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Texture of parenchymatous plant tissue: a comparison between tensile and other instrumental and sensory measurements of tissue strength and juiciness

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Abstract

The cellular basis of textural diversity in selected fruit and root tissue has been investigated using tensile measurements of tissue strength. The mechanism of tissue failure, either cell rupture or cell-to-cell debonding, was determined by examining the fracture surface using Low Temperature Scanning Electron Microscopy (LTSEM). Information provided by tensile measurements was compared with that provided by sensory and other instrumental measurements of tissue hardness and juiciness. Instrumental measurements included penetrometer, Kramer shear cell, apparent juice content, and juice release from a freshly cut surface. During tensile testing, the shape of the force-distance curve, along with maximum force and information on the cause of tissue failure were able to provide a comprehensive characterization of the texture. However, measurements of tensile strength, along with measurements of puncture strength and shear strength, showed a curvilinear relationship with sensory assessments of tissue hardness. This curvilinear relationship is fundamental to the psychophysical basis of human perception of texture. We speculate that the psychophysical laws that govern the relationship between mechanical hardness of a tissue and the associated sensory response may provide a major limitation to further improvements in the instrumental measurement of texture. We also discuss the use of instrumental measurements of juiciness to evaluate fruit quality. © 1997 Elsevier Science B.V.

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1. Introduction

Measurement of texture is an important aspect of objective assessment of quality in fruit and

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vegetables (Bourne, 1980; 1982). Methods for measuring fruit texture include trained analytical sensory panels, and a wide range of instrumental techniques, of which puncture tests (penetrometer) and whole fruit compression tests are the most common (Mohsenin, 1977; Harker et al., 1997b). An important aspect of fruit texture is juiciness (Szczesniak and Ilker, 1988), which is often measured according to the amount of juice released from tissue during homogenization (Chen and Borgic, 1985; Lill and van der Mespel, 1988). In the past, our research on fruit texture has focused on the use of tensile measurements (Harker and Hallett, 1992, 1994; Harker and Sutherland, 1993). The advantage of tensile measurements is that following tissue failure, fracture surfaces can be examined visually using Low Temperature Scanning Electron Microscopy (LT-SEM). Such an examination of the fracture surface can indicate whether tissue failure occurs as a result of cell rupture or cell-to-cell debonding, and indicates whether cells are covered by a layer of juice. We have demonstrated clear differences between juicy and dryish texture in apples (Harker and Hallett, 1992) and nectarines (Harker and Sutherland, 1993). Dryish texture in apple was associated with failure of cells to rupture and release their contents during application of tensile tests, while in nectarines dryish texture was associated with a lack of juice on the surface of cells. These results suggest that tensile measurements combined with microscopic examination of the fracture surfaces have the ability to detect differences in both tissue strength and tissue juiciness.

In recent years we have sought to broaden our knowledge of fruit texture. In a series of preliminary studies we have further examined the usefulness of tensile measurements. To do this we have screened a range of edible plant tissues and compared results with those obtained using instrumental measurements of tissue strength (Kramer shear cell, penetrometer) and tissue juiciness (apparent juice content, juice release from a cut surface), and an analytical sensory panel. Our approach is similar to that of Szczesniak and Ilker (1988) and Szczesniak et al. (1963), in that selected commodities (in this case fruit and root tissues) were chosen to represent different texture types. Our aim was to provide insight into the cellular basis of plant texture, and particularly to identify those cell characteristics which influence sensory texture attributes 'hardness' and 'juiciness'.

2. Materials and methods

Plant material

Banana (*Musa* AAA group, Cavendish subgroup), watermelon (*Cucumis melo* var. cantalupensis), muskmelon (*Cucumis melo* var. inodorus), and carrot (*Daucus carota* L.) were obtained from a local supermarket, whilst avocado (*Persea americana* cv. Hass) and apple (*Malus domestica* cv. Royal Gala) were obtained from a grower's property at Katikati, Bay of Plenty or the HortResearch Orchard, Hawkes Bay, respectively. Avocados were used in an unripe state, to provide a hard, dry texture. Other fruit were eating ripe. Carrots were included in the study as they are a hard plant tissue which is often consumed in a raw state.

All sensory and mechanical measurements were undertaken using four replicate samples of tissue. Generally, each tissue replicate was from a different fruit, with the exception of water melon and muskmelon when samples were taken from 1 and 2 fruit, respectively. Samples for mechanical testing of flesh firmness and juiciness as well as for sensory analysis were taken from the same fruit.

Penetrometer measurements

A slice of skin was removed from the fruit equator and an Effegi 7.9 mm diameter probe (Effegi, Alfonsine, Italy) was driven 8 mm radially into the flesh of whole fruit using an Instron model 4301 materials testing machine (Instron, Canton, Mass. USA). The puncture speed was 240 mm/min as recommended by Blanpied et al. (1978).

Shear measurements

The particular technique we employ when using the Kramer shear cell has been described earlier (Larsen and Watkins, 1995). A slice of tissue 10 mm thick was taken from close proximity to the site of the penetrometer measurement. Weight of the slice was recorded, before placing in a Kramer shear cell for shear measurements. The metal plates in the shear cell were driven through the tissue at speed of 10 mm/min using an Instron. The maximum force applied during the shear test was divided by tissue weight to correct for differences in the area of tissue bisected by the plates of the shear cell.

Tensile measurements

The method for determining tensile strength of tissue has been described earlier (Harker and Hallett, 1992, 1994; Harker and Sutherland, 1993). Briefly, a block of fruit tissue, with notches cut at each side through the middle to provide a weakened zone (6 mm × 4 mm), is fixed to metal strips and placed between the Instron claws. The claws move apart at a rate of 10 mm/min, stretching the tissue until it breaks. Following tissue failure, samples of the fracture surface are examined by LTSEM to determine the mechanism of cell failure.

Juice absorption

Plugs of tissue were cut with a 19 mm diameter cork borer and the surface blotted dry, before cutting the plug in half using a new razor blade. The two cut surfaces were immediately placed on tissue paper, which had been tared on a balance. After 60 s, tissue was removed and weight of juice absorbed by the tissue recorded with a precision of 0.001 g.

Apparent juice content

Another measurement of juiciness was the cellular integrity test, previously used to determine mealiness in stonefruit (Lill and van der Mespel, 1988; Harker and Sutherland, 1993). Fruit tissue was forced through a 5 ml plastic Lauer syringe, into preweighed microfuge tubes. Weight of tissue in the microfuge tube was recorded, and then the tube was centrifuged for 5 min at $12\,000 \times g$, before removing the supernatant and reweighing the tube. Weight of juice is then presented as a percentage of the initial tissue weight.

Tissue density and juice viscosity

Tissue density was determined on plugs of fruit tissue using methods described by Harker and Hallett (1992, 1994). Juice was extracted from tissue by centrifuging freeze/thawed tissue and collecting the supernatant. Viscosity of the supernatant (juice) was measured using a Haake falling ball microviscometer (Haake, Karlsruhe, Germany).

Analytical sensory panel

Blocks of tissue 1 cm^3 were cut from fruit at a location close to the position of instrumental measurements. Dimensions of samples were limited by size of cortical tissue in carrot and pericarp in banana, and the requirement that tissue be sampled from regions close to instrumental measurements. It was important that samples from all commodities were the same size and that samples be taken from a single tissue zone to reduce sample heterogeneity. Each panellist received samples of all six fruit concurrently but in a randomized order.

Sensory profiles were generated using a trained analytical sensory panel, experienced in sensory assessment of horticultural products, consisting of 15 females and one male. Samples were assessed for intensity of hardness and juiciness. Intensity scores for each attribute were recorded on continuous 15 cm line scales, where 0 = absent and 15 = extreme. Hardness was defined as the force required to compress the sample between the back molars, and juiciness was defined as the amount of juice released from sample during first bite. Due to the small size of the tissue sample no other texture attribute was considered. Assessments were performed in individual sensory booths under controlled conditions. Water purified by reverse osmosis was provided for palate cleansing between samples.

A numerical score was assigned to each rating and the data analyzed by ANOVA. Tukey's least significant difference (LSD) values were calculated from the standard error of the difference.

3. Results

Typical force-distance curves for penetrometer, shear and tensile measurements of different types of fruit are presented in Fig. 1. Generally, there was a steady increase up to a maximum force as the penetrometer probe was driven into the flesh, and there was a reduction in the force required to drive the probe further into the fruit following tissue failure (Fig. 1a). The exception to this was apple and banana, where the force tended to remain constant or slowly decline following initial tissue failure (Fig. 1a). During shear measurements, hard tissues such as unripe avocado and carrot tended to break abruptly, resulting in sharp peaks (Fig. 1b). Softer fruit such as apple, muskmelon, watermelon and banana tended to shear in a more gradual fashion, resulting in rounded peaks in force-distance curves (Fig. 1b). The influence of test speed on maximum force measurements during puncture and tensile tests is presented in Table 1. Maximum force was greater when puncture tests were applied at faster speeds, but there was no significant effect of speed during tensile measurements.

Tensile measurements (Fig. 1c) are related to the fracture surfaces shown in Fig. 2. During tensile tests, apple and watermelon tissue broke apart abruptly as indicated by the sharp peaks on the force-distance curves (Fig. 1c). Unripe avocado and carrot tended to reach a plateau where force remained constant for a short period of extension before tissue failure, resulting in a rounded peak (Fig. 1c). Similar rounded peaks were also observed in force-distance curves for muskmelon and banana, although with these fruit, tissue failure did not occur abruptly. Rather, there was a gradual reduction in force as the tissue was stretched beyond the point where peak load occurred, resulting in a long drawn out tail in the force-distance curves before the tissue finally separated (Fig. 1c). Cells at the surface of fractures in watermelon, apple, carrot and unripe avocado broke apart, whilst cells from banana separated from neighbouring cells without breaking (Fig. 2). Most cells from muskmelon broke apart during tensile testing, although a smaller proportion of the cells separated from neighbours

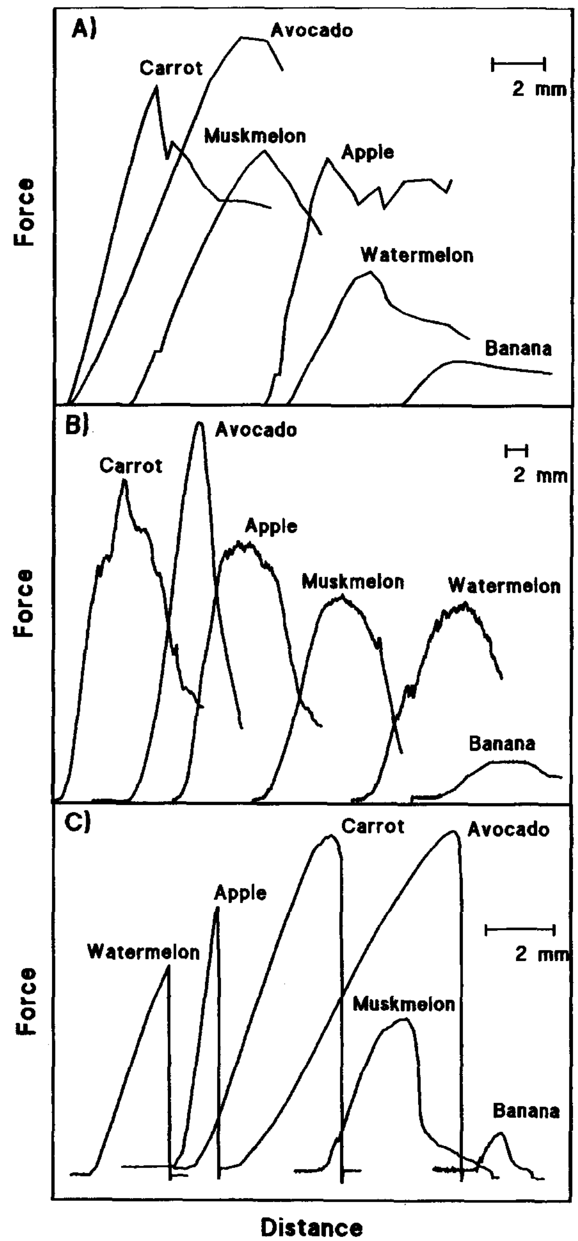

Fig. 1. Force-distance curves obtained during penetrometer (A), shear cell (B), and tensile (C) measurements of fruit texture. Curves are not plotted to scale. Respective maximum forces for banana, muskmelon, water melon, apple, carrot and unripe avocado are given in Fig. 3. Horizontal lines represent a scale of 2 mm.

Table 1
The effect of test speed on mechanical strength of carrot and apple tissue

Type of test	Plant material	Speed of test (mm/min)			
		10	50	100	240
Tensile	Carrot	1196a	1287a	1337a	1221a
Tensile	Apple	220a	238a	246a	223a
Puncture	Carrot	149a	158ab	174c	170bc
Puncture	Apple	24.3a	27.4b	28.2b	30.3c

The tissues were tested using puncture and tensile tests at speeds between 10–240 mm/min.
The values represent the mean maximum force for ten apples or carrots, and units are N and kNm^{-2} for puncture and tensile tests, respectively. Within each row, different letters indicate significant differences LSD; $P<0.05$.

without apparent damage (Fig. 2). The sizes of the cells varied from watermelon (diameter approx 0.5 mm) to avocado (diameter less than 0.05 mm).

Mechanical measurements of fruit hardness vary in their ability to discriminate between textures as defined by sensory analysis. The penetrometer can not discriminate between the texture of muskmelon, watermelon or apple (Fig. 3). Shear measurements were better able to discriminate between textures but still had difficulty with watermelon and muskmelon (Fig. 3). Tensile measurements of fruit hardness showed the closest relationship with sensory evaluation, in that the ranking of increasing tensile strength of the various fruit tissues matched the ranking of flesh hardness according to sensory evaluation.

With the exception of banana, there was a relatively good relationship between juiciness as assessed by mechanical and sensory methods (Fig. 4). Considerable difficulty was experienced in forcing hard tissues through the syringe during the cellular integrity test, and it proved impossible to use this test with unripe avocado.

The dynamic viscosity of fruit juice was 0.89, 0.88, 1.07 and 5.95 mPa/s for carrot, watermelon, apple, and banana, respectively. Density of fruit tissue was 1.03, 1.00, 0.98, 1.00, 0.97 and 0.86 g/ml for carrot, muskmelon, watermelon, banana, avocado and apple, respectively.

4. Discussion

The validity of an instrumental measurement of texture should be based on how well it predicts sensory analysis (Voisey, 1971). Thus, it is useful to examine how force measurements (penetrometer, shear cell, and tension) relate to sensory perception of texture of the different commodities used in this study. Ranking of commodities according to increasing instrumental measurement and increasing sensory measurement was consistent for tensile measurements. However, penetrometer measurements showed little difference between firmness of muskmelon and apple even though substantial difference in sensory perception of hardness was apparent (Fig. 3). Shear cell measurements reversed the ranking of muskmelon and watermelon from that indicated by sensory assessment. Psychophysical relationships between stimulus (in this case hardness) and the resulting sensory sensation are often described by logarithmic and/or power relationships according to Fechner's and Stevens' laws (Meilgaard et al., 1991). Indeed, data obtained by Szczesniak et al. (1963) shows a distinct curvilinear relationship between sensory and instrumental measurements of the textural attributes hardness and brittleness. In a theoretical analysis, Peleg (1980) suggests that there is a sigmoidal relationship between mechanical hardness and its sensory assessment. Mechanical hardness must increase above a threshold before a sensory response is observed, then there is a region of the curve where the mechanical stimulus and sensory responses are

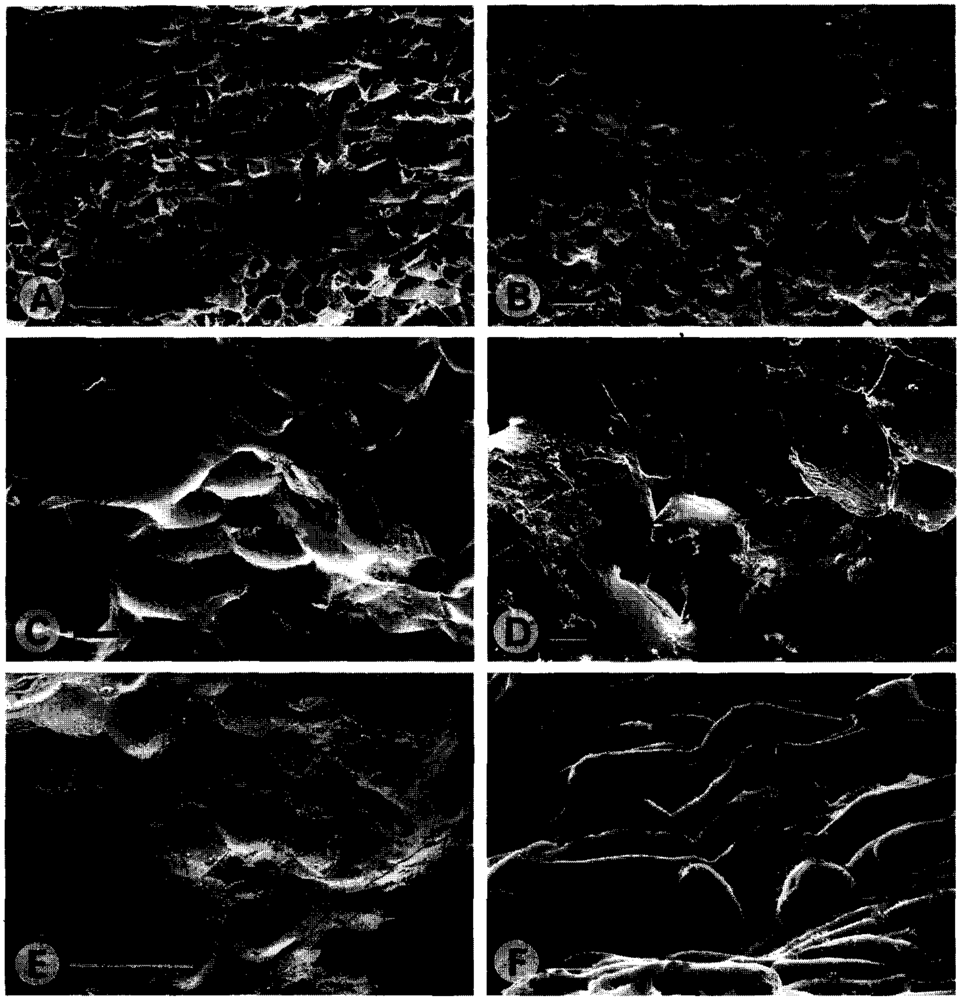

Fig. 2. Fracture surfaces of fruit tissue following tensile tests as observed using Low Temperature Scanning Electron Microscopy. (A) Carrot; (B) Avocado; (C) Apple; (D) Muskmelon; (E) Watermelon; and (F) Banana. Neighbouring cells have separated without breaking in banana, and muskmelon shows a mixture of broken and unbroken cells. The remaining fruit show breakage of all cells on the fracture surface. Bar = 0.1 mm (A, B, C, D, F); 1 mm (E).

described by a 'power law', and this is followed by a plateau where the sensory response is saturated Peleg (1980). In our study there is a clear curvilinear relationship between instrumental measurements and associated sensory responses (Fig. 3). However, neither semilogarthmic nor double logarithmic plots produced a straight line (data not shown). This was not unexpected. Given the range of different commodities examined, it is perhaps too much to expect the data to fit a theoretical relationship. However, psychophysical laws and results from our study suggest that sensory perception of texture is more sensitive than instrumental measurements when soft fruit are being examined. This is an important observation since fruit texture at eating ripeness is most critical in determining consumer responses.

Parenchymatous plant tissues exhibit viscoelastic behaviour in that the ratio of stress to strain changes with strain rate (see Vincent, 1990 for a full description of viscoelasticity). Thus, the rate at which compressive or tensile forces are applied might be expected to have a big impact on values of both maximum force and force at the point of cell rupture. In puncture tests, the effect of the speed with which the probe is driven into the fruit is generally much smaller than might be expected (Bourne, 1965; Harker et al., 1996). In the present study, maximum force varied by as much as 20% when different puncture speeds were used (Table 1). With tensile tests, there was no significant influence of test speed on maximum force (Table 1). In this case, the variability between samples that was associated with cutting and shaping the tissue may have obscured the viscoelastic effects. In the Kramer shear cell, we used a slow speed to minimize the force associated with friction between the blades and the sample chamber. During normal chewing, teeth can close at a rates in excess of 10 cm/s (Dubner et al., 1978). Presumably, with these high rates of tooth closure,

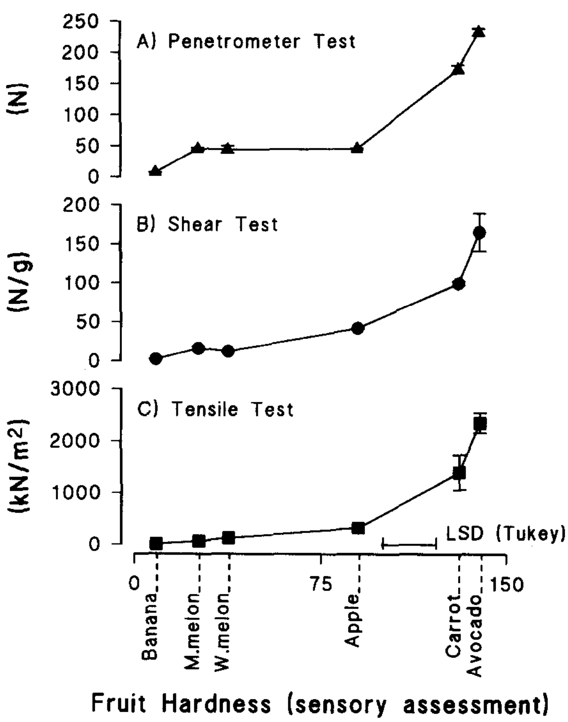

Fig. 3. Relationships between sensory assessment of fruit hardness and mechanical measurements of flesh firmness using a penetrometer (A), shear cell (B) and tension test (C). Points represent means of four measurements and vertical lines represent ± S.E.M. (when larger than points).

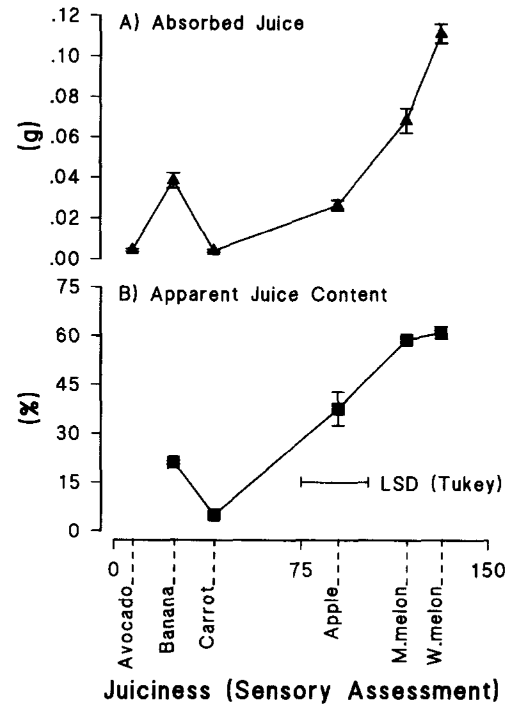

Fig. 4. Relationships between sensory assessment of fruit juiciness and laboratory measurements of juiciness using a gravimetric method involving blotting of juice (A) and the apparent juice content method (B). Methods are described in detail in the text. Points represent means of four measurements and vertical lines represent ± S.E.M. (when larger than points).

the break down of food particles is mainly associated with elastic properties of the food. A critical observation in the present study is that the curvilinear relationship between mechanical and sensory assessments of hardness was not only apparent with all three instruments, but a priori was also apparent at high and low test speeds (e.g. puncture tests at 240 mm/min and tensile tests at 10 mm/min). Further work is required to confirm this observation.

Additional information on fruit texture might be gathered from examination of force-distance curves (Fig. 1). Tensile measurements showed three types of force-distance curve (Fig. 1c):

Type A (associated with unripe avocado and carrot) indicated a steady increase in force, followed by a gradual levelling off and then decrease in force just prior to tissue fracturing (force returns to zero). Examination of fracture surfaces by LTSEM indicated that cell walls had broken at a point close to the cell equator (Fig. 2a, b). In both tissues, cells were small with a high frequency of walls across the plane of fracture. We expect that the rounding of the force-distance curve reflect either a change in the mechanical properties of the cell walls just before tissue failure, or a gradual progression of breakage of individual cells until final catastrophic failure.

Type B (associated with ripe watermelon and ripe apple) indicated a steady increase in force up to a point when the tissue suddenly fractured. Tissue failure was associated with breaking of the relatively large cells (compared with carrot or avocado: Fig. 2c, e). The shape of the force-distance curve probably indicated the brittle nature of the relatively thin cell walls.

Type C (associated with ripe muskmelon and ripe banana) indicated a steady increase in force, followed by a gradual levelling off and decline in force before developing an extended tail. A proportion of the cells from muskmelon and all the cells from banana remained intact, indicating that tissue failure occurred by cell-to-cell debonding. We expect that the tail may be associated with slipping of individual cells across each other and relate to the viscous nature of the middle lamella. Previous studies have visually indicated the viscous tacky nature of the middle lamella of cells from mealy apples (Harker and Hallett, 1992).

While type A, B, and C force-distance curves were associated with hard, moderately hard and soft tissue, respectively, it is clear that the shapes of the curves give additional information on texture. During softening of nectarines and kiwifruit, force-distance curves change from type B to type C (unpublished data). However, such fruit are only consumed when ripe (type C). In the present study, all commodities were at eating firmness, with the exception of unripe avocado. Clearly, plant tissues with different hardness and different modes of cell failure (cell-to-cell debonding and cell rupture) are acceptable to consumers. Acceptability is often based on learned expectations of any particular commodity. For example, dry, soft textures are acceptable in banana, but not in apple (e.g. Harker and Hallett, 1992). We suspect that type A, B, and C curves may be indicative of tough, crisp and soft textures respectively, although further sensory studies are required to confirm this.

There was no obvious relationship between shape of force-distance curves obtained using a penetrometer or a shear cell, and sensory assessment of texture. The force-distance curves obtained using a penetrometer declined after the yield point was reached, except for apple which remained constant and banana which declined only slightly. Thus, the curves were of type B and C, respectively (Bourne, 1965). Szczesniak et al. (1970) used the Kramer shear cell (Texture meter) to examine texture of a range of foods including apples, bananas and carrots. They found that the behaviour of fresh fruit and raw carrot in the Kramer shear cell was most closely classified as a combination of compression and extrusion, and/or shear and extrusion. Thus, values obtained using the shear cell must be considered as empirical measurements rather than fundamental measurements of shear or compression.

Assessment of juiciness using the cellular integrity or blotting tests were closely related to sensory assessments, with the exception of banana which is discussed later in the text (Fig. 4). Instrumental measurements of juiciness are relatively common in fruit such as stonefruit (Lill and van der Mespel, 1988) and pears (Chen and Borgic, 1985), and are occasionally used in studies of other fruit-types (Szczesniak and Ilker, 1988; Paoletti et al., 1993). The present results suggest that instrumental assessment of juiciness may be useful for assessing quality of a wide range of fruit.

Szczesniak and Ilker (1988) found a good relationship between cell size and tissue juiciness. This observation is confirmed by our study. Tissues with low juiciness such as avocado and carrot have smaller cells than juicy tissues such as watermelon (Fig. 2). The diameter of cells might be expected to determine the amount of juice released following cell rupture. Assuming only one layer of cells is damaged during biting or cutting, the amount of juice released should relate directly to the cell size. For example, the volume of cell contents released from the cut surface of watermelon tissue (cell diameter = 0.5 mm) might be expected to be ten times greater than the volume released from cut surface of avocado tissue (cell diameter = 0.05 mm). However, small cells may also have a greater ability to retain cell contents within the damaged region through capillary action. Furthermore, tissues containing small cells will have more cell wall, more cytoplasm and less vacuole per volume of tissue than tissues with large cells. We expect that the ratios of cell wall-to-cell contents and vacuole-to-cytoplasm as well as the absolute volumes of juice released may influence the sensory perception of juiciness.

The poor relationship between sensory and mechanical assessment of juiciness in banana (Fig. 4) probably relates to the way banana cells separate from neighbouring cells without breaking open during tensile tests (Fig. 2). Banana tissue clearly contains a considerable amount of juice which is easily released during mechanical disruption. However, during chewing the cells may not break open and release their contents (as occurs in tensile measurements; Fig. 2F), so that sensory assessments score the tissue as being low in juiciness. Alternatively it may be that the composition of the contents of banana cells have a direct effect on the perception of juiciness. Szczesniak and Ilker (1988) speculate that the presence of partially hydrolyzed starch may account for the perception of a dry mouthfeel by binding free water. In our study, the viscosity of banana juice was five times greater than for other fruit juices, suggesting that the composition of the expressed fluid may have contributed to the mouthfeel.

Plant tissues that are commonly eaten fresh can exhibit a range of mechanical properties. Tensile measurements can provide quantitative information on tissue strength and qualitative information on mechanisms of cell failure. However, the relationship between the mechanical properties and sensory perception of hardness is curvilinear for all of the instruments studied. The implications of this curvilinear relationship are most critical for fruit with 'soft melting' textures, where sensory perception may be more acute than instrumental measurements. Given that such differences in sensitivity may be fundamental to the psychophysical basis of human perception of texture, we conclude that there is a need for basic knowledge of the processes specifically involved in the breakdown of fruit tissues during chewing (Harker et al., 1997a). While information on the breakdown of hard foods is available (e.g. Olthoff, 1986), no such information is available for fruit tissues (Harker et al., 1997a,b). Instrumental measurements of juiciness, by comparison, seem to be more directly related to sensory assessments. Plant tissues which are characterized by juicy textures tend to have large cells which break open during tensile measurements. Low juiciness was associated with tissues with small cells and with cells which did not break open during tensile measurement. We conclude that instrumental measurements of juiciness may well provide a useful technique to include when assessing fruit quality.

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