81–97.
5. Bourne, M.C. 1979. Rupture tests vs small-strain tests in predicting consumer response to texture. Food Technol. 33:67–70.
6. Boyd, J.V. and P. Sherman. 1975. A study of the force compression conditions associated with hardness evaluation in several foods. J. Texture Studies 6:507–522.
7. Breene, W.M. 1975. Application of texture profile analysis to instrumental food texture evaluation. J. Texture Studies 6:53–82.
8. Brennan, J.G., R. Jowitt, and A.M.A. Mohamed. 1977. Instrumental measurement of fruit texture: a study on apples. Ann. Appl. Biol. 87:121–127.
9. Brennan, J.G., R. Jowitt, and O.A. Mughsi. 1970. Some experiences with the General Foods Texturometer. J. Texture Studies 1:167–184.
10. Civille, G.V. and A.S. Szczesniak. 1973. Guidelines to training a texture profile panel. J. Texture Studies 4:204–223.
11. Finney, E.E. 1969. To define texture in fruits and vegetables. Agr. Eng. 50:462–465.
12. Helwig, J.T. and K.A. Council, eds. 1979. Statistical analysis system user's guide. Statistical Analysis System Institute, Inc., Raleigh, N.C.
13. Jowitt, R. 1974. The terminology of food texture. J. Texture Studies 5:351–358.
14. Mohsenin, N.N. 1970. Application of engineering techniques to evaluation of texture of solid food materials. J. Texture Studies 1:133–154.
15. Mohsenin, N.N. 1970. Physical properties of plant and animal materials. Vol. I. Structure, physical characteristics and mechanical properties. Gordon and Breach Science Pub., New York.
16. Sterling, C. and M.J. Simone. 1954. Crispness in almonds. Food Res. 19:276–281.
17. Szczesniak, A.S. and B.J. Smith. 1969. Observations on strawberry texture, a three-pronged approach. J. Texture Studies 1:65–89.
18. Vickers, Z.M. and M.C. Bourne. 1976. Crispness in foods—a review. J. Food Sci. 41:1153–1157.
19. Vickers, Z.M. and M.C. Bourne. 1976. A psychoacoustical theory of crispness. J. Food Sci. 41:1158–1164.
20. Williams, A.A. and C.S. Carter. 1977. A language and procedure for the sensory assessment of Cox's Orange Pippin apples. J. Sci. Food Agr. 28:1090–1104.