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Review

Fruit biomechanics based on anatomy: a review

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Abstract. Fruit biomechanics is needed for quality determination, multiscale modelling and engineering design of fruit processes and equipments. However, these determined fruit biomechanics data often have obvious differences for the same fruit or tissue. In order to investigate it, the fruit biomechanics based on anatomy was reviewed in this paper. First, the anatomical characteristics of fruit biomaterials were described at the macroscopic 'tissue' level and microscopic 'cellular' level. Subsequently, the factors affecting fruit biomechanics based on anatomy and the relationships between fruit biomechanics, texture and mechanical damage were summarised according to the published literature. Fruit biomechanics is mainly affected by size, number and arrangement of cells, quantity and volume of intracellular spaces, structure, thickness, chemical composition and permeability of cell walls, and pectin degradation level and turgor pressure within cells based on microanatomy. Four test methods and partial determined results of fruit biomechanics were listed and reviewed. The determined mechanical properties data of fruit are only approximate values by using the existing four test methods, owing to the fruit biomaterials being non-homogeneous and living. Lastly, further aspects for research on fruit biomechanics were proposed for the future.

Keywords: fruit, anatomy, biomechanics, multiscale modelling, finite element analysis

INTRODUCTION

Fruits are normally the fleshy seed-associated structures of certain plants that are sweet and edible in the raw state, such as apples, oranges, grapes, strawberries, juniper berries, tomatoes and bananas (Martin, 2010). Nowadays fresh fruits have become an important part of the diet of people all over the world as they are high in fibre, water, vitamin C and natural sugars. To satisfy the people living demand, the planting area of fruits is enormous in the world every year and the distribution is extremely wide. Several external forces, which exceed the threshold for tissue failure, always cause mechanical damage to the fruit during mechanical harvesting, sorting, cleaning, packaging and transporting (Linden *et al*., 2006). In order to reduce and prevent mechanical damage, much research has been focused on the effect of fruit biomechanics on bruise susceptibility (Ahmadi *et al*., 2010; Allende *et al*., 2004; Desmet *et al*., 2002; Zeebroeck *et al*., 2007a). In fact, fruit biomechanics parameter is regarded as a quantitative indicator of fruit texture. To accurately review the fruit biomechanics, the anatomy of fruit biomaterials were expatiated in this section.

Fruit anatomy at the macroscopic 'tissue' level: the fruit mainly consist of pericarp and seeds, and the pericarp is typically made up of three layers: exocarp, mesocarp and endocarp (Cutler *et al*., 2008) (Fig. 1). The three layers always have obvious differences in thickness and chemical composition for the same fruit. Exocarp, which is the outermost layer of fruit pericarp, is often composed of cuticle, epidermis and 1~2 subepidermal parenchyma cell layers. The parenchyma cells of exocarp are rich in chloroplasts during unripe stage. As the fruit approaches ripe stage, most of the chloroplasts are transformed into carotenoid-rich chromoplasts. Mesocarp, which is the middle layer of pericarp, is parenchyma tissue composed of cells containing inorganic and organic compounds and constituting the ground tissue of edible portion of the fruit. Many fruits have large differences in physical composition of mesocarp tissue. Some fruits, such as apple, peach, apricot and tomato, whose mesocarp is fleshy or rich in juice, and others, such as orange, whose mesocarp is rich in vascular bundle that is reticulation distribution. Endocarp, which is the inside layer of pericarp, directly surrounds the seeds. Like mesocarp, many fruits endocarp also has differences in physical composition. The endocarp may be membranous as in citrus,

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where it is the only part consumed, or thick and hard as in the stone fruits of the family *Rosaceae* such as peach, cherry, plum, and apricot (Khan, 2001).

Fruit anatomy at the microscopic 'cellular' level: the fruit is composed of cells subject to different processes such as cell division, cell differentiation, cell endoreduplication, cell expansion, metabolic transformations and vacuolar storage (Genard *et al*., 2007). The cells of fruit exocarp, mesocarp and endocarp tissue always have obvious differences in shape, size, number and arrangement (Fig. 2). For example, Souza *et al*. (2008) proposed the cells of *Macfadyena unguis-cati* L. fruit exocarp at maturity are small and their arrangement is compact and dense. The mesocarp is collenchymatous and parenchymatous, with elongated or isodiametric cells of variable size. The subendocarpic mesocarp consists of two to four layers of elongated cells arranged longitudinally, transversally or obliquely in the fruit. The endocarp has fibre-like cells with thickened and non-lignified walls. Endocarpic cells may be arranged longitudinally, transversally or obliquely in the pericarp (Souza *et al*., 2008). Similar observations are also found for Longan (Jaitrong *et al*., 2005), *Hacquetia epipactis* (Karcz *et al*., 2008), *Citrus reticulate* (Kim, 2003), *Chorisia speciosa* (Marzinek and Mourao, 2003), borassoid fruit (Romanov *et al*., 2011), *etc.* Fruit cell consists of cell wall and protoplast; the cell wall is located outside the protoplast and provides the cell with structural support and protection. The cell wall has three layers, namely middle lamella, primary cell wall and secondary cell wall. The middle lamella, which glues the primary cell walls of adjacent fruit cells, is thin and rich in pectin; the primary cell wall is thin and rich in pectin, hemi-cellulose and cellulose; the secondary cell wall is thick and rich in cellulose. The cell walls of fruit tissue are rich in protopectin at the immature stage; the insoluble protopectin content of tissue cell walls gradually decreases with fruit ripening, while the soluble pectin content increases, so the

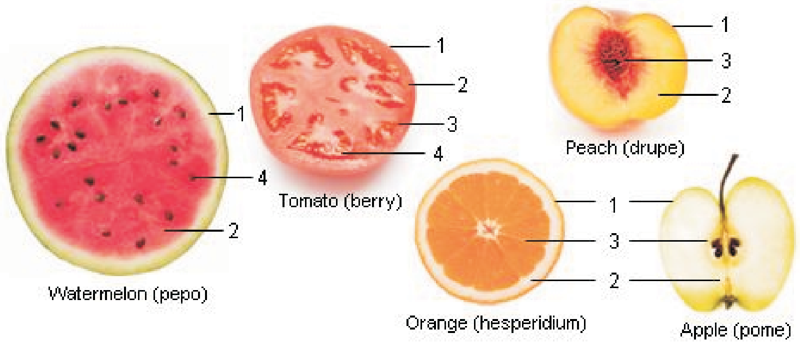

Fig. 1. Fruit anatomy. 1-exocarp, 2-mexocarp, 3-endocarp, 4-seed.

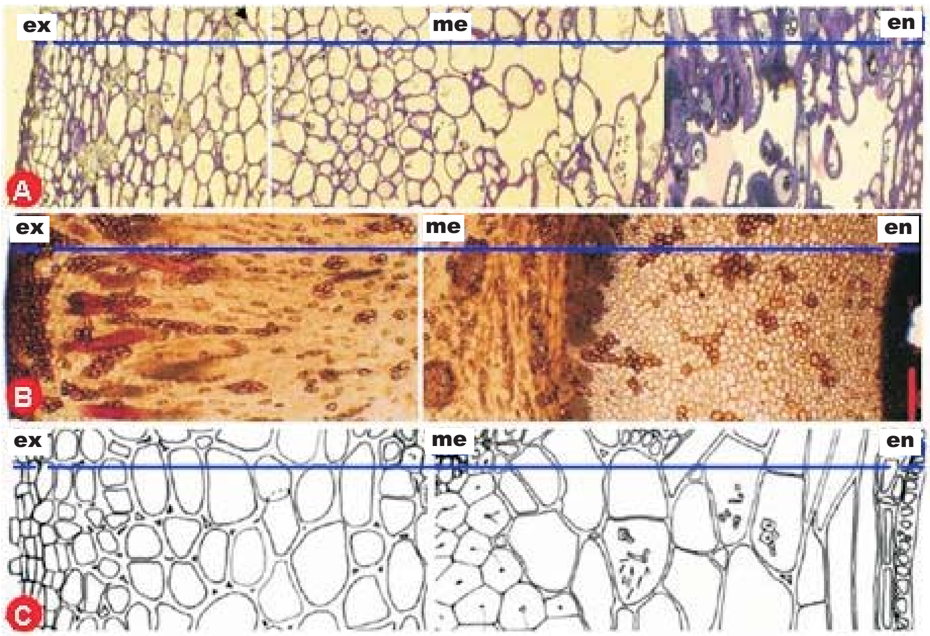

Fig. 2. SEM micrographs of fruit pericarp structure: A – longan fruit pericarp (Jaitrong *et al*., 2005); B – borassoid fruit pericarp (Romanov *et al*., 2011); C – *Macfadyena unguis-cati* L. fruit pericarp (Souza *et al*., 2008); ex – exocarp, me – mexocarp, ep – endocarp.

fruit tissue gradually becomes soft during ripening. Some researchers pointed out that the chemical features of fruit cell wall have a close relationship with its category, growing environment, variety, ripening stage, *etc*. (Abdul Khalil *et al*., 2006; Fischer *et al*., 1996; Ozturk *et al*., 2009; Ratule *et al*., 2007).

The assumption that the material is linearly elastic, homogenous and isotropic must be made before the mechanical parameters of material are determined and calculated from different test methods according to the national standards. The assumption is always regarded as acceptable for metal and plastic materials, but it is very difficult for fruit biomaterials to meet the assumption according to fruit anatomy. The fruit biomaterial seems like a complicated multibody system. Recently there are large amounts of published data on fruit biomechanics determined by different test methods in the literature, but these mechanical properties data often have obvious differences for the same fruit or tissue. In view of this, the objective of this paper is to review the fruit biomechanics based on fruit anatomy.

GENERAL ASPECTS ON FRUIT BIOMECHANICS

Fruit biomechanics is the mechanical behaviour of fruit biomaterial under applied external forces, which is always expressed in terms of stress, strain and time effects. Fruits are usually characterized by some solid and liquid properties and are termed viscoelastic bodies (Barbosa-Canovas *et al*., 2006). Their stress-strain behaviour will be changed not only with the applied strain rate, but also with the applied amount of strain. Fruits are anisotropic in nature and their mechanical properties may vary in the direction of stress application (Kilickan and Guner, 2008; Li *et al*., 2011). Fruit biomechanics are characterized under compression, tension and shear test (Vincent, 1990). As small deformations are exerted under test, fruits can show an approximate straight line in the stress-strain diagram, and its slope is elastic modulus. Fruits standard biomechanical parameters are mainly composed of failure stress and strain, failure energy, elastic modulus and Poisson ratio of fruit biomaterials. In reality, these parameters are calculated from the force-distance curves obtained in tests. In recent research, the peak force, elastic and plastic strain energy, degree of elasticity and loading slope of fruit at different compressibility levels during loading-unloading test and the rupture energy and force, compressibility and loading slope of fruit at initial rupture during compression test are also regarded as fruits biomechanical parameters. This is due to the fruits having irregular spheroid shapes and the contact area between probe and fruit changing continuously during loading, and thus the standard biomechanical parameters are difficult to be obtained while the determined non-standard biomechanical parameters in tests indirectly reflect fruit biomechanics. Fruit biomechanics is needed for quality determination, engineering design of fruit processes and equipments, and finite element prediction of mechanical damage during harvesting, packaging, transporting and handling.

According to the published literature, the factors that affect fruit biomechanics can be summarized as variety (Haciseferogullari *et al*., 2007; Owolarafe *et al*., 2007), ripening stage (Bargel and Neinhuis, 2005; Soltani *et al*., 2011), producing area, planting and harvest time and storage conditions (Singh and Reddy, 2006) at the macro level. In fact it is only apparent that the fruit biomechanics is essentially influenced by size, number, shape, arrangement, structure and chemical composition of cells (Konstankiewicz and Zdunek, 2001), size (Zdunek and Umeda, 2005), structure (Cybulska *et al*., 2010a) and chemical composition (Zykwinska *et al*., 2008) of cell wall, quantity and volume of intracellular spaces (Cybulska *et al*., 2011), pectin degradation level and turgor pressure within cells (Brummell and Harpster, 2001) based on micro-anatomy. Cell walls are the main structural component affecting fruit biomechanics (Cybulska *et al*., 2010b; Waldron *et al*., 2003; Zdunek and Konstankiewicz, 2004). The effect of all macro factors on fruit biomechanics can be explained with the fruit micro-anatomy. For example, the reason why variety has a significant effect on the cracking force and pressure of fresh oil palm fruit is that the chemical composition *eg* neutral sugars, uronic acid and protein content and structure of cell walls in pericarp tissue are diverse for different fruit varieties (Devaux *et al*., 2005; Linden *et al*., 2008). The reason why the elastic modulus of tomato fruit skin increases during ripening can be attributed to that the ripening process involves a chemical change in which protopectin is converted to soluble pectin (Ali and Abu-Goukh, 2005). The significant effect of storage conditions on mechanical properties is due to that the storage conditions change the physiological activity of fruit and the tissue chemical composition is varied (Ding *et al*., 2006). The reason why the stress-strain curve of fruit tissue reveals a biphasic behaviour can be attributed to that intercellular spaces exist in the fruit tissue (Alamar *et al*., 2008). Additionally, several researchers also proposed the loading position (Li *et al*., 2011) and the fruit geometric characteristics (Allende *et al*., 2004) as factors having a significant effect on fruit biomechanics, since mainly because the fruit is non-homogeneous on the inside at the macroscopic 'tissue' level, the structural characteristics change the measured biomechanical parameters, and the obtained biomechanical parameters are not the standard mechanical parameters of fruit biomaterial.

Texture in fruits is generally defined as the overall feeling that a fruit gives in the mouth and is therefore made up of characteristics that can be evaluated by touch, such as hardness, cohesiveness, viscosity, springiness and adhesiveness (Sams, 1999). The multidimensional characteristics not only influence the consumer acceptability, but also have a significant effect on whole quality, shelf-life, and transportability (Guine *et al*., 2011). Fruit biomechanics is always regarded as the basic quantitative analysis for fruit sensory properties related to texture. The determined parameters in mechanics performance testing measure the textural characteristics of fruit. For instance, the texture profile analysis (TPA), which is one of the most classic methods to evaluate fruit texture, correlates the instrumental analysis and sensory evaluation of fruit texture. In a typical TPA curve, hardness is defined as the height of the force peak on the first compression cycle, and cohesiveness is defined as the ratio of the positive force areas under the first and second compressions (Bourne, 2002). Beside this, adhesiveness, springiness and viscosity which is subdivided into three indexes: fracturability, gumminess and chewiness, are also defined using the extracted parameters from TPA curve. In compression test, the degree of elasticity is a measure of the elastic characteristics of fruit (Li *et al*., 2010b). The elastic modulus is regarded as an index of fruit firmness (Barriga-Tellez *et al*., 2011; Garcia-Ramos *et al*., 2005; Gunness *et al*., 2009). To sum up, the quantitative measurement of fruit biomechanics provides an essential foundation for objective evaluation of fruit texture.

Mechanical damage incurred during the harvesting, handling, transporting and sorting of fruit has been identified as a major source of reduced fruit quality (Ahmadi *et al*., 2010). In order to reduce this damage, much research has focused on the relationship between fruit biomechanics and mechanical damage in recent years. Past researches can be summarized into three aspects according to the objective description methods of fruit mechanical damage.

One is the effect of fruit biomechanics on bruise volume or area. Some research results have shown that the fruit mechanical parameters which have a significant effect on bruise volume include loading rate (Yang and Wang, 2008), firmness (Ahmadi *et al*., 2010), peak contact force (Acican *et al*., 2007; Zarifneshat *et al*., 2010; Zeebroeck *et al*., 2007b) and impact energy (Kitthawee *et al*., 2011). Another aspect is the effect of fruit biomechanics on bruise susceptibility. For instance, researchers proposed that the bruise susceptibility of fruit is significantly affected by the strength of fruit skin, firmness of underlying tissue, puncture force and impact energy (Allende *et al*., 2004; Desmet and Lammertyn, 2004; Desmet *et al*., 2002; Linden *et al*., 2006). The third is the effect of fruit biomechanics on bruise severity. Some research results show that the severity of fruit bruise is significantly affected by impact energy (Mohammadi-Aylar *et al*., 2010), compressibility and loading rate (Li *et al*., 2010a). To sum up, lots of research results demonstrated the fruit biomechanics to be closely related to the mechanical damage, and this can be attributed to fruit texture.

DETERMINATION METHODS OF FRUIT BIOMECHANICS

Currently, there is no national standard test method available for determining the biomechanical properties of fruit and vegetable. According to the published literature, the test methods can be summarized as follows:

– Compression test on whole fruit:

The whole fruit, which is assumed to be a homogeneous spheroid, is placed on a metal base plate and then pressed by the moving parallel plate probe of instrument *eg* TA-Xi2 Texture analyzer or universal testing device until the fruit skin is ruptured or at a certain compressibility level (Goyal *et al*., 2007). Force-deformation curves are recorded in real time during loading. This is a standard parallel plate contact model for Hertz contact stress theory and the Young modulus of a whole fruit according to the ASAE standards for compression testing of food materials of convex shape will be given by the Hertz theory equation (Kiani Deh Kiani *et al*., 2009). Apart from this, the mechanical parameters such as peak force, elastic and plastic strain energy, degree of elasticity and loading slope of fruit at different compressibility levels and rupture energy and force, compressibility and loading slope of fruit at initial rupture can also be extracted from each recorded curve.

By using this method, some researchers determined the mechanical parameters of tomato (Kabas and Ozmerzi, 2008; Li *et al*., 2006, 2011; Liu *et al*., 2008), apple (Yurtlu and Erdogan, 2005), olive (Kilickan and Guner, 2008), Barbados nut (Sirisomboon *et al*., 2007), apricot (Haciseferogullari *et al*., 2007) and orange fruits (Pallottino *et al*., 2011). Some test results can be seen in Table 1. Three main characteristics can be showed comparing these data. Firstly, one fruit compressed from different loading directions may show a significant difference in mechanical properties, such as tomato and olive fruits, and the reason is that some fruits have irregular spheroid shapes and complex internal structures, and some locules are surrounded by the fruit pericarp. Secondly, different varieties of fruit may have an obvious difference in mechanical properties, and this is mainly caused by different content of fruit chemical constituents according to macro anatomy (Zykwinska *et al*., 2008). Thirdly, the same mechanical parameter value of different kinds of fruits has no huge discrepancy and varies within a certain range, and this is because the fruit biomaterials have the approximate major physicochemical composition while their contents have discrepancy (Jamilah *et al*., 2011; Narain *et al*., 2001). In the flat plate compression test of whole fruit, the elastic modulus of tomato fruit varies from 0.16 to 0.47 MPa, and the elastic modulus of apricot fruit varies from 2.44 to 4.64 MPa.

– Micromechanical test on standard specimen:

Firstly, the whole fruit is regarded as a multibody system, and each body tissue is assumed to be a homogeneous material. Subsequently, the body tissue is made into standard specimens using a sampler for micromechanical testing according to the ASTM D5379, E8, E9 and E290 standards. The test types include compression, tension, shear and bend testing and the test instruments, such as texture analysis and universal testing machine, have corresponding probes for different types of test (Singh and Reddy, 2006).

Table 1. The means of certain mechanical parameters of several fruits

Author	Fruit	Variety	Loading direction	Mechanical parameters				
				E	λ	F_r	E_r	ε
Li *et al*. (2011)	Tomato	Fenguan906	CW			49.61	3.23	14.31
			L			51.68	2.11	17.85
Liu *et al*. (2008)		Jinpeng1	TF			72.52		
Kilickan *et al*. (2008)	Olive	Gemlik	LF			94.45	0.32	20.2
			TF			57.38	0.26	22.61
Sirisomboon *et al*. (2007)	Barbados nut	Kanlueang	TF			135.4	0.3	15
Yurtlu *et al*. (2005)	Pear	Willians	TF	1.68	0.3	59.12	1.22	
		Ankara		1.34	0.43	49.63	0.095	
	Apple	Starkspur		1.45	0.37	44.05	0.076	
		Starking		1.51	0.34	44.35	0.074	
Pallottino *et al*. (2011)	Orange	Tarocco	TF	0.35	0.16	220		30
Li *et al*. (2006)	Tomato	04042	TF	0.47		36.06		
Kabas *et al*. (2008)		ZuccheroF1	LF	0.25	0.35			
		MosaicaF1		0.16	0.22			
		1018F1		0.28	0.34			
Haciseferogullari *et al*. (2007)	Apricot	Zerdali	TF	2.44				
		Hasanbey		2.58				
		Kabaasi		4.64				

Fruit loaded from: CW – cross wall tissue, L – locular tissue, LF – longitudinal axis, TF – transverse axis; E – elastic modulus (MPa), λ – Poisson ratio, F_r – rupture force (N), E_r – rupture energy (J), ε – compressibility (%).

The geometric sizes of specimen are measured with an electronic digital caliper before and after test. The force-displacement curve of tissue specimen is recorded in real time during the test. At last, the standard mechanical parameters of fruit tissues such as elastic modulus, failure stress, failure strain and failure energy are calculated using corresponding equations (Fidelibus *et al*., 2002). In view of the real sigmoid characteristic of stress-strain curve (obtained from the force-displacement curve) of fruit tissue, some researchers proposed that the elastic modulus of fruit tissue can be denoted by the slope of the first and second part of curve (Alamar *et al*., 2008; Matas *et al*., 2005). Apart from this, some researchers also showed three point bending test as an alternative experimental method to measure tensile elastic modulus, as sample preparation for uniaxial tensile test of fruit tissue is difficult (Harker *et al*., 2006; Pitts *et al*., 2008).

According to this method, some researchers determined the biomechanical parameters of tomato tissue (Bargel and Neinhuis, 2005; Hetzroni *et al*., 2011), orange tissue (Singh and Reddy, 2006), apple tissue (Alamar *et al*., 2008), watermelon tissue (Sadrnia *et al*., 2008) and melon tissue (Cardenas Weber *et al*., 1991). Some test results are presented in Table 2. Three main characteristics can be summarized comparing these data. Firstly, the obtained mechanical properties of the same tissue have an obvious difference for different fruit varieties, and the reason is that the chemical composition and cell wall structure of fruit tissues will change with the variety according to microanatomy (Cybulska *et al*., 2011; Sams, 1999). Beside this, another important reason is that the prepared specimens have large differences in size and shape. Secondly, the obtained mechanical properties of different tissues have a significant difference for the same fruit variety. In general, higher failure stress and elastic modulus values are obtained for outer layer tissue of fruit as compared to inner layer tissue. This is because the cells of exocarp tissue are small and their arrangement is compact and dense, the cell walls are thick according to fruit anatomy. On the contrary, the cells of mesocarp and locular gel tissues are large and their arrangement is sparse and loose, the cell walls are thin (Chiarini and Barboza, 2009; Jaitrong *et al*., 2005; Rancic *et al*., 2010). Thirdly, the mechanical parameters of fruit tissue such as elastic modulus and failure strain display

Table 2. The means of certain mechanical parameters of several fruit tissues

Author	Fruit	Variety	Tissue	Test type	Mechanical parameters			
					E_{C1}	E_{C2}	σ	ε
Li *et al*. (2011)	Tomato	Fenguan906	Exocarp	Tension	9.59		0.582	6.93
			Mesocarp	Compression	0.726		0.122	25.76
			Locular gel		0.124		0.012	20.18
Hetzroni *et al.* (2011)		7423	Exocarp	Tension	116.25		7.097	
		7497			172.67		10.1	
Bargel *et al*. (2005)		Harzfeuer	CM	Tension	102.0		13	11
			FS		182.6		33	12
		Vanessa *F*1	CM		141.7		16	10
			FS		229.2		39	13
Singh *et al*. (2006)	Orange	Nagpur *M.*	Peel	Tension	1.57		0.173	
Alamar *et al*. (2008)	Apple	Braeburn	Flesh	Compression	0.35	1.72	0.25	23.76
		Jonagored			0.42	2.01	0.4	28.26
		Braeburn	Flesh	Tension	3.91		0.22	7.83
		Jonagored			3.19		0.24	10.21
Sadrnia *et al*. (2008)	Watermelon	Crimson *S.*	Red flesh	Compression	0.536		0.027	5.2
			White rind		0.902		0.272	31
			Green rind	Tension	4.937		1.231	26.6
		Charleston *G.*	Red flesh	Compression	0.396		0.037	9.5
			White rind		1.202		0.262	21.9
			Green rind	Tension	5.357		1.144	21.5
Cardenas-Weber *et al*. (1991)	Melon	Superstar	Outer flesh	Compression	0.802		0.132	24.3
			Middle flesh		0.457		0.075	30.1
			Inner flesh		0.263		0.035	24.3

CM – isolated cuticular membrane, FS – fruit skin, E_{C1} – elastic modulus of tissue obtained from the first part of stress-strain curve (MPa), E_{C2} – elastic modulus of tissue obtained from the second part of stress-strain curve (MPa), σ – failure stress (MPa), ε – failure strain (%).

a large difference between compression and tension tests. This can be explained by the structure characteristic of fruit tissue. There are lots of intercellular spaces in fruit tissue according to fruit anatomy, and hence the rupture ways and displacement of fruit tissue specimen for compression test will be different from those for tension test (Alamar *et al*., 2008). This also results in the biphasic behaviour in the stress-strain curve of fruit tissue during loading. The stress-strain curve allows the calculation of tensile modulus from the slope of the linear elastic phase of curve and from the linear viscoelastic phase (Matas *et al*., 2005).

– Micromechanical test on a single cell:

So far, about three micromanipulation methods are used to measure the mechanical properties of single fruit cells according to the published literature. The first method is showed by Hiller *et al*. (1996). First, the standard slice of fruit tissue is prepared for test specimen, which is composed of 2~5 cells in thickness. Subsequently, the micro-penetration test of tissue is performed by the universal test machine, thin parallel-sided glass probe and sensitive load- and deflection-transducers, and the force-deflection data are obtained. The test is equivalent to the penetration of several cell walls during each test. Thus, a closer assessment of mechanical parameters of cell walls, such as penetration energy and theoretical energy, will be attempted by the load/unload cycling of individual walls to progressively higher deflections until failure. Young modulus will be predicted by fitting simulation data from a FEA model of cell compression to experimental force-deflection data (Hiller *et al*., 1996). The second method is proposed by Blewett *et al*. (2000). First, single fruit cells are suspension-cultured and separated. Subsequently the cells are compressed between two parallel flat surfaces of micromanipulation equipment in order, and their force-deformation curves are generated. The force required to deform and break the cell is obtained (Blewett *et al*., 2000). The third method is proposed by Wang *et al*. (2004, 2006). Firstly, a single cell is released from the inner tissue of fruit by gentle washing and assumed to be a liquid-filled sphere with thin compressible linear-elastic walls. Subsequently, the loading-unloading test of a single cell is performed by the high strain-rate microcompression tester, and the force-deformation data are obtained. Meanwhile, a camera is used to measure the initial height and width of single cell, and monitor the cell for permanent deformation during the test. At last, the force-deformation data are fitted to simulated data from a mechanical model of cell compression and the material properties of the cell wall, such as initial stretch ratio, elastic deformation limit and Young modulus, will be derived accordingly (Wang *et al*., 2004; 2006).

Using these methods, Hiller *et al*. (1996) reported that the total energy expended in penetrating unit area of potato cell wall is 9.55 kJ m^{-2} and the theoretical energy required to break the requisite number of chemical bonds in a unit area of cell wall is 0.103 J m^{-2} . The elastic modulus of potato cell wall is about 600 MPa (Hiller *et al*., 1996). Blewett *et al*. (2000) showed that the mean height of single suspension-cultured tomato (variety: *vf*36) cells is 68 μm and the mean bursting force is 3.6 mN at 23 $\mu m\ s^{-1}$ in compression test. The relaxation, however caused, is not significantly affecting the force required to burst the cells in relaxation test. Both turgor and wall are essential to maintain cell strength as the mean burst force of protoplast is only 0.003 mN (Blewett *et al*., 2000). Wang *et al*. (2006) pointed there is a very good fit between simulation and experiment data. The elastic deformation limit of single tomato fruit cells are just over 11%, the elastic modulus of cell wall varies from 30 to 80 MPa, and the cell walls yielded at about 2% wall strain (Wang *et al*., 2006). In recent years, these micromanipulation techniques have also been successfully applied in biomechanics measurements involving a variety of types of single cells such as mammalian cells, yeast cells, bacterial cells and microbial cells (Dintwa *et al*., 2011). The fruit is a hierarchically organized organ composed of cells from different tissues (Genard *et al*., 2007). The measurement of mechanical properties of single fruit cells will be helpful to investigate the injury mechanism and mechanical behaviour of fruit tissues.

– Finite element prediction of fruit biomechanics:

Recently, the finite element prediction is regarded as an essential method to measure fruit biomechanics, and past researches can be summarized into two aspects. One is to validate the determined mechanical properties data of fruit tissues or cells by finite element prediction. For a fruit, the mechanical parameters of whole fruit, constituent tissues and its cells can be obtained by three test methods according to the published literature, but it is not known whether the measured mechanical parameters are accurate or not. Some researchers first created a finite element model of fruit using the determined mechanical parameters value of fruit tissues or cells (George, 2000; Pieczywek *et al*., 2011; Pitt and Chen, 1983), subsequently validated the determined mechanical properties data of fruit tissues by comparing the fruit finite element model predictions with measured deformations in whole-fruit compression tests (Cardenas Weber *et al*., 1991; Dintwa *et al*., 2011; Sadrnia *et al*., 2008). The other is to predict the mechanical properties of fruit tissues by finite element analysis. In fact, a fruit is composed of a complex conglomerate of different tissues *eg* exocarp, mesocarp and endocarp, and each tissue has many microscopic constituents such as cells, middle lamella and interstitial spaces according to the fruit anatomy (Dintwa *et al*., 2011). In view of the irregularity of fruit shape, complexity of fruit structure and constituents, and of the limitations of existing instrumentation and measurement techniques, it is difficult to determine the mechanical properties of each constituent of fruit, such as endocarp and middle lamella tissue. Therefore, some researches attempted to predict the mechanical properties of certain tissues by finite element analysis. Firstly, an unknown mechanical parameter of fruit tissue or cell is assumed in finite element analysis, the finite element model of a fruit can be constructed by its constituent tissues, and the unknown mechanical parameter of the tissue is predicted by comparing the experimental data with the simulated data of whole fruit compression later. By using this method indicated that the elastic modulus of apple fruit is 3.27 and 7.732 MPa, respectively (Kim *et al*., 2008; Lu *et al*., 2006). Qing *et al*. (2011) proposed that the elastic modulus of longan flesh is 2.5 MPa.

DISCUSSION

Comparing these determined methods and results of fruit biomechanics, the same fruit, tissue or cell have obvious differences in the mechanical parameters value for several test methods. This can be attributed to the ideal assumption that these biological materials (*eg* fruit, tissues or cells) behave as a linear and elastic continuum. In actual fact, postharvest fruit continues its respiratory activity to preserve the integrity of cellular microstructure. The microscopic histological and cellular features such as the types of tissue, the geometric properties of cell, the presence of an adhesive middle lamella between individual cells, the cellular water potential, the mechanical properties of cell wall, and the presence of intercellular spaces determine the mechanical properties of fruit and tissues as well as how they perform or fail when a load is applied during postharvest handling (Mebatsion *et al.*, 2008). Therefore, the assumption has a narrow limitation, and the obtained mechanical properties data are only approximate values by using the existing test methods. Additionally, it is also difficult to obtain the mechanical properties of each constituent of fruit with existing instrumentation and measurement techniques.

SUMMARY

Fruit biomechanics is mainly affected by the size, number and arrangement of cells, quantity and volume of intracellular spaces, structure, thickness, chemical composition and permeability of cell walls, and pectin degradation level and turgor pressure within cells based on micro-anatomy, and cell walls are the main structural component affecting fruit biomechanics. The significant effect of macro factors such as variety, ripening stage and storage condition on fruit biomechanics can be explained with fruit micro anatomical characteristics.

Due to the fact that the fruit biomaterials are non-homogeneous and living, and thus different from metal and plastic materials, therefore the actual fruit biomechanics cannot be obtained by using the test and calculation methods whose assumptions do not follow the anatomical characteristics of fruit, and the determined mechanical properties data of fruit are only approximate values by using the existing four test methods up to now. Additionally, in view of the complexity of fruit structure and constituents, only partial biomechanical properties of tissues can be determined for a fruit by using the existing instrumentation and measurement techniques.

In order to make the determined value of fruit biomechanics more approximate to the actual value, future research is required in fruit biomechanics as follows:

– how to obtain the standard physical and mechanical parameters of each constituent for a real fruit?
– how to prepare the test specimen and make it better to meet the assumption which is essential for existing measurement methods of fruit biomechanics?
– how to construct a multiscale 3D finite element model of fruit which will contain different tissues and cells. The reasonable model can be used to better validate and predict fruit biomechanics?

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