Texture

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Introduction: Texture is a quality attribute that is critical in determining the acceptability of fruits and vegetables. It is convenient to define *quality* as the composite of intrinsic characteristics that differentiate units of the commodity - individual pieces of the product - and to think of *acceptability* as people's perceptions of and reactions to those characteristics. Although the term is widely used, *texture* is not a single, well-defined attribute. It is a collective term that encompasses the structural and mechanical properties of a food and their sensory perception in the hand or mouth. Although some definitions of texture restrict its use to only sensory attributes or to sensory attributes and the mechanical properties directly related to them, the term texture is sometimes extended to include some mechanical properties of commercial interest that may not be of direct interest to consumers, such as resistance to mechanical damage. In this review, we will use the term *texture* in the broadest sense.

A few of the many terms used to describe sensory texture of fruits or vegetables are hard, firm, soft, crisp, limp, mealy, tough, leathery, melting, gritty, wooly, stringy, dry, and juicy. There are no accepted instrumental methods for measuring each of these attributes. In fact, there is some disagreement among sensory, horticultural, and engineering uses of certain terms, particularly *firmness* which is discussed later.

Textural attributes of fruits and vegetables are related to the structural, physiological, and biochemical characteristics of the living cells; their changes over time; and their alteration by processes such as cooking or freezing. The continuous physiological changes in living cells plus the inherent variability among individual units of the commodity make the assessment of fruit or vegetable texture difficult. Because of their continuous change, textural measurements are often relevant only at the time of evaluation; that is, they usually cannot be used to predict condition much later in the storage period or marketing chain.

Physiological Basis of Texture: To understand the texture of a product, it is important to identify the main elements of tissue strength and to determine which elements are responsible for the textural attributes of interest. For example, it may be necessary to avoid tough strands of vascular material when measuring texture of soft tissues because the small amount of fiber produces an artificially high reading that does not agree with the sensory assessment of softness. On the other hand, it is important to measure the strength of fibers when determining toughness, such as in asparagus spears or broccoli stalks. Thus, method development and the solution to many texture problems requires a good understanding of the anatomy of tissues within the fruit or vegetable, the structure of their cells, and biological changes that occur following harvest as well as some understanding of sensory texture perception.

Parenchyma Cells. Fruits are derived from flower parts; while vegetables are derived from roots, stems, leaves, or flowers and several that we call vegetables are actually fruit (Table 1). The common factor is that all are relatively soft, even carrots and apples, when eaten (either raw or after cooking), largely due to the presence of parenchyma cells. These parenchyma cells are not lignified, and their primary walls are separated by a morphologically distinct region known as the middle lamella, which separates adjacent cells and is rich in pectic substances. The unique mixture of matrix (pectic and hemicellulosic) and fibrous (cellulosic) polysaccharides in the cell wall mostly determines the mechanical properties of these cells. The polysaccharides confer on the wall two important but seemingly incompatible properties. The first is the wall's plasticity which enables it to expand as the cell enlarges during plant development. The second is its rigidity, which confers strength and determines cell shape. However, on its own, the cell wall is unable to provide much mechanical support. Rather it is the interaction between rigidity of the wall and internal hydrostatic pressure (turgor) of cell contents that provides support.

Table 1. Examples of fruits and vegetables derived from various plant parts.

Plant part	Fruit	Vegetable	Seasoning or Garnish
root		beet, carrot, cassava (yucca, *Manihot*), parsnip, radish, sweet potato (*Ipomoea*), turnip, yam (*Dioscorea*)	licorice
tuber		potato, Jerusalem artichoke, taro	
rhizome			ginger, turmeric
bulb		onion, shallot	garlic
corm		water chestnut	
sprouted seeds		bean sprouts, etc.	
stem		asparagus	cinnamon (bark)
leaf buds		cabbage, Brussels sprouts, Belgian endive (etiolated)	
petiole		celery, rhubarb	
leaf		collards, kale, leek, lettuce, mustard greens, onion (green), spinach, watercress	basil, bay, chives, cilantro, dill leaf, marjoram, mint, oregano, parsley, rosemary, sage, tarragon, thyme
flower buds		artichoke (globe), broccoli, cauliflower, lily bud	capers, cloves
flowers		squash blossoms	edible flowers (garnishes)
floral receptacle	strawberry, fig		
fruit, immature		chayote (christophene, mirliton), cucumber, eggplant, beans (green), snap peas, pepper (*Capsicum*), Summer squash, zucchini	gherkin (pickled)
fruit, mature	apple, atemoya, avocado, blueberry, carambola, cherimoya, cherry, citrus, cranberry, date, grape, jackfruit, mango, olive, papaya, peach, pear, pineapple, pomegranate, strawberry	breadfruit, tomatillo, tomato, Winter squashes (pumpkin, hubbard, acorn, etc.)	allspice, caper berries, juniper, mace, pepper (red, *Capsicum*), tamarind, vanilla bean
seeds	nuts, inclusions in numerous fruits	beans (mature), coconut, peanuts, sweet corn, nuts, inclusions in numerous fruit-type vegetables (eg., squashes, tomatoes, beans)	anise, caraway, cardamon, cumin, dill seed, fennel, mustard, nutmeg, pepper (black, *Piper*), pomegranate, poppy seed, sesame seed
fungi		mushrooms, truffles	

The arrangement and packing of parenchyma cells within the tissue is another factor that influences mechanical strength of produce. In carrots, the cells are small (approximately 50 μm in diameter), isodiametric in shape, and closely packed with a high degree of contact between neighboring cells and a small volume of intercellular gas filled spaces. The cells can be arranged either as columns or as a staggered array where each cell overlays the junction of the two lower cells (Sørensen et al., 1999). These differences in cell packing may, in part, explain genotypic differences in susceptibility to harvest splitting in carrot. In apple cortical tissue, the cells are large (up to 300 μm in diameter), elongated along the direction of the fruit radius, and organized into distinct columns (Khan and Vincent, 1993). As a result of this orientation of apple cells, the tissue stiffness (elastic modulus) is higher and the strain at failure is lower when tissue plugs are compressed in a radial rather than a vertical or tangential orientation (Khan and Vincent, 1993; Abbott and Lu, 1996). Up to 25% of the volume of apple tissue may be gas-filled intercellular spaces, which indicates relatively inefficient cell packing and a low degree of cell-to-cell contact, both of which correlate well (negatively) with tissue stiffness (Vincent, 1989).

Cell Wall. From a chemical perspective, the primary cell wall of parenchyma cells is composed of a mixture of cellulose, hemicellulose, and pectin. The specific intermolecular interactions among these polysaccharides are poorly understood but usually assumed to follow the models described by Carpita and Gibeaut (1993). The cell wall itself is an important constituent of produce, providing dietary fiber, thought to protect against colorectal cancer (Harris et al., 1993).

Changes that occur in the cell wall during ripening of fruit, storage of produce, and cooking are critical to the texture of the final product. During maturation of some vegetative parts, especially stems and petioles, cell walls become lignified (Okimoto, 1948; Price and Floros, 1993). Lignification results in toughening of the product, such as woodiness in asparagus, broccoli, pineapple, and rutabaga. During fruit ripening, cell wall changes include solublization and degradation of pectin and a net loss of the non-cellulosic neutral sugars galactose and arabinose, and there may be a decrease in the molecular weight distribution of hemicelluloses (Harker et al., 1997). Numerous enzymes have been suggested as being critical to these changes in the cell wall including polygalacturonases and several glycosidases, including β-galactosidase, xyloglucanase, endotransglycosylase, and cellulases (Dey and del Campillo, 1984; Huber, 1992; Seymour and Gross, 1996; Harker et al., 1997). In recent years, the possible role of expansins, proteins that are proposed to disrupt hydrogen bonds within the cell wall, has been considered (Civello et al., 1999). The use of molecular approaches, including antisense technologies, has been a powerful tool in the search for an understanding of fruit softening (Giovannoni et al., 1989). However, no single enzyme has been identified as the major determinant of fruit softening, suggesting wall breakdown results from coordinated action of several enzymes, or that the key enzyme has not been identified.

Cooking often results in degradation of pectic polymers via β-elimination, which is usually related to the degree of methyl esterification of pectin (Waldron et al., 1997). Along with turgor loss, this process is responsible for thermal softening. However, some vegetables either don't soften or soften very slowly during cooking, eg., Chinese water chestnut, sugar beet, and beetroot. In Chinese water chestnut, the thermal stability of texture is associated with the presence of ferulic acid in the cell wall (Waldron et al., 1997).

Postharvest treatments involving dipping or infiltrating with calcium maintain firmness during storage of a wide range of fruit (Conway et al., 1994). Examination of fracture surfaces following tensile testing of apple cortex indicated that tissue failure from calcium-treated fruit was due to cell rupture, whereas failure in control apples was due to cell de-bonding (Glenn and Poovaiah, 1990). While evidence suggests that calcium influences texture through its interaction with the cell wall (pectin), it may also affect texture through interactions with membranes.

The cell wall may also influence perception of juiciness through its ability to hold and release fluid. In some fruits, the cell wall swells considerably during ripening (Redgwell et al., 1997). It has been suggested that hydrated cell walls and perhaps the presence of free juice over the surface of undamaged cells could be responsible for the sensation of juiciness in fruit with soft melting textures (Harker et al., 1997). In stonefruit, loss of juiciness is thought to occur when pectates bind water into a gel-like structure within the wall (Ben-Arie and Lavee, 1971). Separation of cells at the middle lamella rather than rupture of cells during chewing is at least partially responsible for the dry, mealy mouth-feel of overripe apples and wooliness of peaches (Harker and Hallett, 1992).

Cell Turgor. Plant cells tend to maintain a small positive pressure, known as turgor pressure. This pressure develops when the concentration of solutes inside the cell (more specifically inside the plasma membrane) is higher than outside the cell. The extracellular solution fills the pores of the cell wall, sometimes infiltrates into gas filled spaces, and usually is continuous with vascular (water conducting) pathways of the plant. Differences in solute concentration at the inner and outer surface of the plasma membrane cause water to flow into the cell by the process of osmosis. This net movement of water is halted by the physical constraint of the rigid cell wall and, as a result of this, turgor develops inside the cell. At equilibrium, $\Psi = \Psi p + \Psi\pi$, where Ψ is the turgor (generally a positive value), Ψp is the water potential (water activity, generally a negative value) of the tissue, and $\Psi\pi$ is osmotic pressure (generally a positive value) of the cell (Tomos, 1988).

Turgor has the effect of stressing the cell wall. The consequences of this stressing depend on whether compressive or tensile loads are applied. When tissues are subjected to compressive loads, higher turgor tends to make the cell more brittle, ie., makes it fail at a lower force (Lin and Pitt, 1986). When tissues are subjected to tensile measurements, turgor tends to harden the cell wall and a greater force is needed before cells fail (De Belie et al., 2000a). However, turgor is unlikely to influence tissue strength if the mechanism of failure is cell-to-cell de-bonding, rather than fracturing across individual cells, unless an increasing turgor and thus swelling reduces cell-to-cell contact area (Glenn and Poovaiah, 1990; Harker and Hallett, 1992).

The importance of turgor has been demonstrated in a number of ways. The rapid phase of cooking-induced softening of carrot occurs as a result of membrane disruption and the elimination of the turgor component of texture (Greve et al., 1994). Similarly, when produce experiences a freeze-thaw cycle the membranes are damaged and the tissues become more flaccid in the case of leafy vegetables and softer in the case of fruits, and often leak much juice upon thawing. Firmness and turgor correlate well in apple (Tong et al., 1999), and turgor declines during tomato ripening (Shackel et al., 1991). Also, turgor is thought to play a central role in softening and development of mealiness during storage of apples (Hatfield and Knee, 1988).

Cell-to-Cell De-bonding versus Cell Rupture. The strength of the cell wall relative to the adhesion between neighboring cells will determine whether cell rupture or cell-to-cell de-bonding is the mechanism of tissue failure. Cell rupture is generally associated with crisp and often juicy produce, as well as with unripe fruit and raw vegetables. Cell-to-cell de-bonding is frequently associated with dry, unpleasant texture such as in mealy apples, chilling injured stonefruit and tomato, and juice loss in citrus (Harker et al., 1997). However, a dry texture is not always unacceptable to consumers, ex., banana. In some fruits, cell-to-cell de-bonding does not result in a dry texture; rather, a layer of juice covers the intact cells exposed following cell separation (Harker et al., 1997). Furthermore, cell-to-cell de-bonding is a common outcome of cooking of vegetables such as potato (Waldron et al., 1997) and carrot (Ng and Waldron, 1997). In fresh produce, cell adhesion is presumed to be a function of three factors: strength of the middle lamella; the area of cell-to-cell contact; and the extent of plasmodesmatal connections (Harker et al., 1997). Tissue collapse can also occur without cell wall breakdown or cell separation. In some tissues, fluids are forced out of cells by compressive forces known as 'cell relaxation' (Peleg et al., 1976) or 'exosmosis' (Jackman and Stanley, 1995).

Other Elements of Tissue Strength. The strength and integrity of many edible plant organs are influenced by a number of additional factors (Harker et al., 1997). Many fruits and vegetables contain a number of tissue zones - periderm, pericycle, and phloem parenchyma in carrot; skin, outer pericarp, inner pericarp, and core in kiwifruit; and outer pericarp, locular gel, seeds, and columella in tomato. These tissues differ in strength and biological properties and often need to be considered individually when measuring texture. For example, failure of the core of kiwifruit to soften to the same extent as the pericarp causes a texture that is unacceptable to consumers. In some multiple fruit that do not adhere to the receptacle, such as raspberry, the main element of strength is the adhesion between neighboring drupelets due to hair-like protuberances. However, it is the skin of many types of produce that plays a key role in holding the flesh together, particularly in soft fruit. The cuticle of epidermal cells and thickened cell walls of hypodermal cells contribute to strength of simple skins. In harder inedible skins, specialized cells may be present: collenchyma, sclerenchyma, tannin-impregnated cells, and cork.

The presence of tough strands of vascular tissue may strengthen the flesh, but often results in an unpleasant fibrous texture. For example, toughness of asparagus spears is principally due to fiber content and fiber lignification (Lipton, 1990). Rarely, the stringiness is desirable, as in spaghetti squash. In most commercial fruits, with the exception of pineapple (Okimoto, 1948), fibrousness of the flesh is not a major problem. However, some fruits including peaches and muskmelons can have a problem with stringiness (Diehl and Hamann, 1979). Generally, the perception of stringiness is enhanced in very ripe fruit due to the contrast between the soft melting texture of the parenchyma cells and the fibrousness of the vascular tissues. Similarly the gritty texture of pear and guava (Harker et al., 1997) becomes particularly noticeable when the surrounding cells are soft. However, while stringiness is caused by vascular tissues, grittiness is caused by sclerenchymatous stone cells (Harker et al., 1997).

Sensory Evaluation of Texture: People sense texture in numerous ways: the look of the product, the feel in the hand, the way it feels as they cut it, the sounds as they bite and chew, and most important of all, the feel in their mouth as they eat it. Szczesniak (1963) proposed a texture profile, a systematic approach to sensory texture analysis based on mechanical, geometrical, and other characteristics. Mechanical characteristics included basic parameters (hardness, cohesiveness, viscosity, elasticity, and adhesiveness) and secondary parameters (brittleness or fracturability, chewiness, and gumminess). Geometrical properties related to size, shape, and orientation of particles. The other characteristics comprised moisture and fat content. Sherman (1969) and others have proposed revisions of the texture profile classification scheme, but the original is generally used with only minor changes by sensory texture specialists. Most sensory analysis text books contain a small chapter on evaluation of texture, eg., Meilgaard et al. (1999). Harker et al. (1997) reviewed fruit texture and included extensive discussion of oral sensation of textural attributes.

Shewfelt (1999) suggested that the combination of characteristics of the product be termed quality and that the consumer's perception and response to those characteristics be referred to as acceptability. Texture may be a limiting factor in acceptability if textural attributes are outside the individual's range of acceptability for that commodity; people have different expectations and impose different limits for various commodities. The relationship of instrumental measurements to specific sensory attributes and their relationship to consumer acceptability must be considered (Shewfelt, 1999). Instruments may be designed to imitate human testing methods or fundamental mechanical measurements may be statistically related to human perceptions and judgments to predict quality categories. Only people can *judge* quality, but instruments that *measure* quality-related attributes are vital for research and inspection (Abbott et al., 1997).

Instrumental Measurement of Texture: The ability to measure texture is critical for evaluation and control of quality. The complex nature of texture is associated with the diversity of tissues involved, the attributes required to describe textural properties, and changes in these attributes as the product ripens and senesces. Instrumental measurements are preferred over sensory evaluations for research and commercial applications because instruments reduce variation among measurements due to human factors; are more precise; and can provide a common language among researchers, companies, regulatory agencies, and customers. It is often suggested that the relevance of instrumental measurements depends on how well they predict sensory attributes (Voisey, 1971), but there are also valid uses for mechanical property measurements that relate only to functional behavior of the fruit or vegetable, such as bruise resistance or the ability to be sliced for fresh-cut preparations.

There have been numerous reviews of methods for instumental measurement of fruit and vegetable texture (Bourne, 1980; Chen and Sun, 1991; Abbott et al., 1997; Harker et al., 1997). Interaction among characteristics and the continuing physiological changes over time complicate the measurement of fruit or vegetable texture. For example, as the parenchymal tissue of honeydew melon softens, the perception of fibers (vascular bundles) increases (Diehl and Hamann, 1979). On the other hand, the fibrousness in asparagus is related to active lignification of fiber and vascular bundles (Chang, 1987). Similar effects can affect instrument measurements. For example, fibers are held relatively rigidly in a hard melon, and so contribute to the overall force required to cut through the flesh, but the fibers are displaced by the instrument's probe in a soft one and alter distribution of forces within tissue. The displaced fibers can also effectively change the shape of the probe as it progresses through the flesh accumulating a "cap" of fibers.

Most instrumental measurements of texture have been developed empirically. While they may provide satisfactory assessments of the quality of produce, they often do not fulfill engineering requirements for fundamental measurements (Bourne, 1982). Fundamental material properties measurements were developed to study the strength of materials for construction or manufacture. After the failure point of such a material is exceeded, there is little interest in the subsequent behavior of the material. On the other hand, scientists that deal with food are interested in initial failure, but they are also interested in the continuous breakdown of the food in the mouth in preparation for swallowing. As Bourne (1982) pointed out, "food texture measurement might be considered more as a study of the weakness of materials rather than strength of materials." In fact, both strength and breakdown characteristics are important components of texture.

Elastic and Viscoelastic Behavior: Fruits and vegetables exhibit viscoelastic behavior under mechanical loading, which means that force, distance, and time - in the form of rate, extent, and duration of load - determine the value of measurements. For example, impact of the fruit against a hard surface is very rapid loading, whereas the weight of other fruit on an individual fruit at the bottom of a bin and the force of a carton wall against tightly packed fruit are long-term loads. The fruit will respond quite differently to the two forms of loading. Because of the viscoelastic character of fruit and vegetable tissues, every effort should be made to use a consistent action and speed when making manual texture measurements, such as the Magness-Taylor puncture test (Blanpied et al., 1978; Harker et al., 1996). The rate of loading should be controlled and specified in mechanized measurements. The optimal rate of loading differs for different commodities. Indeed, people use different loading rates (chewing speeds) when eating foods of different textures (Harker et al., 1997); but the optimum loading rate for instrumental measurements may not resemble the rate of human mastication (Thybo et al., 2000).

There are many types of mechanical loading: puncture, compression, shearing, twisting, extrusion, crushing, tension, bending, vibration, and impact. And there are four basic values that can be obtained from mechanical properties tests: force (load), deformation (distance, displacement, penetration), slope (ratio of force to deformation), and area under the force/deformation curve (energy). The engineering terms based on these measurements are stress, strain, modulus, and energy, respectively. Stress is force per unit area, either of contact or cross-section, depending on the test. Strain is deformation as a percentage of initial height or length of the portion of sample subject to loading. Modulus of elasticity (tangent, secant, chord, or initial tangent) is a measure of stiffness based on the stress/strain ratio. Force and deformation values are more commonly used in food applications than stress and strain values and are sufficient, provided that the contact area and the distance the probe travels are constant and sample dimensions are similar from sample to sample. (Sample here means the portion of tissue tested, not necessarily the size of the fruit or vegetable.) In many horticultural texture tests, deformation is kept constant and the force value is reported. For example, in penetrometer tests of fruit firmness such as the Magness-Taylor test discussed later, the force required to insert a probe into the flesh to an inscribed mark is read from a gauge. No compensation is made for different probe diameters (contact areas), so the value read is force, not pressure or stress. In a few horticultural tests, a known force is applied to the product and the deformation after a specified time is reported; an example is the tomato creep test (Hamson, 1952; Ahrens and Huber, 1990).

Puncture, compression, bending, and shear tests made on instruments such as those listed in Table 2 are made at relatively low speeds, usually 60 to 300 mm min^{-1} (0.1 to 20 in min^{-1}). In contrast, typical impact velocities in fruit and vegetable handling systems are likely to be around 400 mm s^{-1} (945 in min^{-1}), equivalent to a drop of only 8.1 mm, and sometimes much greater.

Table 2. Magness-Taylor fruit firmness tester and related penetrometers.

Instrument	Type	Force[1]	Readout	Manufacturer
Magness-Taylor	MT	manual	gauge	D. Ballauff Mfr. Co., Laurel, MD
Effe-gi[2]	MT	manual	gauge	Effe-gi, Ravenna, Italy
McCormick[2]	MT	manual	gauge	McCormick Fruit Tech Co., Yakima, WA (Mfr. by Effe-gi)
Wagner	MT	manual	gauge	Wagner Instruments, Greenwich, CT (mfr. by Effe-gi)
EPT	MT	mechanical	electronic	Lake City Technical Products, Kelowna, BC, Canada
U.C. (Univ. California)	MT	mechanical	gauge	None. Uses Ametec force gauge and manual drill press
universal testing machines or materials testers	universal	mechanized	Electronic	AMETEK Test and Calibration Instruments (Paoli, PA) Chatillon (Largo, FL) Food Technology Corp. (of General Kinetics, Inc.,) Instron Corp. (Canton, MA) Lloyd Inst. Material Testing Prod. (Hampshire, UK) Stable Micro Systems, Ltd.(Surrey, UK) Tinius Olsen Testing Machine Co. (Willow Grove, PA)

[1] MT firmness, regardless of instrument, is measured as force and should be reported in pounds force (lbf, English units) or Newtons (N, metric units), not in kilograms force (kgf) although the gauges of some instruments indicate kg. To convert: lbf x 4.448 = N; kgf x 9.807 = N; N x 0.225 = lbf; N x 0.102 = kgf.
[2] Other labels, for example “McCormick” and others may occur on Effe-gi instruments.

Idealized and typical force/deformation (F/D) curves for a cylindrical piece of apple tissue compressed at constant speed are shown in Fig. 1 A and B, respectively. F/D curves for puncture tests look similar to compression curves. The portion of the initial slope up to point A in Fig. 1A represents nondestructive elastic deformation; point A is the inflection point where the curve begins to have a concave-downward shape and is called the elastic limit. The region before point A is where slope or elastic modulus should be measured. Beyond the elastic limit, permanent tissue damage begins. There may be a bioyield point (point B in Fig. 1A) where cells start to rupture or to move with respect to their neighbors, causing a noticeable decrease in slope. Point C in Fig. 1A marks rupture, where major tissue failure causes the force to decrease substantially. In some F/D curves, including the one in Fig. 1B, bioyield may not be distinguishable from rupture. Beyond rupture, the force may again increase, level off, or decrease as deformation increases (Bourne, 1965). At the maximum deformation point specified by the user, the probe is withdrawn and the force diminishes until contact is lost. In the apple tissue shown in Fig. 1B, maximum force occurred at the maximum deformation, point c; but other apples in the same lot had maxima at rupture (point a) or at some point between rupture and maximum deformation, such as marked by point b. Of course, F/D curves that differ from the ones shown in Fig. 1 are also reported for apple and for other commodities. F/D curves for very soft, noncrisp, or spongy tissues do not have sharp peaks but show gradual increase in force to a rupture point, followed by gradual decrease. Some may not even show rupture; for example, a cylinder of eggplant tissue compressed like the apple tissue in Fig. 1B may show smoothly increasing force to the point of maximum deformation. Products containing a mixture of parenchyma and fibers or stone cells may have quite jagged F/D curves, with several local maxima and ruptures as the probe encounters resistant clusters of stone or fiber cells.

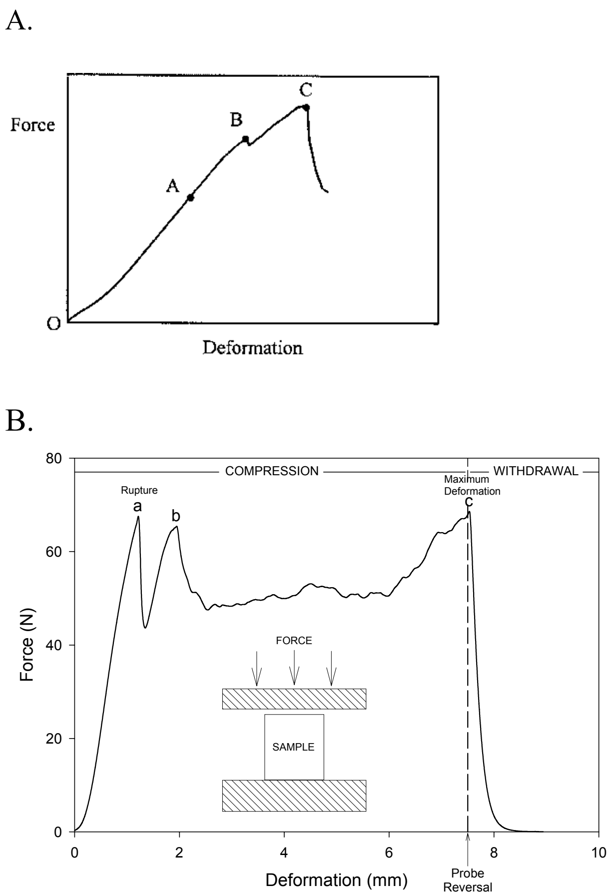

Figure 1. Force/deformation curves. A: idealized curve demonstrating A elastic limit, B bioyield, and C rupture or massive tissue failure. B: Actual force/deformation curve of a cylindrical piece of apple tissue under compression at 1 mm s^{-1}. Maximum force is at point c, but could also occur at point a or point b in other apples. Force/deformation for Magness-Taylor puncture would look similar (with somewhat different maximum forces), but would terminate at 5/16 in or 8 mm, depending on whether original or metric specification was selected to control the universal testing instrument.

Firmness of horticultural products can be measured at different force or deformation levels in all three regions of Fig. 1A, depending on the purpose of the measurement and the definitions of the quality attributes. F/D characteristics beyond the elastic limit may be more important than those before it because they simulate the destruction that occurs in bruising or eating (Szczesniak 1963; Bourne 1968). The two most common texture tests of fruits and vegetables, the Magness-Taylor puncture and the Kramer Shear report only the maximum force attained, regardless of the deformation at which it occurs. On the other hand, elastic modulus or Young's modulus is often used by engineers as an index of product firmness. The modulus of elasticity is the ratio of stress to strain as calculated from the slope of the force/deformation curve before the elastic limit. Any nondestructive method should limit the force or deformation level to the elastic region so that negligible tissue damage will be sustained during measurement. It is important to recognize and understand the fundamental properties measured by both destructive tests and nondestructive methods, the differences between them, and the factors that can affect the tests.

Numerous mechanical instruments have been developed over the past century for measuring textural attributes of horticultural products. Despite the large variations in design, these mechanical instruments either measure or control functions of force, deformation, and time. The types of loading by these instruments include: puncture, compression, shearing, twisting, extrusion, crushing, tension, and bending.

Puncture Tests. Puncture testers based on the original Magness-Taylor pressure tester, also called the USDA or Ballauff tester (Magness and Taylor, 1925; Haller, 1941) and more correctly called the Magness-Taylor fruit firmness tester, are used to measure firmness of numerous fruits and vegetables to estimate harvest maturity or for postharvest evaluation of firmness. There are several adaptations of the Magness-Taylor (MT) tester that differ in instrument size and shape, manual or mechanical use, and dial (analog) or digital readout (Table 2). The term “Magness-Taylor firmness” is used generically for the measurements made with the several variants of the MT. All use rounded-tip probes of specific geometry and measure the maximum force required to insert the probe 7.94 mm (5/16 in) into the flesh (Haller, 1941). Note that the rounded portion of a Magness-Taylor probe is only a portion of a full hemisphere (Fig. 2; dimensions provided by John Cook, former Pres., Ballauf Mfr., Laurel, MD). An 11.11 mm (28/64 in) diameter probe

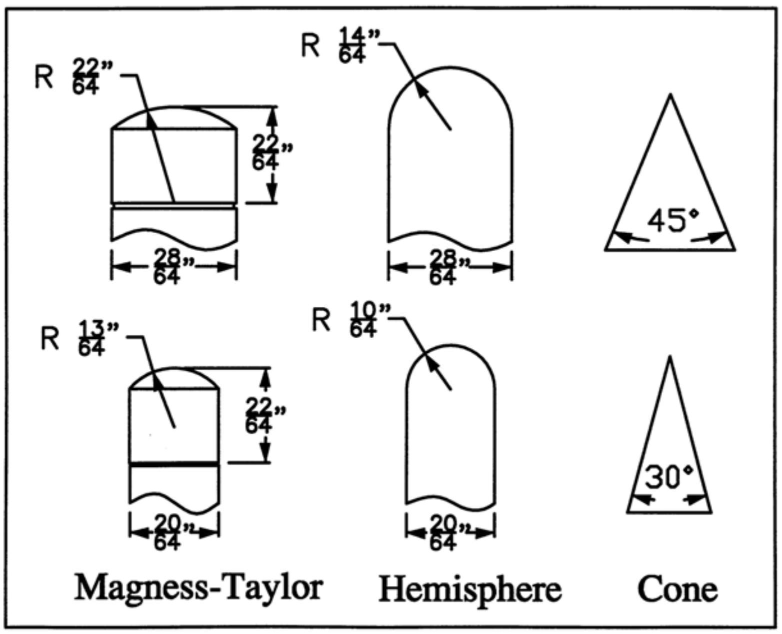

Figure 2. Magness-Taylor fruit firmness, hemispherical, and conical probes. Similar probes of other dimensions are sometimes used for measuring texture of fruits and vegetables, as well as probes of different geometry. Note that the larger Magness-Taylor probe is used for apples and the smaller probe is used for most other commodities (nominally 11 and 8 mm, respectively).

with a radius of curvature of 8.73 mm (11/32 in) is used for apples. A 7.94 mm (5/16 in) diameter probe with a radius of curvature of 5.16 mm (13/64 in) is used for cucumber, kiwifruit, mango, papaya, peaches, pears, and plums. A thin slice of skin (about 2-mm thick and slightly larger diameter than the probe) should be removed from the area to be tested except for cucumbers, which are tested with the skin intact. A group of U.S. researchers published recommendations for making manual penetrometer tests (Blanpied et al., 1978), stating that steady force should be applied such that the probe is inserted to the inscribed depth mark in 2 s. The probes can also be mounted in materials testers (universal force/deformation testing machines) made by numerous manufacturers (some are listed in Table 2) (Bourne, 1974; Breene et al., 1974; Abbott et al., 1976; Harker et al, 1996; Lehman-Salada, 1996). A group sponsored by the Commission of the European Communities recommended that a materials tester should be used to drive the probe to a depth of 8 mm at speeds between 50 and 250 mm min^{-1} (Smith, 1985). Because of the curvature of the MT probes and the fact that firmness as measured in puncture is a combination of shear and compression in variable proportions, it is not possible to convert measurements made with one size MT probe to the other MT size, or to accurately convert to or from values for probes of other geometries (Bourne, 1982). A random sample of 20 to 30 fruit of similar size and temperature should be tested with punches on two opposite sides, depending on uniformity of the lot. Peaches are often more variable around the circumference than other fruit so the larger number is recommended (Blanpied et al., 1978). Similar measurements are made on cherry, grape, and strawberry using a 3-mm probe and on olive using a 1.5-mm probe on the U.C. tester (E.J. Mitcham, 2000, personal communication). Numerous puncture tests with flat-faced cylindrical or hemispherical probes and a few with conical probes have been conducted. None have achieved the acceptance of the Magness-Taylor fruit firmness test.

Shear Tests. Shearing in engineering terms does not mean cutting with a knife or scissors, but instead sliding adjacent parallel planes of cells past one another. Engineering shear tests are seldom used on fruits and vegetables, but shear modulus can be obtained from compression (Mohsenin, 1986), torsion (Diehl et al., 1979), impact (Bajema and Hyde, 1998), extrusion, and dynamic (Ramana and Taylor, 1992) tests. Although it does not measure true shear, the Kramer Shear device (FTC Texture Test System, Food Technology Corporation, Reston, VA) is used extensively in the food processing industry and is used by some fresh-cut processors for quality control. The key component of the original Kramer Shear device is a multiblade cell with ten blades 2.9 mm (about 7/64 in) thick that mesh with slots in the bottom of a 67 x 67 x 63 mm cell (approximately 2 5/8 x 2 5/8 x 2 1/2 in; internal dimensions) that can be used on any materials tester with sufficient load capacity. The cell is generally filled with randomly oriented pieces of the product, either to full capacity or to 100 g. The force measured by the test involves compression, shear, extrusion, and friction between the tissue and blades. While the maximum force to pass the blades through the sample may relate to the complex of material properties sensed in the mouth during chewing, the test does not satisfy requirements for engineering tests because of the undefined and uncontrolled stresses and strains applied to the food. The amount of sample and the pattern of loading the cell, size and orientation of pieces, etc., affect the maximum force value as well as the shape of the force/deformation curve (Szczesniak et al., 1970; Voisey and Kloek, 1981). The orientation of pieces of fruit or vegetable, especially with regard to vascular bundles and fibers, and the spaces between pieces would be expected to affect significantly the force/deformation profile as the blades penetrate through the contents of the shear cell, therefore some standardization of loading practice is advisable. Adaptations with smaller cells and fewer blades are available, eg., Stable Micro Systems. As with the MT probe, comparisons should not be made between results from cells of different geometries.

Compression. Although compression tests are not commonly used by the fruit and vegetable industry, they are widely used in research on horticultural products. They can be made on tissue specimens or intact products using a variety of contact geometries (Mohsenin, 1986; ASAE Std. 368.4, 2000). Although fruits and vegetables are viscoelastic, they are often treated as elastic, so the force required to attain a specified deformation or to rupture (bruise or burst) the product is generally measured. Modulus of elasticity, stiffness, force and deformation to bioyield and to rupture, and contact stress can be calculated from elastic measurements, dimensions of the specimen, and Poisson's ratio (the ratio of transverse strain to axial strain at less than the elastic limit). For convex specimens such as whole or halved fruits, see ASAE Std. 368.4 (2000). Often, for food science applications, only maximum force or distance is reported.

Compression tests using pieces of tissue, usually cylindrical, excised from the fruit or vegetable are quite common in research (Fig. 3) (Bourne, 1968; Khan and Vincent, 1993; Abbott and Lu, 1996; Wann, 1996). Intact product compression tests involve contact with small flat or curved indentors or with parallel plates significantly larger than the area of contact (ASAE Std. 368.4, 2000). Modulus of elasticity values from whole fruit compression represents fruit morphology, size, shape, cellular structure, strength, and turgor. Although elastic properties can be determined nondestructively (discussed later), horticultural and food science measurements are frequently made beyond the elastic limit. Sundstrom and Carter (1983) used rupture force of intact watermelons pressed between parallel flat plates to evaluate causes of cracking. Jackman et al. (1990) found that whole tomato compression was relatively insensitive to small differences in firmness due to chilling injury. Kader et al. (1978) compressed tomatoes between a pair of spherical indentors as a measure of firmness.

If the viscous element is a significant contributor to the texture, as it is for intact tomatoes and citrus, measurement of continuing deformation under a constant force (creep) (Hamson, 1952; El Assi et al., 1997) or decrease in force under a fixed deformation (relaxation) (Sakurai and Nevins, 1992; Errington et al., 1997; Kajuna et al., 1998;Wu and Abbott, 2002) provides textural information in addition to elastic properties. To minimize the effect of loading position on firmness measurement in tomato, Kattan (1957) designed a creep tester that applied force around the fruits circumference with a belt. The failure of creep or force-relaxation testers to be adopted commercially is due to time required for adequate relaxation, which can be up to 60 s.

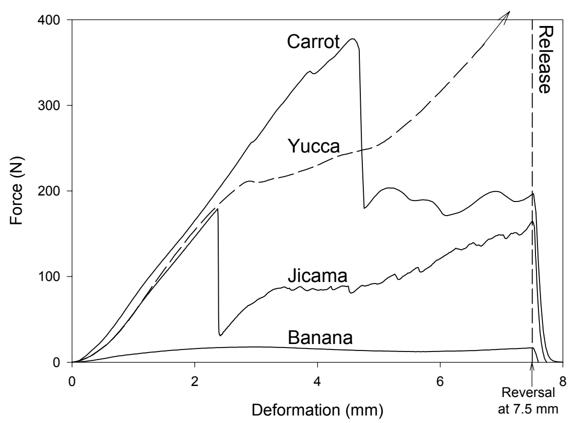

Figure 3. Force/deformation curves for several fruits and vegetables, illustrating diversity of texture. All curves are for 15 mm diameter × 10 mm high cylinders cut parallel to the product axis, compressed between flat plates at 2 mm/second to 75% compression, and then released at the same rate. Note that the maximum force for yucca root greatly exceeded the capacity of the load cell used and that yucca showed a clear bioyield at about 230 N. (Abbott, unpublished)

Tension Test. Tensile tests measure the force required to stretch or to pull a sample apart. Failure can be through cell rupture, cell separation, or a combination of both. Tensile measurement has not been as popular as puncture or compression testing because it is not intuitively as related to crushing or chewing as are puncture or compression and because it requires gripping or otherwise holding the ends of the sample so they can be pulled apart without crushing the tissues where they are held. Schoorl and Holt (1983) used clamps to hold apple tissue. Stow (1989) and Harker and Hallett (1992) used shaped samples held by special claw-like hooks. Harker and Hallett (1994) used quick-set adhesive to glue the ends to instrument fixtures. Researchers often examine the broken ends of tensile test samples to determine the mode of fracture. Microscopic analyses of the broken ends (Lapsley et al., 1992; Harker and Sutherland, 1993; Harker and Hallett, 1994; Harker et al., 1997) reveal that tissue from unripe fruit generally fractures due to individual cells breaking; whereas, cells from ripe fruits which tend to be crisp (apple and watermelon) usually break or rupture and cells from ripened soft fruits (banana, nectarine and kiwifruit) tend to separate at the middle lamellae.

Torsion Test. True torsion tests are rarely used on horticultural specimens because of the difficulties in shaping and holding the tissue (Diehl and Hamann, 1979; Diehl et al., 1979).

Twist Test. Studman and Yuwana (1992) proposed a simple twist tester, consisting of a sharp spindle with a rectangular blade that is forced into the flesh and then the torque (twisting force) required to cause crushing or yielding of the tissue is measured. Although called a twist test, this is not to be confused with a torsion test; the properties tested are likely a combination of shear and compression. Harker et al. (1996) found the twist test to be more precise than several testers using the MT puncture probe; however, Hopkirk et al. (1996) suggest that puncture and twist tests may measure different mechanical properties, resulting in quite different firmness judgments. The twist test has the advantage of being able to measure strength of tissue zones at specific depths from the surface without requiring the excision of tissue samples.

Non-destructive Measurements for On-line Sorting: Most force/deformation measurements are destructive, for example the familiar Magness-Taylor fruit firmness test and the Kramer shear test, or are too slow for on-line use, such as the Cornell firmness tester. However, remember that eating is destructive! Rupture forces usually provide the best correlation with sensory texture evaluations of foods. Unfortunately destructive tests cannot be used to sort fruits and vegetables for subsequent sale, so a great deal of research has gone into developing nondestructive methods to estimate the mechanical properties and the textural quality of fruits and vegetables (Chen and Sun, 1991; Abbott et al., 1997; Hung et al., 2001). None of these nondestructive methods has attained wide commercial acceptance to date.

During development, new instrumental texture measurements are most often initially calibrated against existing instruments. If they are to be used to predict sensory attributes or acceptability, the new measurement should also be compared directly to descriptive sensory analyses to develop calibration equations for quantitative attributes (how much of a trait is present) or to consumer evaluations to predict acceptability. Alternatively, instrumental measurements may be compared to commercially useful traits like bruising, days from bloom, or storage life to develop predictive equations. After the relationship between an instrumental measurement and a quality attribute or acceptability is well established, the instrumental measurement is usually used to replace human evaluations. It is advisable to verify the relationships occasionally, because changes in factors such as genetics, growing or storage conditions, consumer preference, or wear on the instrument may change the relationships.

Laser Air-Puff Test. A nondestructive, non-contact firmness detector was recently patented (Prussia et al., 1994) that uses a laser to measure deflection caused by a short puff of high-pressure air, similar to some devices used by ophthalmologists to detect glaucoma. This is essentially a nondestructive compression test. Under fixed air pressure, firmer products deflect less than softer ones. Laser-puff readings correlate well with destructive Magness-Taylor firmness values for apple, cantaloupe, kiwifruit, nectarine, orange, pear, peach, plum, and strawberry (Fan et al., 1994; Hung et al., 1998; McGlone et al., 1999; McGlone and Jordan, 2000).

Impact or Bounce Test. When one object collides with another object, its response is related to its mechanical properties, its mass, and the contact geometry. Numerous studies have been conducted on the impact responses of horticultural products and a number of impact parameters have been proposed to measure firmness, including peak force, coefficient of restitution, contact time, and the impact frequency spectrum. The coefficient of restitution is the ratio of the velocities of the product just before and after impact and reflects the energy absorbed in the product during impact. There is no agreement on the best parameter to measure; selection seems to depend on commodity, impact method, and the firmness reference used by the investigators. Most impact tests involve dropping the product onto a sensor (Rohrbach, 1981; Delwiche et al., 1987; Zapp et al., 1990; McGlone and Schaare, 1993; Patel et al., 1993) or striking the product with the sensor (Delwiche et al., 1989; Brusewitz et al., 1991; Chen et al., 1996; Bajema and Hyde, 1998). Delwiche et al. (1989, 1991) developed a single-lane firmness sorting system for pear and peach. Impact measurements often do not correlate highly with the Magness-Taylor puncture measurement (Hopkirk et al., 1996). A potential problem with impact tests is that bruising may occur, unless a soft sensor is developed (Thai, 1994).

Sonic or Acoustic Tests. Sonic (or acoustic) vibrations are those within the human audibility range of 20 to about 20,000 Hz (vibrations sec^{-1}). Sonic measurements provide a means of measuring fruit and vegetable firmness. The traditional watermelon ripeness test is based on the acoustic principle, where one thumps the melon and listens to the pitch of the response. A number of sonic instruments and laboratory prototype sorting machines have been developed and tested (Abbott et al., 1968, 1992; Armstrong et al.,1990; Peleg et al., 1990; Zhang et al., 1994; Stone et al, 1998; Schotte et al., 1999; De Belie et al., 2000b; Muramatsu et al., 2000). When an object is caused to vibrate, amplitude varies with frequency of the vibration and will be at a maximum at some particular frequency determined by a combination of the shape, size, and density of the object; such a condition is referred to as resonance. Resonance measurement can be achieved by applying an impulse or thump that contains a range of frequencies. Modulus of elasticity values obtained from resonant frequency data have correlated well with those measured by conventional compression tests, but often were correlated poorly with MT puncture forces. Abbott et al. (1968) proposed a stiffness coefficient, f^2m, which was based on the modulus of elasticity using the resonant frequency (f) and mass (m) of the specimen; this was later modified by Cooke and Rand (1973) to $f^2 m^{2/3}$. Farabee and Stone (1991) developed a portable sonic instrument for field determination of watermelon ripeness and hollow heart detection. Kawano et al. (1994) reported a commercial sorting machine for detecting internal voids in Japanese watermelon. Shmulevich et al. (1995) developed a sonic instrument using a lightweight flexible piezoelectric film sensor to follow changes in fruit during storage. Muramatsu et al. (2000) examined the relationship of both phase shifts and resonant frequencies to firmness. Nybom (1962) and Peleg et al. (1990, 1999) examined the sonic energy transmitted by the specimen rather than the resonant frequencies. Despite considerable research, sonic vibration has not yet become a viable option for the horticultural industry. However, there are several advanced commercial prototypes currently being evaluated.

Ultrasonic Tests. Ultrasonics (frequencies > 20,000 Hz) is widely used in the medical field and for analyzing meat. Ultrasonics has been used with limited success for measuring physical and chemical properties of fruits and vegetables because of the high attenuation (energy absorption) of plant tissues. The commonly measured ultrasonic parameters are velocity, attenuation, and frequency spectrum composition. Bruises in apples (Upchurch et al., 1987) and hollow heart of potatoes (Cheng and Haugh, 1994) could be detected in the laboratory using ultrasonics. Mizrach and Flitsanov (1999) and Mizrach et al. (1994, 1999) have followed the softening process in avocados, melons, and mangoes, respectively.

Light Scatter Imaging. As light passes through tissue, cellular contents such as starch granules, cell walls, and intercellular spaces cause scatter. The extent of scatter of collumated light such as a laser beam may change during ripening due to changes in cell-to-cell contact and compositional changes. Measurement of the scatter using computer vision may thus provide an indirect indication of textural changes. Significant correlations between mechanical properties and image size have been shown in apples (Duprat et al., 1995; McGlone et al., 1997; Cho and Han, 1999; De Belie et al., 2000a) and tomatoes (Tu et al., 2000).

Juiciness: The importance of juiciness has been demonstrated by numerous consumer awareness studies; however, there has been little progress in developing instrumental measurements of juiciness. Intuitively, one would expect total moisture content to determine juiciness, but the correlations between them are often low for fruits and vegetables (Szczesniak and Ilker, 1988). Apparently, inability of cells to release juice has a greater impact. For example, water content of juicy and chilling-injured peaches is similar, yet injured fruit have a dry mouth-feel; also mealy apples feel dry to the palate because cells separate at the middle lamella, rather than being ruptured and releasing juice during chewing. Generally, juiciness is characterized as weight or percentage of juice released from a fixed weight of tissue. Juice can be extracted from tissue using a press (like a cider press), homogenizing and centrifuging to separate juice from solids, using juice extractors, or measuring juice released during compression testing of excised tissue (Harker et al. 1997).

Summary: Texture measurement has become widely accepted by horticultural industries as a critical indicator of non-visual aspects of quality. The ability to measure texture has allowed industries to set standards for quality at pack-out and to monitor deterioration in quality that occurs during storage and distribution. Furthermore, the study of the chemical, physiological, and molecular changes that control and/or influence texture has been underpinned by the development of methods for quantifying texture change. Much of the commercial and research interest in texture has focused primarily on the mechanical properties of the tissues. The diversity of tissues involved, the variety of attributes required to fully describe textural properties, and the changes in these attributes as the product ripens and senesces contribute to the complexity of texture measurement. This complexity of texture can still only be fully measured by sensory evaluation, which involves using a panel of assessors that have been trained to score defined attributes against a set of standards. However, instrumental measurements are preferred over sensory evaluations for both commercial and research applications because instruments are more convenient to use, widely available, tend to provide consistent values when used by different (often untrained) people, and are less expensive than sensory panels. These instrumental measurements are widely understood and can provide a common language among researchers, industry, and customers. There are numerous empirical and fundamental measurements that relate to textural attributes. Mechanical methods measure functions of force, deformation, and time. Some indirect methods measure chemical constituents or physical characteristics. Destructive mechanical methods generally relate more closely to sensory evaluations than do nondestructive measurements; but, by their destructive nature, they cannot be used for sorting produce. Therefore, the commodity, purpose of measurement, and sometimes regulations, guide the choice of textural measurement.

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