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Review

Quantitative evaluation of mechanical damage to fresh fruits

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Fresh fruits are very susceptible to mechanical damage during harvesting, packaging and transport, which can result in a substantial reduction in quality. Ideally, such damage would be minimized through improved understanding of the mechanisms. If damage occurs, economic losses might be minimized by grading affected fruits, based on the severity of damage, into those that need more than minimal further processing and those that do not. In either case, an objective and quantitative evaluation of the degree of mechanical damage is required. However, this is still far from being realized and remains an important challenge of past and proposed research in food safety.

This review concerns the quantitative evaluation of mechanical damage to fresh fruits. Firstly, the sources of damage to fresh fruits during mechanical handling are summarized. The mechanisms are described in detail. Existing quantitative assessments characterizing surface and internal mechanical damage and its prediction are then reviewed. Finally, future research directions are discussed. The main challenge in evaluating mechanical damage to fresh fruit objectively is to develop a method to assess accurately the extent of internal damage to fruits caused by excessive external forces.

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Introduction

Fruits play an important role in providing essential vitamins, minerals, and dietary fiber to the world, and nowadays have become an important component of many human diets. The Food Agricultural Organization of the United Nations (FAO) has predicted that the world population will top eight billion by the year 2030. Furthermore, perceptions of health benefits have increased the popularity of minimally processed fruits whilst there has also been an ongoing trend to eat out and to consume ready-to-eat foods (Alzamora, Tapia, & Lopez-Malo, 2000). The demand for fresh and processed fruits and vegetables should therefore increase dramatically. To satisfy this demand, large-scale planting and mechanical handling (e.g. harvesting, packaging and transport) of fruits is necessary but fleshy fruits are very susceptible to mechanical damage (Li, Yang, *et al.*, 2013). Mechanical damage to fruits is mainly inflicted during field harvesting operations but also occurs in grading and packing lines, during transport, and in handling at the end of the supply chain for example during produce display and selection by retailers and consumers (Margarita, 1996). The quality of these crops can be substantially reduced by poor care and handling, especially if they are not consumed immediately, which is a serious food safety and economic issue.

Food security and agricultural efficiency require that urgent action is taken to minimize such losses. The potential mitigation schemes include (i) minimizing the incidence of damage by investigating the effects of the application of external forces during harvesting, packaging and transport and therefore to recommend improved handling methods to growers and others in the supply chain; and (ii) assessing the surface and internal damage of post-harvest fruits nondestructively and then sorting them into different damage grades for immediate or optional handling (i.e. not storable or storable). However, both (i) and (ii) require an objective and quantitative evaluation of the surface and internal mechanical damage to fruits. Surface damage of fruits is easily observed and may be determined objectively but internal damage is difficult to assess and measure. Unfortunately, internal damage usually leads to subsequent accelerated rot of a whole fruit (Van Linden, De Ketelaere, Desmet, & Baerdemaeker, 2006). Many fruits with apparently little damage during harvesting are subsequent discarded and losses in the harvest–consumption system might be as high as 51% (FAO, 2003). The objective of this paper is to review the literature in this field and to discuss future research directions.

Sources of mechanical damage

Improper physical handling during harvesting, grading, packaging and transport can result in structural, tissue and cell damage to fruits caused by impact, compression, abrasion, puncturing, testing, or several actions combined. Structural failure may increase susceptibility to decay and growth of microorganisms.

Impact damage

Impact damage occurs when an item hits a surface with sufficient force to rupture or even separate cells. The external sign is a bruise or crack. Common impact damage usually happens in free drops of fruits from trees to ground during harvesting and in dynamic impacts between single fruits and between them and packaging or containers. The latter results from vibrations (e.g. vibration of transporting vehicles, fruit containers subjected to transport vibration, conveyor belts with grading system vibration). Impact damage is the most severe mechanical damage mechanism in fruit handling (Van Zeebroeck *et al*., 2007a).

Free drop tests have shown that impact on metal surfaces inflicts the greatest damage to tomato fruits compared to five other potential packaging materials, whilst damage is least with foam (Idah & Yisa, 2007). Weeds, mulch and shock absorbing canvases covering the ground have been shown to reduce impact damage to fresh citrus fruits during mechanical harvesting (Ortiz, Blasco, Balasch, & Torregrosa, 2011). The percentage of damaged apples in single-wall and double-wall corrugated boxes increased with drop height during transport and handling and damage to apples in the lower layer of both boxes was notably higher than in the upper layer (Lu, Ishikawa, Kitazawa, & Satake, 2010). Bruise prediction models from impact tests show that factors such as impact energy, cultivar, impact location, ripeness, storage temperature and curvature radius at the location of impact have a significant effect on the bruise susceptibility of tomato fruits (Van Zeebroeck *et al*., 2007a) whilst the duration of impact plays a critical role. The bruising potential of low and medium energy impacts is largely controlled by the fruit texture whilst the effects of high and very high energy impacts depend mainly on fruit ripeness and the impact location (Van Linden, Scheerlinck, Desmet, & De Baerdemaeker, 2006). Simulations of impact damage to fruit during the passage of a truck over a speed bump showed that higher truck loads led to less bruising and that apples in bulk bins behind the rear axle suffered more damage than those in bins in front of the rear axle (Van Zeebroeck *et al*., 2008). Impact damage is alleviated by the harvesting of fruits at the half ripe stage when the fruit stiffness is higher than that of ripe fruits. This is because the extent (volume) of impact damage to fruit is inverse proportional to stiffness (Abedi & Ahmadi, 2013; Armstrong, Stone, & Brusewitz, 1997; Zarifneshat *et al*., 2010). Clearly, impacts during mechanical handling should be avoided as much as possible.

Compression damage

Compression also causes bruising and cracking. Compression damage occurs primarily during or after packing as a result of forcing too much product into too small a container. While fruits such as melon should be packed firmly enough to avoid chafing, they should not be stuffed in so tightly that their curved surfaces become flat. Compression damage also occurs during mechanical harvesting if grasp forces exceed a threshold for tissue failure. Compression tests have shown that the extent of compression, the curvature of the finger surfaces and internal structural characteristics affect mechanical damage to tomato fruits (Li, 2013; Li, Li, & Liu, 2010; Li, Li, & Yang, 2013; Li, Li, Yang, & Liu, 2013). Locular gel tissues were damaged before mesocarp and exocarp tissues.

Advancing fruit ripeness or increased vibration levels increase the susceptibility of packaged fruit to damage by compression loading. The factors (ripeness and vibration) are inter-related and together determine the intensity of compression damage inflicted on packaged fruits. Because of this, half-ripe tomatoes fruits should be preferred for road transportation in packaging containers (Babarinsa & Ige, 2012).

Strawberry fruits subjected to impact showed bruise volumes lower than compressed fruits, indicating the possibility of their being handled and graded in a packing line (Ferreira, Sargent, Brecht, & Chandler, 2008). The cultivar of the fruit may be important. For example, ‘Sweet Charlie’ strawberries showed bruise volumes about 40% higher than the others cultivars when subjected to compression. Aliasgarian, Ghassemzadeh, Moghaddam, and Ghaffari (2013) reported that the operations related to picking, packing and delivery to the market, fruit position in the box and box position on the truck, had significant effects on the extent of the mechanical damage to strawberry fruits.

The pattern of fruit bruising caused by slow compression is quite different from that caused by impact. Chen, Ruiz, Lu, and Kader (1987) reported that the cross section of a pear compression bruise resembled a parabola, similar to that in apples and peaches, but the cross section of an impact bruise often had long spikes extending radially from the impact area into the body of fruit. The irregular pattern of impact bruises makes it more difficult to quantify damage than with compression damage.

Abrasion

Abrasion occurs during movement of one body against another leading to the removal of surface layers. This may occur (i) during harvest when roots or tubers are dug up; (ii) when fruits are conveyed at excessive speed; and/or (iii) when the fruit surface is rubbed away by friction against dirt or sand or container surfaces during packing. Abrasion requires enough energy to be absorbed to remove surface material but not enough to cause tissue failure. Santana Liado and Marrero Dominguez (1998) showed that mechanical abrasion at 1 and 4 cm^2 per fruit significantly affected the physiological development of banana fruits (changes in respiration and ethylene production) and reduced final quality. The severity of the symptoms appeared to be correlated negatively with air humidity with effects on green life and commercial quality (Santana Liado & Marrero Dominguez, 1998).

Macleod, Kader, and Morris (1976) proposed that development of symptoms of tomato abrasion varied with ripeness. Abraded immature-green and partially mature-green tomato fruits developed a brownish, callus-like blistering over the injury. Fully mature-green tomato fruits developed no blisters, but the affected skin failed to develop normal color. Immature-green abraded fruit lost more water, shriveled more, and developed more severe symptoms than the mature green fruits.

Abrasion depends on the surface contacting the fruit and the design of the container or handling equipment. Timm, Brown, and Armstrong (1996) suggested that the U.S. apple industry could maintain low abrasion damage if bulk transport of apples was in plastic bins of specific designs and on semi-trailers having air-cushioned suspensions. Puchalski and Brusewitz (1996) proposed that different abrasive surfaces produced failure associated with different layers of the watermelon surface. For example, a masonite surface mainly caused removal of skin and deeper layers, fabric belting caused wax removal, and a steel surface caused changes in appearance and smoothing of the wax (Puchalski & Brusewitz, 1996).

Finally, Crisosto, Johnson, Day, Beede, and Andris (1999) demonstrated that the skin discoloration of abraded peach fruit was caused mainly by the combination of physical injury and contaminants resulting from foliar-nutrient, fungicide and insecticide preharvest sprays. Abrasion damage releases anthocyanin/phenolic pigments, which are located in the skin cells, allowing the reaction of these pigments with the heavy-metal contaminants.

Puncture

Puncture damage may occur during harvesting and manipulation of loose fruits when the stems of harvested fruits perforate the skin of neighboring fruits. Stems are not removed because they can contribute to the specific aroma of fruits and prevent the postharvest invasion of pathogens. Puncture wounds lead to a reduction in fruit value and considerable economic losses, a decrease of shelf-life and an increase of susceptibility to diseases and water loss. Some research has shown the elasticity and firmness of fruit and the toughness of the skin affect susceptibility to puncture injury (Desmet, Lammertyn, Verlinden, & Nicolai, 2002). This may be the reason that some cultivars are less susceptible and also why tomatoes have been found to be less susceptible after storage for several days (Desmet, Lammertyn, Scheerlinck, Verlinden, & Nicolai, 2003). There is also a significantly higher incidence of puncture injury for machine harvested compared to hand harvested fruit, and tomatoes are much more sensitive to puncture injury than abrasion during machine harvesting (Studer, Chen, & Kader, 1981). Puncture (and abrasion) injuries were more important than impact injury for papaya fruit during postharvest handling (Quintana & Paull, 1993). Peterson and Bennedsen (2005) reported that cuts and punctures seemed to be the most serious problem in mechanical harvesting experiments on five apple cultivars, and this might explain why apples growing inside the canopy are significantly more susceptible to damage than apples growing below the canopy. Except for these reports, there appears to have been little research on puncture damage of any fruits.

Mechanical damage to fruit

Fruits are hierarchically structured at the macro-scale, consisting of different types of tissue at the meso-scale, each of which is a highly structured arrangement of cells at the micro-scale. Fig. 1 shows this for tomato fruits but similar structures appear in apples, peaches and other fruits. Mechanical damage to fruit, manifested at the macro scale, is caused by failure of cells at the micro scale, although cells from different tissue types react differently to external forces (Abera *et al.*, 2013; Li, Li, Yang, & Liu, 2013; Mebatsion *et al.*, 2006). Mitsuhashi-Gonzalez, Pitts, Fellman, Curry, and Clary (2010) reported that bruised apple tissue was comprised of both live cells and dead cells that appeared to have burst, been crushed or sometimes were without apparent damage. The greater the amount of intercellular space present in the tissue, the more tissue damage from bruising occurred. Because airspaces

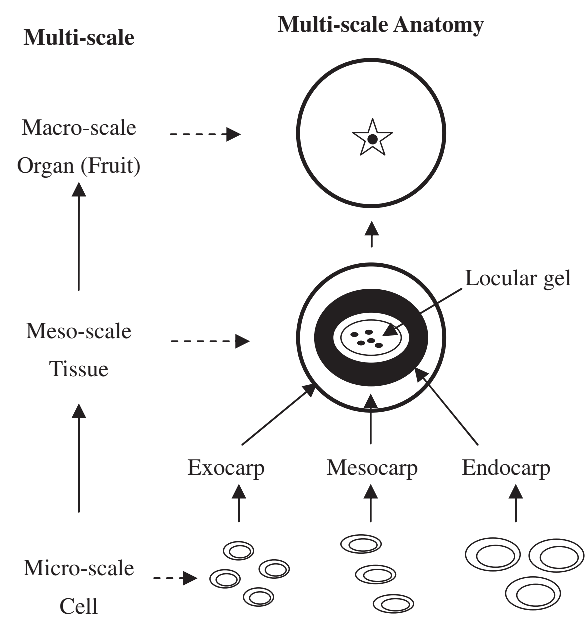

Fig. 1. Multi-scale structure of tomato fruit.

weakened the tissue, damage was initiated close to these sites. As apples matured, there was an increase in damaged cells surrounding larger intercellular spaces.

On the whole, browning in fruits due mechanical damage, can be considered to be a three-step process.

Cell damage: External forces applied directly to the surface of fruits cause damage to cells internally, which mainly consists of breakage of cell structures and the failure of membranes (Lin, Xi, & Chen, 2002). Because fruit tissues from different varieties have significant differences in their chemical composition (e.g. neutral sugars, uronic acid, pectin, protein content) and structures of their cell walls (e.g. mobile arabinan pectic side-chains), there will be different proportions of damaged cells after their tissues are mechanically broken during handling (Devaux *et al.*, 2005).

Enzymatic oxidation: For damaged cells, phenolic substances contained in the vacuole and enzymes contained in cell walls, membranes or cytoplasm, mainly polyphenol oxidase (PPO) and peroxidase (POD) will be brought into direct contact, possibly resulting in oxidative damage in the presence of oxygen (Billaud, Brun-Merimee, & Nicolas, 2004; Victoria Martinez & Whitaker, 1995). Enzymatic oxidation in the damaged cells transforms phenolic substances into quinine (Holderbaum, Kon, Kudo, & Guerra, 2010). Because phenolic substances from damaged cells will be in close contact with enzymes in adjacent cells, the oxidation will extend to nearby intact cells during storage. Because the presence of oxygen is necessary for enzymatic oxidation, the latter can be reduced if fruits are appropriately packed after mechanical damage. For example, Jiang and Fu (1999) proposed that the litchi fruit storied at 1 °C under controlled atmosphere (3–5% O_2 and 3–5% CO_2) at 90% RH gave good browning control and fruit quality maintenance.

Browning: The formation of quinine during oxidation results in imbalanced reduction so that it accumulates and can be oxidized further and polymerized to a brown pigment (Franck *et al.*, 2007). Transformation of phenolic compounds also leads to the "hardness" of damaged cells being reduced, observed as soft brown bruises appearing on the fruit during storage (Van Linden & De Baerdemaeker, 2005). Many types of phenolic substances can cause browning. For banana and lichee (sometimes lychee or litchi) this mainly results from dopamine and catechol compounds respectively (Jiang, Duan, Joyce, Zhang, & Li, 2004; Quevedo, Diaz, Ronceros, Pedreschi, & Aguilera, 2009; Sun *et al.*, 2012; Wuyts, De Waele, & Swennen, 2006) whilst the browning of pear, apple, tomato and peach mainly results from chlorogenic acid (Amaki, Saito, Taniguchi, Joshita, & Murata, 2011; Brandelli & Lopes, 2005; Gomes, Vieira, Fundo, & Almeida, 2012; Huang & Rohde, 1973; Weurman & Swain, 1953). Browning is usually inhomogeneous because the content of phenolic substances and the activity of PPO and POD is different between exocarp, mesocarp and endocarp tissues. For lichee, the phenolic content and PPO and POD activity are higher in external tissues so that is where browning always occurs. Conversely, the phenolic content and PPO and POD activity are lower in the external tissues of pear, tomato and longan and therefore browning occurs internally (Casado-Vela, Selles, & Bru, 2005; Quevedo, Diaz, Caqueo, Ronceros, & Aguilera, 2009). The activity of PPO and POD is also different between different varieties affecting their susceptibility to enzymatic browning, as shown for tomato (Spabna, Barbagallo, Chisari, & Branca, 2005). The activity of some enzymes does not vary with fruit damage. For example, the activities of pectin methylesterase and polygalacturonase in cell walls show no substantial changes with bruising of tomato fruit over short times (Van Linden, Daniel, Duvetter, De Baerdemaeker, & Hendrickx, 2008).

Mechanical damage has a significant effect on some physiological changes of post-harvest fruits such as mass loss, ethylene production, relative electrical-conductivity, respiration and transpiration (Elshiekh & Abu-Goukh, 2008; Li, Li, & Liu, 2011a). The speed and level of response of these physiological changes always vary with fruit type and location, variety, mechanical stimulation degree and so on (Yan, Zhao, Chen, Liang, & Hu, 2005). In comparing peach, pear and apple for example, Zhao (2005) showed that the respiration response of peach was the most sensitive to mechanical damage reaching its peak after 30 min; the respiration intensity of the other two fruits reaching peak responses 3–5 h after damage. The respiration intensity increased with the degree of damage to the fruit. The potential reasons include i) mechanical stimulation enhances the ethylene preparation and then induces respiration; ii) self healing and heal of damaged fruit increases the respiration. The aggravation of physiological changes during storage will accelerate fruit ripening or senescence and therefore decreasing shelf life. Furthermore, exocarp damage will result in a higher risk of bacterial and fungal contamination during storage and may provide another route to rot of a whole fruit (Blasco, Aleixos, & Moltó, 2003).

Quantitative evaluations of mechanical damage

Consumers demand high quality fruits, but how do farmers, wholesalers and retailers assess quality non-destructively, and how do researchers assess damage to fruits in order to understand mechanisms and to predict damage that may result from mechanical handling? Terms such as mechanical damage, bruising, puncture and abrasion are only qualitative terms. A quantitative and objective description of the degree of damage to fruits is important for producers and buyers to assess fruit quality and for research into improving fruit handling. Some quantitative analyses of mechanical damage to fruits have been carried out by assessing surface damage, for example using such parameters as the diameter, area or volume of damage ("damage diameter", "damage area" and "damage volume" respectively). Other approaches attempt to classify fruits as damaged or not and define a "probability of damage" from chosen handling conditions, or attempt to relate fruit mechanical parameters to damage or the likelihood of damage. These are described in more detail below. The purpose of such quantification is either for grading fruits for sorting or for investigations into the effects on fruit quality of the damage mechanisms described in Mechanical damage to fruit.

Surface mechanical damage

Surface damage means any defect or defects in the exocarp of a fruit. The application of an external force or forces can cause surface and/or internal mechanical damage. These might be associated, with the internal damage immediately beneath the damaged exocarp, or they might be separate, with internal damage in (parts of) tissues not in contact with the exocarp. In either case, any visible manifestations will be on the surface only. Surface damage of fresh fruits (browning and/or rupture) is visible and therefore also measurable. As can be seen from Table 1, Timm *et al.* (1996) and Vursavus and Ozguven (2004) quantified surface damage to apple fruits according to the damage diameter of the brown region appearing on the fruit surface, and used this parameter to evaluate the effects of packaging method and transportation conditions. They showed that vibration frequency, acceleration and duration, as well as the packaging method, significantly affected the extent of bruising. Apples in pattern packaging had by far the lowest bruising making this the most suitable method for transit.

Damage diameter is a simple measurement but assumes the visible damage is circular; it is essentially a one-dimensional parameter. On the other hand, damage area is particularly suitable for characterizing abrasion because it is a 2-dimensional parameter matching the nature of the damage. For example, Puchalski and Brusewitz (1996) graded surface abrasion of watermelon by linking 1–20 sensory scores to the area of wax spots and skin removed, and further investigated the effect of the abrasive surface and absorbed energy per unit contact area on the sensory score by a friction test. These researchers pioneered this quantitative evaluation method for assessing fruit surface abrasion. Damage area is also a rapid method of assessing bruising. Pang, Studman, Banks, and Baas (1996) and Idah and Yisa (2007) assessed the severity of apple and tomato surface damage objectively by calculating the damage area assuming that the surface shape of damaged tissue was circular or elliptical. Hadi, Ahmad, and Akande (2009) developed a bruise index (BI) related to average bruise area and the percentage weight of the fruits in various bruising categories by making a visual assessment on a lot consisting of 750 g of stripped oil palm fruits and screening the individual fruits into one of several bruising categories. The weight was chosen to represent the unmeasurable surface area of the oil palm fruits. A regression analysis on the free fatty acid of different ripeness levels and the bruise index was then performed successfully (Hadi *et al.*, 2009). For non-circular damage, the area should be a better measure of surface damage than the "diameter".

As can also be seen in Table 1, some researchers have estimated or measured the volume of damage directly associated with surface damage. This can be done by assuming a shape for the internal damage, which is not visible, or by measuring the depth of a bruise. In most studies, the diameter, width and sometimes the depth of the damaged tissues were measured by digital calipers and then the damage volume was calculated, by assuming that the shape of the damaged tissue was spherical (Ahmadi, Ghassemzadeh, Sadeghi, Moghaddam, & Neshat, 2010; Van Zeebroeck *et al.*, 2007b), an elliptical cone (Maness, Brusewitz, & McCullum, 1992) or ellipsoidal (Kitthawee, Pathaveerat, Srirungruang, & Slaughter, 2011; Lu *et al.*, 2010). The damage volume was then used as objective measure of the damage to fruits under various handling conditions. However, if the internal shape of the damage is assumed, damage volume, despite its name, is essentially another measurement of surface damage.

Although the damage area of fresh fruits is often found manually, it can also be measured by means of an automatic machine vision system (Blasco, Aleixos, Cubero, Gómez-Sanchis, & Moltó, 2009; Cubero, Aleixos, Moltó, Gómez-Sanchis, & Blasco, 2011). Existing national standards for grades of fresh fruits depend mainly on visible surface defects (USDA, 1931–2008). Therefore, quantitative inspection technologies based on surface damage are used for in-line non-destructive grading of fresh fruit quality. Blasco, Aleixos, Gómez-Sanchis, and Moltó (2009) and Blasco, Cubero, Gómez-Sanchis, Mira, and Moltó (2009) developed a machine for the automatic sorting of pomegranate arils based on computer vision and the grading success ratio was approximately 90%.

It should be noted that in all fruits, the degree of browning depends on the content of phenolic substances and the activity of PPO and POD in the tissues, as described in Mechanical damage to fruit. In some cases therefore, visual methods are hardly suitable, for example with ripe tomatoes where the color is close to that of damaged tissue. Furthermore, in some fruits, it is very hard to measure the extent of bruised areas because bruising results in only small changes at the surface (Salamolah, Shahzad, & Azimi, 2010). Some researchers have therefore defined bruises by class based on a visual examination, assumed to be related severity of damage. Typical damage classes for tomato fruits are: no bruise, a little skin softness, medium skin softness, severe skin softness, little faded- and completely faded- black area. Fluck and Halsey (1973) scored four types of damage on a true or false basis, calculated an overall damage rating for each damage type and then investigated the effect of drop height, cultivar and maturity on the incident of damage by linear and power function regression analysis. This research successfully pioneered the quantitative

Table 1. Measurement and calculation of damage diameter, area or volume of fruits.

Fruit	Parameter	Measurement method	Application	References
Apple	Damage rating index related to ***BD***	Digital caliper measurement	Degree of damage was divided into 5 classes: None, Trace, Slight, Medium and Severe based on measured ***BD***	Vursavus and Ozguven (2004)
Apple	Abrasion rating related to ***BD***		Each bruise was given a rating of A, B, C, D and E corresponding to its abrasion diameter	Timm *et al.* (1996)
Apple	Bruise region related to ***BA*** and ***BD***	Hyperspectral and thermal imaging technology	Detection of early or subtle bruises	Zhao *et al.*, 2008 Baranowski *et al.* (2009, 2012)
Citrus	Bruise region related to ***BA***	3-CCD camera	Recognition of external skin damages	Blasco, Aleixos, Gómez-Sanchis, *et al.* (2009), Blasco, Cubero, *et al.* (2009)
Watermelon	Sensory scores related to ***BA***	Visual inspection and feeling the surface with the finger	Sensory evaluation of abrasion was developed on the basis of a 1–20 score involving wax appearance, ***BA*** of skin and deeper layers of fruit	Puchalski and Brusewitz (1996)
Tomato	$BA = (\pi bd^2)/4$	Digital caliper measurement	Assessment of damage severity by ***BA***	Idah and Yisa (2007)
Oil palm	***BI*** related to ***BA***		1) Bruises classified into four based on ***BA*** 2) Effect of ***BI*** on the free fatty acid	Hadi *et al.* (2009)
Apple, olive	$BA = (\pi w_1 \cdot w_2)/4$ $BV = \pi d(3w_1 \cdot w_2 + 4d^2)/24$	1) Anatomy and digital caliper measurement 2) Measurement of digital caliper and pressure-sensitive film	1) Calculating bruise numbers and ***BA*** per fruit 2) Assessment of bruise susceptibility by ***BV*** 3) Regressing bruise prediction models by relating ***BV***, ***BA*** to impact force respectively	Pang *et al.* (1996) Lu *et al.* (2010) Saracoglu, Ucer, and Ozarslan (2011)
Young coconut	***BA*** $BV = (\pi w^2 \cdot d)/8$	Automatic leaf area measurement system Digital caliper measurement	Calculating bruise numbers and ***BA*** per fruit Bruise threshold determination of impact and compression tests	Kitthawee *et al.* (2011)
Apple	$BV = (\pi d \cdot BD^2)/6$	Digital caliper measurement	Regressing bruise prediction models by relating ***BV*** to contact force, curvature radius, storage temperature, stiffness, ripeness and harvest date	Van Zeebroeck *et al.* (2007b) Zarifneshat *et al.* (2010)
Peach	$BV = (\pi d \cdot BD^2)/6$	Digital caliper measurement	Regressing bruise prediction models by relating ***BV*** to contact force, stiffness and temperature	Ahmadi *et al.* (2010)
Pear	$BV = (1.33\pi w_1 \cdot w_2 \cdot d)/8$	Digital caliper measurement	Effect of drop height, ripeness and cultivar on ***BV***	Maness *et al.*, (1992)

BD – Bruise diameter, ***BA*** – Bruise area, ***BV*** – Bruise volume, ***BI*** – Bruise index, ***d*** – Bruise depth, w_1 and w_2 represent bruise widths along the major and minor axes, ***w*** – Bruise width.

evaluation of mechanical damage to fresh fruits. Subsequently, Salamolah *et al.* (2010) defined six types of deterioration for impacted fruits and found the percentage of each type for various tomato cultivars at various ripening stages. Evaluating the percentage of damage by a similar method was also used by Zhou, Su, Yan, and Li (2007) for pears. On the whole, the differences between the bruise classes are difficult to assess reliably, but a potential advantage is that the bruise classes can be used as a multi-level dependent variable in regression models for quantitative investigation of mechanical damage to fruits during handling.

Near infrared hyperspectral and thermal imaging technology is a new breakthrough for non-destructive detection of early or subtle surface (i.e. superficial) damage to fruits. It generates no waste, requires little or no sample preparation, is less expensive to run than conventional methods and can be used for a wide range of fruit species. Xing, Landahl, Lammertyn, Vrindts, and De Baerdemaeker (2003) investigated the effects of damage type on discrimination of damaged and undamaged apples by near infrared spectroscopy, and showed good discrimination of both impact and compression damage from undamaged tissues. There was greater misclassification occurred between the groups 'Non-damage' and 'Compression damage' than between the 'Impact damage' and 'Non-damage' groups. Lu (2003) investigated the potential of near–infrared hyperspectral imaging (NIHI) for detecting surface damage on apples in the spectral region between 900 nm and 1700 nm, and showed that 1000 nm–1340 nm was most appropriate range for damage detection. The NIHI system was able to detect both new and old surface damage with a correct detection rate from 62% to 88% for *Red Delicious* and from 59% to 94% for *Golden Delicious*. Zhao, Liu, Chen, and Saritporn (2008) proposed that the subtle damage of apple could be detected by hyperspectral imaging at 547 nm wavelength with close to a 89% success rate. Baranowski, Mazurek, Witkowska-Walczak, and Sławiński (2009) and Baranowski, Mazurek, Wozniak, and Majewska (2012) reported that early damage in apple tissues can be distinguished using hyperspectral data and thermal imaging. So far these methods distinguish between intact and damaged tissues but it is possible they could be extended to obtain damage area and depth based on the difference in reflectance between regions at a certain wavelength. Meanwhile, this is potentially a practical technology for grading fruits.

Internal mechanical damage

Internal damage means any defect or defects inside the tissues of the fruit, excluding its exocarp. In this section internal damage that is not associated directly with external bruising is considered. Such damage is the critical problem affecting the quality of fresh fruits e.g. their firmness, sugar content and acid content (Alfatni, Shariff, Abdullah, Marhaban, & Saaed, 2013; Montero *et al*., 2009) but it is very difficult to detect and assess quantitatively. Furthermore, damaged tissue blocks are always irregular in shape and are often segregated inside the fruit.

Damaged tissues of fruits always become brown during storage, which can be identified visually by cutting the fruit and observing any discoloration and indentation (Pang *et al*., 1996) or by allowing the fruit to rot so the damage becomes visible on the surface (Van Zeebroeck *et al*., 2007c). These methods are of course destructive and therefore are primarily used to quantify damage in order to understand damage mechanisms. Visual identification of the extent of damage relies on browning, the degree of which depends on the content of phenolic substances and the activity of PPO and POD in the tissues, as described in Mechanical damage to fruit. There is a significant difference in the content of phenolic substances and the activity of PPO and POD between external and internal tissues of a fruit (Lin *et al*., 2002; Underhill & Critchley, 1995). The lower the content of phenolic substances and the activity of PPO and POD, the less obvious the browning of damaged tissue, which might result in inaccurate quantification. To overcome this problem whilst still making useful measurements, some workers have used a statistical approach to assess the susceptibility of fruit to damage when handled. In these studies, summarized in Table 2, it was assumed that fruits are damaged or not after mechanical handling and on this basis, the probability and percentage of mechanical damage were calculated. Bruising was regarded as a binary response variable, present (1) or absent (0). Logistic regression is the appropriate statistical method to relate such binary responses to handling or test conditions. Based on a subjective sensory score that evaluated the damage area of fruit after a two day incubation following an impact test, Van Linden, De Ketelaere, *et al*. (2006) and Van Linden, Scheerlinck, *et al*. (2006) recorded bruising and used a logistic regression model to successfully predict the probability of various tomato cultivars developing bruises under different impact conditions. Lammertyn, Aerts, Verlinden, Schotsmans, and Nicolai (2000) made a similar logistic regression model to predict objectively the probability of damage to pears based on a visual binary score after cutting each pear in two (Lammertyn *et al*., 2000) whilst Desmet *et al*. (2003) and Desmet, Van Linden, Hertog, and Verlinden (2004) used a binary bruising response to identify the damaging impact energy threshold (Desmet *et al*., 2003, 2004). Modeling methods like these may allow the likelihood of damage to be predicted from the external forces applied to fruits in handling, and therefore may permit mitigating measures to be suggested.

Severe damage during mechanical handling can result in fruit rupture. This may be higher risk for food safety than internal damage. Fortunately it may be identified objectively, so Li (2013) predicted the effect of compressibility, loading position and probe shape on the probability of rupture of tomato fruits during robot harvesting. In yet another approach, Menesatti, Beni, Paglia, Marcelli, and D'Andrea (2001) and Menesatti *et al*. (2002) estimated the "drop damage index" (DDI) of apple, pear, peach and apricot by multiple linear or nonlinear regression models based on drop height threshold, and proposed that the values of the DDI predicted by logarithmic models are more suited to describing the reality of impacts and cultivar-specific sensitivity to damage.

Sensory evaluation methods are rather subjective but nuclear magnetic resonance (NMR) imaging may be a more objective (and non-destructive) technology for distinguishing between sound and damaged tissues of fruit based on characterizing the environment of water protons in plant tissue. Hernandez-Sanchez, Barreiro, Ruiz-Altisent, Ruiz-Cabello, and Fernandez-Valle (2004) and Hernandez-Sanchez, Hills, Barreiro, and Marigheto (2007) investigated the difference in magnetic resonance imaging between sound and damaged tissues of pears and reported that the disordered tissue showed higher transverse relaxation rates and the proton pools in disordered tissue were grouped into a smaller number of populations compared to sound tissue. Several studies have shown that internal browning and core breakdown can be detected in apples (Gonzalez *et al*., 2001), pears (Hernandez-Sanchez *et al*., 2007), mangoes

Table 2. Measurement of probability and percentage of mechanical damage to fruits.

Fruit	Parameter	Measurement method	Application	References
Pear	***p***	Logistic regression modeling based on visual evaluation score	Effect of storage environment, picking date, firmness, size and weight on ***p***	Lammertyn *et al.* (2000)
Tomato	***p***	Logistic regression modeling based on sensory evaluation score	Effect of impact energy, impact location, restitution coefficient, contact time, storage temperature, ripening, mass and cultivar on ***p***	Van Linden, De Ketelaere, *et al.* (2006), Van Linden, Scheerlinck, *et al.* (2006)
Tomato	***π***	Logistic regression modeling based on damaging impact energy threshold	Effect of impact energy, impact angle, cultivar, storage time and velocity on ***π***	Desmet *et al.* (2003, 2004)
Apple	***DDI***	Multiple non-linear modeling based on drop height threshold	Effect of drop height and firmness on ***DDI*** during free drop tests	Menesatti *et al.* (2002)
Apple Pear Apricot Peach	***DDI***	Multiple linear modeling based on drop height threshold	Effect of fruit type, physical variables, maturity variables and post-impact variables on ***DDI*** during free drop tests	Menesatti *et al.* (2001)
Tomato	***D***	Power function regression analysis based on visual evaluation score	Effect of drop height, cultivar and maturity on ***D***	Fluck and Halsey (1973)
Tomato	***SQ***	3D bar diagram analysis based on visual evaluation	Effect of ripening stage and variety on ***SQ***	Salamolah *et al.* (2010)
Avocado	***DS***	Damage severity evaluation based on surface discoloration	Effect of firmness, ripening stage and variety on ***DS***	Arpaia, Mitchell, Katz, and Mayer (1987)
Pear	***PD***	Visual evaluation	Effect of loading position on bruise number and ***PD*** of fruits during transport	Zhou *et al.* (2007)
Orange	***PD***	Relative loss rate of mass	Effect of conveyor chain velocity on the mean value of the *PD* at different values of stopping time and sphericity percentage during grading	Gamea, Aboamera, and Ahmed (2011)
Peach	***PD***	Statistic calculation	Effect of drop height on ***PD*** during free drop	Menesatti *et al.* (2001)

p – Impact bruise probability of fruit, ***π*** – Puncture injury probability defined by the proportion of punctured tomatoes, ***D*** – Incidence of damage from free drop impact, ***SQ*** – Severity classes and quantity of damage, ***DS*** – Damage scale, ***PD*** – Percentage of damage during transport, ***DDI*** – Drop damage index from free drop.

(Joyce, Hockings, Mazucco, Shorter, & Brereton, 1993) and tomatoes (Milczarek, Saltveit, Garvey, & McCarthy, 2009). Milczarek *et al.* (2009) developed an in-line method to detect damaged pericarp tissue of tomatoes using multivariate analysis of NMR images. NMR is promising but expensive and impractical for fruit handling at its current technological level. If it became cheap and easy to use, possibly as an in-line method (Milczarek *et al.*, 2009), it might be used to optimize fruit harvesting, handling and processing.

Mechanical parameters

From a material science viewpoint, fruit mechanical damage is the failure of a biomaterial, and as such closely relates to fruit mechanics. It is not surprising therefore that fruit mechanical parameters have been used as surrogates for mechanical damage. Many mechanical parameters can be derived from force–time (Van Linden, De Ketelaere, *et al.*, 2006) and force–displacement curves (Li, Li, & Liu, 2011b) found by impact, quasi-static compression, puncture and abrasion tests. Measured or calculated parameters include impact energy, rebound energy, absorbed energy, restitution coefficient, contact time, peak force, compression energy, compressibility and loading slope (Kilickan & Guner, 2008; Pallottino, Costa, Menesatti, & Moresi, 2011; Van Linden, De Ketelaere, *et al.*, 2006). Some of these can be correlated and this can be tested statistically by calculating Pearson correlation coefficients (Desmet *et al.*, 2002). For example, for impact tests on tomato fruits, Desmet, Van Linden, Hertog, and Verlinden (2004) proposed that there was a linear relationship between impact energy and peak force at high levels (>0.01 J) although the relationship was no longer linear at low energy levels.

Since fruits are hierarchically structured materials, responses of fruits to loads during handling and in tests can include structural, tissue and cell deformations (Ho *et al.*, 2013). These deformations are the mechanical basis of bruising. When the bruising threshold of fruit is exceeded during handling, load-induced stresses exceed cell and tissue failure stresses and a bruise results (Ruiz-Altisent & Moreda, 2011). This suggests changes in mechanical parameters might be used to quantify damage directly, comparing the effects of processing or test conditions on the values of those parameters. Examples of this approach in which single mechanical parameters have been used to represent mechanical damage to fruits are given in Table 3.

In mechanical tests, part of the applied energy is permanently stored in the fruit because of plastic deformation of the structure and viscous and plastic deformations of tissue

Table 3. Mechanical damage quantified by mechanical parameters of fruits.

Fruit	Parameter	Measurement method	Application	References
Apple	$\boldsymbol{E_a}$	Derived from time–force curve of free drop test	Effect of fruit mass, drop height, shear stress and storage time on $\boldsymbol{E_a}$	Yuwana and Duprat (1998)
Tomato	$\boldsymbol{E_a}$	Derived from time–force curve of impact test	Effect of ripeness, stiffness, storage temperature, impact location, curvature radius and peak force on $\boldsymbol{E_a}$	Van Zeebroeck *et al.* (2007a)
Kiwifruit	$\boldsymbol{E_a}$	Derived from time–force curve of impact test	Effect of stiffness, storage temperature, curvature radius, impact energy and peak force on $\boldsymbol{E_a}$	Ahmadi (2012)
Tomato	$\boldsymbol{E_a}$	Derived from displacement–force curve of compression test	Effect of ripeness stage, vibration level and container type on $\boldsymbol{E_a}$	Babarinsa and Ige (2012)

$\boldsymbol{E_a}$ – Absorbed energy.

or cell. Ignoring losses, the absorbed energy is equal to the difference between the applied (impact or compression) energy and the rebound energy. Higher absorbed energy indicates higher bruise damage (Van Zeebroeck *et al.*, 2007a). Some researchers have proposed using absorbed energy to quantify bruising damage (Ahmadi, 2012; Babarinsa & Ige, 2012; Van Zeebroeck *et al.*, 2007a). However, not all absorbed energy is transferred into plastic deformation (damage) as some is a viscous response. A hypothesis has been made by Van Zeebroeck and colleagues that the ratio of viscous to plastic energy is constant at a given applied energy. However, this needs to be verified before absorbed energy is used as a surrogate for bruising.

Blahovec and Paprstein (2005) proposed that the susceptibility of pear fruit to bruising increases with both decreasing elasticity and hysteresis losses in loading-unloading compression tests. Kitthawee *et al.* (2011) proposed that the bruise volume of young coconut husk could

Table 4. Relation between mechanical damage and mechanical parameters.

Fruit	Regression models	References
Apple	$\boldsymbol{BV} = 0.239\boldsymbol{PF}^{1.796} + 43.488X_2 + 3.484T - 1.596X_2\cdot\boldsymbol{PF} - 0.112\ \boldsymbol{PF}\cdot T - 3.664r + 0.102r\cdot\boldsymbol{PF}\ (R^2 = 0.896)$ $\boldsymbol{BV} = 478 + 3748\boldsymbol{E_i} + 920X_1 + 375X_2 + 0.62T - 3.82w - 14S - 4r + 520\boldsymbol{E_i}\cdot X_1 - 630\boldsymbol{E_i}\cdot X_2 - 53\boldsymbol{E_i}\cdot T + 67\boldsymbol{E_i}\cdot r - 0.79X_1\cdot w - 25X_1\cdot S - 12X_2\cdot S + 0.14w\cdot S (R^2 = 0.934)$	Van Zeebroeck *et al.* (2007c)
Peach	$\boldsymbol{BV} = 50.877 + 68.914\ \boldsymbol{PF} + 21.069T - 57.751S - 9.683r - 0.353\ \boldsymbol{PF}\cdot T + 1.218\ \boldsymbol{PF}\cdot S\ (R^2 = 0.97)$ $\boldsymbol{BV} = 530.88 + 24{,}516\boldsymbol{E_i} + 9.836T - 20.102S - 1.218r - 97.142\boldsymbol{E_i}\cdot T (R^2 = 0.98)$	Ahmadi *et al.* (2010)
Apple	$\boldsymbol{BV} = 22.9\boldsymbol{PF} - 4.5S - 3.25r + 0.97T - 0.097\ \boldsymbol{PF}\cdot T - 0.23\ \boldsymbol{PF}\cdot r (R^2 = 0.93)$ $\boldsymbol{BV} = 7186.95\boldsymbol{E_i} - 6.97r - 1.48T + 1.94S - 16.09\boldsymbol{E_i}\cdot T + 5.97\boldsymbol{E_i}\cdot r (R^2 = 0.98)$	Zarifneshat *et al.* (2010)
Young coconut	Impact test: $\boldsymbol{BV}(14\ \text{mm}) = 1172.6\boldsymbol{E_i} - 21.5\ (R^2 = 0.98)$ $\boldsymbol{BV}(19\ \text{mm}) = 1259\boldsymbol{E_i} - 20.4\ (R^2 = 0.99)$ $\boldsymbol{BV}(25\ \text{mm}) = 1460.6\boldsymbol{E_i} - 48.9\ (R^2 = 0.97)$ $\boldsymbol{BV}(19\ \text{mm}) = 1869.6\boldsymbol{E_i} - 82.7\ (R^2 = 0.99)$ Compression test: $\boldsymbol{BV}(14\ \text{mm}) = 865.7\boldsymbol{E_c} - 270.3\ (R^2 = 0.88)$ $\boldsymbol{BV}(19\ \text{mm}) = 822.33\boldsymbol{E_c} - 333.4\ (R^2 = 0.95)$ $\boldsymbol{BV}(25\ \text{mm}) = 840.2\boldsymbol{E_c} - 250.0\ (R^2 = 0.95)$ $\boldsymbol{BV}(32\ \text{mm}) = 651.9\boldsymbol{E_c} - 271.0\ (R^2 = 0.99)$	Kitthawee *et al.* (2011)
Pear	$\boldsymbol{BV} = 0.0637\boldsymbol{HL}^2 - 7.2208\boldsymbol{HL} + 201.96\ (R^2 = 0.8999)$	Blahovec, Mares, and Paprstein (2004)
Tomato	$\text{Logit}(\boldsymbol{p}) = 0.0706 + 1.1355\boldsymbol{E_i} + 0.5484L - 0.5484CW + 0.2432cv.Trad - 1.122cv.Adm + 0.8788cv.SG + 0.7063Time + 0.3763r_c + 0.4627\boldsymbol{E_i}\cdot r_c$	Van Linden, De Ketelaere, *et al.* (2006)
Tomato	$\text{Logit}(\boldsymbol{\pi}) = 0.5028 - 0.41\boldsymbol{F_{max}} - 0.08D - 0.42\boldsymbol{E} - 0.22\boldsymbol{T} - 0.33A_f$ $\text{Logit}(\boldsymbol{\pi}) = -5.39 + 0.07\boldsymbol{E_i} - 2.63C - 0.19ST + 0.007\boldsymbol{E_i}\cdot ST + 0.31ST\cdot C$ $\text{Logit}(\boldsymbol{\pi}) = -6.27 + 74.9\boldsymbol{E_i} - 3.17C$	Desmet *et al.* (2002, 2003, 2004)

$\boldsymbol{BV}$ – Bruise volume, $\boldsymbol{X_1}$ and $\boldsymbol{X_2}$ – Dummy variables for harvest date, $\boldsymbol{T}$ – Temperature, $\boldsymbol{PF}$ – Peak contact force, $\boldsymbol{r}$ – Radius of curvature on location of impact, $\boldsymbol{E_i}$ – Impact energy, $\boldsymbol{w}$ – Mass, $\boldsymbol{S}$ – Stiffness, $\boldsymbol{E_c}$ – Compression energy, $\boldsymbol{r_c}$ – restitution coefficient, $\boldsymbol{HL}$ – Hysteresis losses, $\boldsymbol{L}$ and $\boldsymbol{CW}$ – Two impact positions, *cv.Trad*, *cv.Adm* and *cv.SG* – Three tomato cultivars, $\boldsymbol{F_{max}}$ – Maximum force to puncture the intact tomato, $\boldsymbol{D}$ – Penetration depth of the probe, $\boldsymbol{E}$ – Slope, $\boldsymbol{T}$ – Puncture energy, $\boldsymbol{A_f}$ – Firmness, $\boldsymbol{C}$ – Cultivar, $\boldsymbol{ST}$ – Storage time, $\boldsymbol{p}$ – Impact bruise probability of fruit, $\boldsymbol{\pi}$ – Puncture injury probability.

be correlated linearly with either compression or impact energy above the bruise threshold limit. The latter depended on whether the fruits were immature, mature or overmature, with the corresponding impact energy thresholds being 0.264 J, 0.245 J and 0.207 J and compression energy thresholds being 2.17 J, 1.13 J and 0.76 J. Despite these reports, it seems optimistic to hope that susceptibility to bruising could be characterized by a single mechanical parameter and most researchers have therefore used multi-variable regression analysis to relate mechanical damage (bruising, probability of bruising on impact, probability of puncture injury) to a range of mechanical, geometrical, harvesting and cultivar parameters. Table 4 summaries these studies. It can be seen that there is little consistency although it seems that the most important mechanical parameters determining differences in susceptibility of fruits to mechanical damage are peak force (on impact) and impact or compression energy.

Future research directions

Likely directions for future research on quantitative evaluation of mechanical damage to fresh fruits can be summarized as follows:

(1) Improvements in methods to assess internal damage of fruits after mechanical handling. This has not been achieved so far because such damage cannot be visualized non-destructively and because different tissues in different fruits have different extents of browning, as described in Mechanical damage to fruit. NMR can distinguish intact and damaged tissues and is a method for assessing internal damage volume of fruit objectively, at least in the laboratory. This approach is worth further investigation, although transfer of these high technology methods to the supply chain may be problematic.

(2) Studies on the relationship between surface and internal mechanical damage. Surface damage can be evaluated as the area of damaged exocarp and predictions of associated internal damage could be validated using existing experimental methods (Idah and Yisa, 2007; Van Linden, De Ketelaere, *et al*., 2006; Van Zeebroeck *et al*., 2007a). Should any relationships exist between surface and internal damage, it would be possible to predict internal damage from surface damage and allow future research using absorbed energy or peak contact force (Van Zeebroeck *et al*., 2007a) as a surrogate measure of damage.

(3) Logistic regression modeling of damage could be enhanced by combining it with NMR, hyperspectral imaging, X-rays or ultrasonic techniques. Existing sensory evaluation methods are somewhat subjective and the use of new, more objective, technologies could lead to a better understanding of how handling causes bruising.

(4) Table 4 shows little consistency in regression models linking bruising and mechanical parameters from compression and impact tests. Fewer, better understood, correlations would be preferable. This will require multiscale mathematical modeling using nonlinear finite element methods to interpret test results. Furthermore, high quality models will strengthen the accuracy of predictions of damage to fruits from mechanical handling.

(5) Investigation of the food safety and quality implications of structural damage to fruits. The emphasis of research has been on bruising but many fruits such as tomato are inhomogeneous bodies and may suffer structural damage as well as cell and tissue damage. The former has been neglected although it may lead to increased decay during storage.

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