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Methods for detecting and quantifying mechanical damage in fruits: Advances, challenges, and future perspectives

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ABSTRACT

Mechanical damage is a major factor affecting postharvest fruit quality, causing substantial economic losses throughout the supply chain. In addition to intrinsic factors such as species, cultivar, and growing conditions, fruit quality is strongly influenced by mechanical stresses during harvesting, handling, transport, and storage. Understanding the mechanisms and extent of such damage is essential for developing strategies to reduce losses and improve postharvest management. This review provides a comprehensive overview of current methods for detecting and quantifying mechanical damage in fruits, including finite element modelling (FEM) for analysing stress distribution and deformation, pendulum impact tests for evaluating bruise susceptibility, penetrometers for assessing firmness, and various non-destructive spectroscopic and imaging techniques for early damage detection. Particular attention is given to recent advances in non-destructive approaches and their potential for rapid and objective quality assessment. The paper highlights current challenges, including standardisation of measurement protocols and scalability of advanced technologies, and outlines future perspectives for improving detection accuracy and reducing postharvest losses.

Key words: postharvest fruit quality, manipulation, damage intensity, destructive and non-destructive methods

INTRODUCTION

Importance of fruit quality and mechanical damage

In addition to the type and quantity of fresh fruit used in the diet, the quality and healthiness of the fruit are also important, as governed by relevant national regulations (Croatian Ordinance on Fruit Quality, 2008). Scientists in agronomy, the food industry, and experts in mechanization research mechanical damage to fruit. Peterson (2005) studied excessive damage to apples, peaches, and cherry fruit during separation and collection, finding that successful mechanical harvesting can be achieved if machine characteristics and construction are integrated into a compatible system and if the cultivars have uniform fruit maturity. Uniform maturity allows the harvesting of firm fruits that are resistant to mechanical damage during separation, collection, and transport. Fenyvesi et al. (2013) investigated stresses in apple and pear fruits and concluded that during harvesting, transport, and handling, a certain percentage of damage occurs with smaller loads on the fruit surface, while more intense loads cause damage inside the fruit. Damage analysis for pear and apple fruits was carried out using finite-element (FEM) and discrete-element (DEM) models. The results confirm that maximum stress develops in the core, meaning the core accumulates stresses, and the load affects the fruit differently depending on where it is applied (skin, flesh, core, or seed). FEM is a numerical method that has been used in the last thirty years to investigate the dynamic behavior of objects. The use of machines and equipment in harvesting fruit, grapes, and vegetables requires knowledge of the dynamic behavior of particles. Fruits, like other agricultural crops, are exposed to various mechanical loads and behave under such stress conditions as highly elastic materials. According to Miyawaki (2000), the mechanical behavior of highly elastic agricultural objects such as fruit is a complex integrated effect defined by geometry, shape, and surface roughness, and the movement of objects under stress results in deformation and fractures.

Opara and Pathare (2014) state that understanding a product's susceptibility or resistance to damage is important for developing problem reduction strategies, and that damage quantification can be determined using destructive manual measurements and subsequent analysis, such as technologies including near-infrared spectroscopy, hyperspectral imaging, thermal imaging, and imaging nuclear magnetic resonance. The study also notes that there are various objective indices for quantifying the potential for product damage under mechanical load, but the most emphasized is damage sensitivity, expressed as the amount of damage per unit of absorbed impactor compression energy. Fruits, as well as the woody tissue of plants, are sensitive to mechanical loads and are frequently damaged. For this reason, manufacturers of machines used in fruit production are required to make improvements to minimize damage to both the fruit and the fruit tree itself. To ensure that machine construction meets agrotechnical requirements, designers must know the physical and mechanical properties of fruits and plant tissues. Shirvani et al. (2014) investigated the mechanical properties of fruit and concluded that it is very important to know the mechanical properties of fruit species to assess and predict deformations under external loads during transport, processing, and packaging. Abbott et al. (1984) conducted sensory and instrumental measurements of apple fruit texture and stated that texture description can be achieved using mechanical properties such as hardness, elasticity, and deformation. Salarikia et al. (2017) conducted a study aimed at evaluating the patterns of stress distribution and deformations inside a pear resulting from the collision of the fruit with a flat surface made of different materials. Their results indicate that developing a strategy to reduce damage during the supply chain requires an understanding of the dynamic behavior of fruit under different forced loads, and that the FEM is one of the best techniques in terms of accuracy and cost-effectiveness for studying damage caused by impacts during harvesting, handling, packaging, and storage.

Modelling, simulation and experimental approaches

Kim et al. (2008) determine the modulus of elasticity and analyze the stress distribution of whole apple fruits under parallel plate compression using FEM simulation based on the 3D geometry of real apple fruits, and compare the results with the application of the ASAE standard. Based on their research, they suggest that the widely accepted ASAE standard S368.4, for compression testing of agricultural materials of convex shape, should be further studied due to its suitability in predicting both the maximum contact stress and the apparent modulus of elasticity. In addition to FEM, other methods such as FDM (Finite Difference Method), BEM (Boundary Element Method), and MM (Meshless Method) are also used to determine the physical properties and analyse the behavior of fruits. Słupska et al. (2022) present a simple method to estimate damage volume based on drop height and substrate material. Based on their results, linear regression models were developed to predict the volume of bruising with regard to the height of the fall and the type of surface. The same authors consider that numerical models are a practical tool for rapid damage volume estimation, with an accuracy of about 75% for collective models and 93% for individual models. Mechanical damage to cellular tissues is closely related to their microstructure. Therefore, the behavior of fruits under load depends on many microstructural properties such as cell size, cell wall thickness and stiffness, cell orientation, etc. (Stropek and Gołacki, 2020). According to Raji and Favier (2004), optimal design and control of primary production and harvesting operations require an understanding of the dynamic behavior of agricultural products. The first step in FEM is to create objects with the appropriate shape and size in virtual space. The position of the objects is determined by the coordinates of the center of gravity for a spherical or other primitive shape, as shown schematically in Fig. 1.

Figure 1. A pair of spherical objects in contact (Raji and Favier, 2004)

The aim is to develop a suitable theory to describe the behavior of a deformable, highly elastic spherical particle under mechanical load and to incorporate it into FEM for agricultural final products such as fruit. The constitutive equation, which includes all forces (F) and moments acting on a moving particle in contact with neighboring particles, can generally be expressed using Newton's second law of motion:

$$m\ddot{x} = \Sigma F \quad \text{and} \quad I\theta = \Sigma F_t \, R_c \tag{1}$$

where: m – mass of the particle; $\ddot{x}$ – translational acceleration of particles; F – the sum of all forces acting on the body; θ – rotation acceleration; I – moment of inertia; F_t – tangential force; R_c – vertical distance from the line of action to the center of the particle

In fruit mechanics, this equation is practically applied to model how fruits move, collide, and distribute forces during processes such as handling, transport, and sorting, helping to predict and minimize mechanical damage.

Raji and Favier (2004) state that the study conducted can serve as a starting point for researching the behavior of soft and deformable materials, such as agricultural products, under mechanical load. Song et al. (2006) investigate the physical properties of pears using FEM. To obtain a non-symmetrical and non-spherical geometric model of the pear, they use a new image processing technique. The object (pear fruit) is placed on a table, and the processing system consists of a camera, a memory card, and the ANSYS 7.0 software. The light values of the background object are used to separate the points. After obtaining the 24-bit photos, they are processed with laboratory-made Visual Basic software, and the cross-section is obtained using the ANSYS 7.0 software. After the objects (pear fruits) are exposed to different vibrations (below 100 Hz), the authors conclude that the final quality of the pear fruit is influenced by its shape, volume, and density. Fig. 2 schematically shows the procedure for obtaining a cross-section of a pear.

Figure 2. Geometric modelling of pear fruit (Song et al., 2006)

Farkas et al. (2016) also investigated the deformation of fruits under various mechanical influences, concluding that the occurrence of damage or deformation depends on several factors, including the height from which the fruit falls, the static load exerted on the fruit within the container, and the vibrational acceleration experienced during transport. Authors state that if mechanical injuries are undetected, the fruit spoils, which can infect other fruits and ultimately reduces the quality of the final product. If a defective product is detected, it can be removed from the process. For this purpose, several methods of image and heat processing can be used to distinguish bruised fruit from non-bruised fruit. Visual and infrared spectroscopy, as well as early damage detection using hyperspectral data and thermal imaging, are most commonly used. These methods can detect damaged fruits and thus prevent further mechanical injuries. In their research, the authors utilized an instrument with computer-controlled compression, the so-called DyMa Test. The deformation in this test can be measured with a laser sensor, and the collected data are stored directly in the computer. The measuring circuit and settings are shown in Fig. 3.

Figure 3. Schematic representation of the application of mechanical load in the DyMa Test (Farkas et al. 2016)

In the research by Farkas et al. (2016), load wedges of Ø 4 mm, Ø 5 mm, and Ø 6 mm were used. The results indicate that this method can determine the sensitivity of individual fruits under different load forces. Li et al. (2017) investigated the influence of impacts and other mechanical contacts between fruits or between fruits and surface. In their work, 25 mechanical models related to compressive and impact loads on fresh fruits were reviewed. The authors state that it is crucial to develop accurate mathematical models that relate the mechanical properties of fresh fruit at different stages of ripening, as well as to characterize the microscopic behavior of fruit materials, especially internal properties such as tissue damage and microcracks, and then develop appropriate damage criteria for such materials.

Fu et al. (2023) present a method for measuring damage to fresh apple fruits caused by repeated impacts using a pendulum. In their research, they use a pendulum with an arm length of 0.15 m, a rotating angle sensor, and a piezoelectric impact force sensor. To assess the amount of damage, they use the indices BA, BV, and BS, which significantly affect the occurrence of damage. BA is an index of the amount of damage with respect to the size of the damage and is useful for rapid visual grading and sorting decisions. BV is the damage index for the size of internal damage and is particularly relevant for evaluating hidden defects that affect storage life and marketability. BS is the index most commonly used to quantify the potential for fruit damage due to mechanical stress, making it especially important for optimizing handling, packaging, and transport conditions to reduce postharvest losses. These indices are determined using the following equations:

$$BA = \frac{\pi\, w_1\, w_2}{4} \quad \text{and} \quad BV = \frac{\pi\, d_b}{24}\,(3w_1w_2 + 4d_b^2) \qquad (2)$$

where: w_1 – greater width of damage; w_2 – smaller width of damage, d_b – depth of damage, as shown in Fig. 4.

Figure 4. Display of damage measurements on an apple (Fu et al., 2023)

The BS index (ratio of BV to impact energy E_{td}) is determined by the equation:

$$BS = \frac{BV}{E_{td}} \qquad (3)$$

The same authors conclude that repeated shocks can significantly affect both the extent of damage and susceptibility to damage.

Non-destructive sensing and artificial intelligence approaches

When determining the quality of agricultural products, non-destructive methods should be used, as they are faster and more economical than conventional methods. Non-destructive methods can assess the quality of fruits without causing damage. These include common sensor techniques such as imaging, spectroscopic, acoustic, mechanical methods, as well as E-nose and E-tongue techniques. Aboonajmi and Faridi (2016) state that qualitative and quantitative measurements of agricultural products without any physical, chemical, thermal or mechanical damage can be considered non-destructive tests, whose advantages should play a more significant role in the fruit and vegetable industry. Mohd and Hashim (2022) also study these methods and conclude that non-destructive techniques represent future trends in agricultural products quality assessment. Fathizadeh et al. (2021) state that non-destructive methods are accurate, fast and suitable for online applications, and that the use of artificial intelligence and data fusion techniques can further increase the accuracy of product quality measurements.

Optical sensing approaches have become central to modern bruise detection, enabling fast, non-contact inspection. Visible/NIR and SWIR (Short-Wave Infrared) hyperspectral imaging can detect biochemical and structural changes associated with bruised tissue before symptoms become visible. Okere et al. (2023) demonstrated that Vis-NIR and SWIR hyperspectral imaging could classify pomegranate bruise severity with high accuracy, while also reducing data dimensionality through informative wavelength selection. Similar progress has been reported for apples, pears, blueberries, strawberries, kiwifruit, and peaches, where spectral imaging has been combined with machine learning or deep learning to detect early bruises and hidden defects (Zhang et al. 2024; Sun et al. 2026; Liu et al. 2023; Liu et al. 2026; Locatelli et al, 2026).

Recent research has shifted towards rapid, non-destructive, data-driven methods capable of detecting visible, subsurface, and latent mechanical damage. These approaches integrate optical, spectroscopic, acoustic, and imaging techniques with artificial intelligence to enable objective, high-throughput quality assessment. The review by Nicolai et al. (2007) remains a cornerstone, having established near-infrared spectroscopy as a fundamental tool for non-destructive quality assessment of fruits and vegetables and providing the methodological basis for subsequent spectroscopic and imaging applications.

Deep learning has further improved the detection of subtle or irregular damage patterns. Convolutional neural networks (CNN), YOLO (You Only Look Once)based detectors, faster R-CNN (Region-based Convolutional Neural Networks) models, and hybrid spectral–spatial architectures can segment damaged regions, classify bruise severity, and support automated grading. Recent studies have reported effective early bruise detection in apples using hyperspectral imaging and YOLObased models, in strawberries using hyperspectral imaging and deep learning, and in blueberries using hyperspectral feature fusion with machine-learning classifiers (Zhang et al. 2024; Sun et al. 2026). These methods are promising for industrial applications as they reduce subjectivity and enable rapid inspection, although model robustness across cultivars, lighting conditions, maturity stages, and acquisition systems remains a significant limitation.

X-ray imaging, computed tomography, and thermal imaging provide complementary information for internal or subsurface defects that may not be detectable using surface-based optical methods. X-ray imaging has recently been applied for internal quality inspection of pears, while active infrared and thermal imaging have shown potential for detecting subsurface bruises based on thermal contrast and heat-transfer differences between healthy and damaged tissue (Yang et al. 2025; Bharadwaj et al. 2025). Although these technologies offer strong diagnostic potential, their cost, processing requirements, radiation safety considerations, and integration into high-throughput sorting lines must be carefully addressed.

Overall, recent advances indicate that the future of mechanical-damage detection lies in multimodal sensing, sensor fusion, and artificial intelligence. Combining mechanical measurements with spectral, thermal, X-ray, and image-based data can provide a more comprehensive description of fruit damage, while machine learning can transform large sensor datasets into objective quality decisions. However, wider adoption will require standardised protocols, open datasets, validation under commercial conditions, and cost-effective hardware suitable for integration into industrial grading and supply-chain systems (Chamorro-Padial et al. 2024; Mei and Li 2023).

DISCUSSION

The mechanical properties depend on fruit structure, as well as on other factors. Fig. 5 schematically shows the structure of a pear, apple and peach, highlighting the basic elements that primarily determine their mechanical properties.

Figure 5. Schematic representation of the structure of a pear, apple and peach

Textural properties of fruits can be determined by precise indicators obtained through measurement or by descriptive terms based on visual inspection. Along with nutritional properties, taste and appearance, texture is one of the main indicators in the quality assessment of agricultural products. According to Jašić (2007), the mechanical attributes of texture are divided into five basic characteristics: hardness, cohesiveness, viscosity, elasticity and adhesiveness. The hardness or degree of damage to fruits and vegetables is determined by measuring the force required to cause damage or by measuring the area of the damage. Fig. 6 schematically shows the procedure for determining the hardness of pear fruit.

Figure 6. Schematic representation of hardness determination

Hardness H can also be defined as a property of a material that resists the penetration of a foreign body (penetrator) into its structure. The hardness of the material is also determined by the equation:

$$H = \frac{F}{A} \tag{4}$$

where: H – hardness; F – the force with which the probe acts on the fruit (N); A – penetrator surface area (mm^2)

Skendrović Babojelić and Fruk (2016) state that monitoring the hardness of fruit is important when deciding on its intended use, i.e. whether it can be stored for a longer period or not. The same authors state that hardness is mainly influenced by the nature and size of the fruit, calcium content, maturity at harvest, temperature, light, time, storage conditions, and other factors. Hardness can be determined by various devices, including a penetrometer designed for materials such as fruit or vegetables. Fig. 7 shows the analogue, digital, and digital penetrometers on the support.

Figure 7. Analogue, digital, and digital penetrometer on the carrier

Fruits do not have the same characteristics, and for each fruit type, specific penetrators are used that differ in the surface area they penetrate into the fruit. Fig. 8 shows several penetrators with different diameters (*d*).

Figure 8. Penetrators with different diameters (Skendrović Babojelić and Fruk, 2016)

Table 1. Penetrator diameter values for some types of fruit (Skendrović Babojelić and Fruk, 2016)

Fathizadeh et al. (2021) investigated the hardness of apples and stated that it is related to juiciness and freshness, and that it is a more important indicator of quality than sugar and acid content. Based on information about hardness values, the nano-mechanical properties of the fruit during the ripening period can be inferred, which can help determine the optimal time for harvesting fruit or vegetables. During harvesting, fruits and vegetables are subjected to various static and dynamic loads. When a fruit strikes a working element or collides with another fruit, deformation occurs, consuming energy. The impact strength of fruit is most commonly assessed using the coefficient of specific energy loss (*k*), which represents the energy required to destroy 1 mm^3 of apple fruit (Lukač and Pandurović, 2011).

$$k = \frac{E_k}{V} \tag{5}$$

where: k – energy loss coefficient (J/mm^3); E_k – kinetic energy of the impact (J); V – volume of fruit deformation (mm^3)

The fruit elasticity factor (k_e) is determined by the ratio of the velocity after impact (V_2) to the velocity at the start of impact (V_1).

$$k_e = \frac{V_2}{V_1} \tag{6}$$

where: k_e – elasticity factor; V_1 – velocity at the start of impact (m/s); V_2 – velocity after impact (m/s)

The elasticity factor (k_e) is determined by dropping a fruit from a certain height (h_1) and measuring the height of its bounce from the substrate (h_2). Fig. 9 schematically illustrates the procedure for determining the elasticity factor (k_e).

Figure 9. The procedure for determining the elasticity factor

Factors such as specimen conditioning prior to testing, geometry, and loading rate can affect test results, so it is desirable to standardise testing and reporting procedures to ensure that data from different sources are comparable. Factors such as variety, drying temperature, storage technique, maturity, and processing technique should also be taken into account (ASABE, 2008). Chen et al. (2013) state that texture profile analysis (TPA) establishes a "bridge" from objective measurement to subjective sensation and makes food characteristics predictable. Khodabakhshian et al. (2021) report that determining the elastic properties of agricultural products at the macro level results in very different values for certain samples. When researching the elasticity of fruits and vegetables, Young's modulus is very practical. Young's modulus represents the ratio of tensile stress to elongation and is also a measure of material stiffness. For most materials, Young's modulus of elasticity is used when calculating the change in volume that occurs under the action of an external force (impact, compression).

Opara et al. (2007) described the application of a newly designed device for determining damage from mechanical impact on fruits as a consequence of mechanical damage. The same authors state that a major limitation of existing devices is the lack of an objective measurement of the height of the bounce, which is necessary when determining the actual impact energy. Fig. 10 shows their impact on energy testing device.

Figure 10. Schematic representation of the components of the new impact testing device (Opara et al., 2007)

Opara et al. (2007) state that the new device is superior to the device using subjective assessment of bounce height, providing a simple and cost-effective tool for researching damage to fruits and vegetables. An additional problem in direct strain measurement is the need to eliminate oscillations during impact that affect the measuring device (Abedi and Ahmadi, 2013). This issue can be addressed by using a high-speed camera that is not rigidly attached to the research device (Horabik et al., 2017; Surdilović et al., 2018; Liang et al., 2018). Nassiri and Jafari (2013) conducted research with the main objective of introducing an analytical method for predicting the allowable static load applicable to apple fruits. To predict the deformation energy absorbed by the fruit, a point load is applied to a solid spherical object, and the test is carried out at two different temperatures, 0 and 25 °C. To simplify the problem, the shape of an apple is approximated as a sphere, and a point load P is applied to the contact surface, as shown in Fig. 11.

Figure 11. A spherical object subjected to an external point load (Nassiri and Jafari, 2013)

The same authors state that the transient strain energy in the domain (0, t0) was calculated using the method of variables (where t0 is the duration of the load during the stress relaxation test), and that strain energy can therefore be calculated as a function of time and the geometry of the apple. Emadi et al. (2011) investigated the physical and mechanical properties of peaches, such as mass, volume, arithmetic mean diameter, density, sphericity, and stiffness. Their results showed that determining the stiffness value non-destructively is feasible using the arithmetic mean diameter. The aim of the research conducted by Zhang et al. (2017) was to develop quadratic polynomial regression models using near-infrared spectroscopy to determine differences in skin color, fruit hardness, soluble dry matter content, and their relationships with chlorophyll absorbance (absorption difference index, IAD) in nectarine fruits. They state that the quadratic polynomial regression method can be used to investigate the relationship between fruit quality indicators and the degree of maturity, and that the regression relationship between hardness and IAD can be applied to predict the maturity of other varieties of peaches and nectarines.

CONCLUSIONS

Mechanical damage remains a major cause of postharvest losses in fruit production and supply chains, significantly affecting quality and economic value. Conventional methods such as compression tests, penetrometers, and impact devices provide useful information on fruit mechanical resistance, but are often destructive and limited in detecting hidden damage.

Modern non-destructive approaches including acoustic sensing, spectroscopy, hyperspectral imaging, X-ray/CT, thermal imaging, and machine vision offer strong potential for rapid and objective quality assessment. The integration of artificial intelligence and machine learning further enhances bruise detection, classification, and prediction of damage severity.

However, key challenges remain, including the standardisation of measurement protocols, variability among fruit types, scalability of advanced technologies, and high implementation costs. Future research should focus on cost-effective sensors, multimodal data fusion, and robust AI models suitable for real-world applications. These developments could significantly improve detection accuracy and reduce postharvest losses.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Vlado Kušec: Conceptualization, Methodology, Investigation, Writing – original draft, Visualization. Igor Kovačev: Methodology, Investigation, Writing. Martina Skendrović Babojelić: Investigation, Resources. Ante Galić: Conceptualization, Supervision, Writing.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Not applicable.

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The authors used InstaText and Grammarly solely for language editing purposes, including grammar correction and language translation. No AI tools were used for generating scientific content, data analysis, interpretation of results, or drawing conclusions. All scientific content, analysis, and conclusions remain the sole responsibility of the authors.

SAŽETAK

Metode za otkrivanje i kvantificiranje mehaničkih oštećenja voća: napredak, izazovi i buduće perspektive

Mehanička oštećenja glavni su čimbenik koji utječe na kvalitetu voća nakon berbe, uzrokujući značajne ekonomske gubitke u cijelom lancu opskrbe. Osim unutarnjih čimbenika kao što su vrsta, sorta i uvjeti uzgoja, na kvalitetu plodova snažno utječu mehanička naprezanja tijekom berbe, rukovanja, transporta i skladištenja. Razumijevanje mehanizama i opsega takvih oštećenja ključno je za razvoj strategija smanjenja gubitaka i unapređenje postupaka nakon berbe. Ovaj pregledni rad daje sveobuhvatan prikaz suvremenih metoda za otkrivanje i kvantificiranje mehaničkih oštećenja plodova, uključujući modeliranje metodom konačnih elemenata (FEM) za analizu raspodjele naprezanja i deformacija, testove udara njihalom za procjenu osjetljivosti na modrice, penetrometre za procjenu čvrstoće te različite nedestruktivne spektroskopske i slikovne tehnike za rano otkrivanje oštećenja. Posebna je pozornost posvećena najnovijim dostignućima u području nedestruktivnih metoda i njihovu potencijalu za brzo i objektivno ocjenjivanje kvalitete. Rad ističe aktualne izazove, uključujući standardizaciju mjernih protokola i primjenu naprednih tehnologija u praksi, te ocrtava buduće perspektive za poboljšanje točnosti otkrivanja i smanjenje gubitaka nakon berbe.

Ključne riječi: kvaliteta plodova nakon berbe, rukovanje, intenzitet oštećenja, destruktivne i nedestruktivne metode

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Table 1. Penetrator diameter values for some types of fruit (Skendrović Babojelić and Fruk, 2016)

Fruit type	The diameter of the penetrator (roller probe) (mm)
Berries, grapes and other small fruits	3
Avocados, berries, etc.	6
Pears, stone fruit, avocados, etc.	8
Apples	11

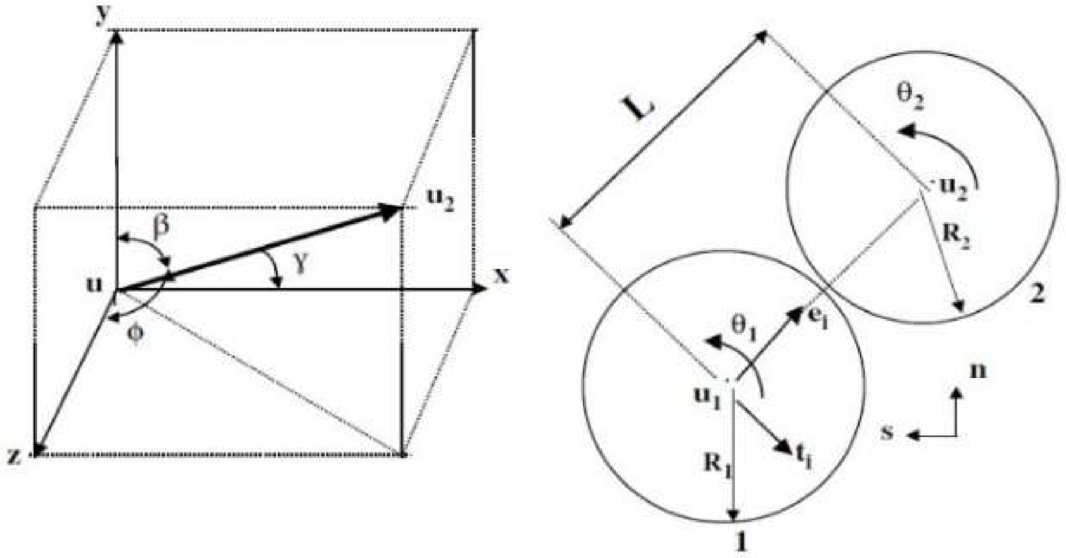

Figure 1. A pair of spherical objects in contact (Raji and Favier, 2004)

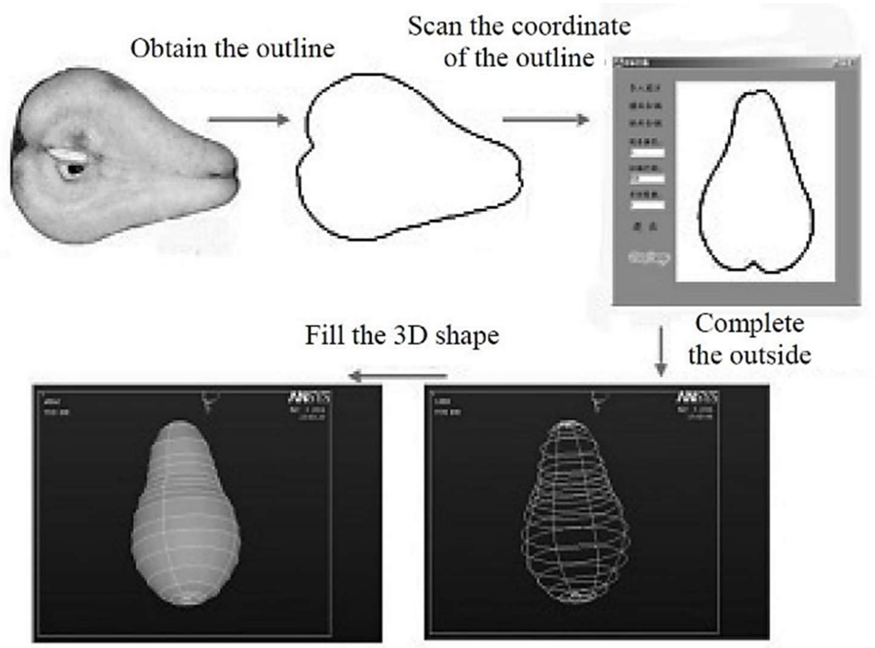

Figure 2. Geometric modelling of pear fruit (Song et al., 2006)

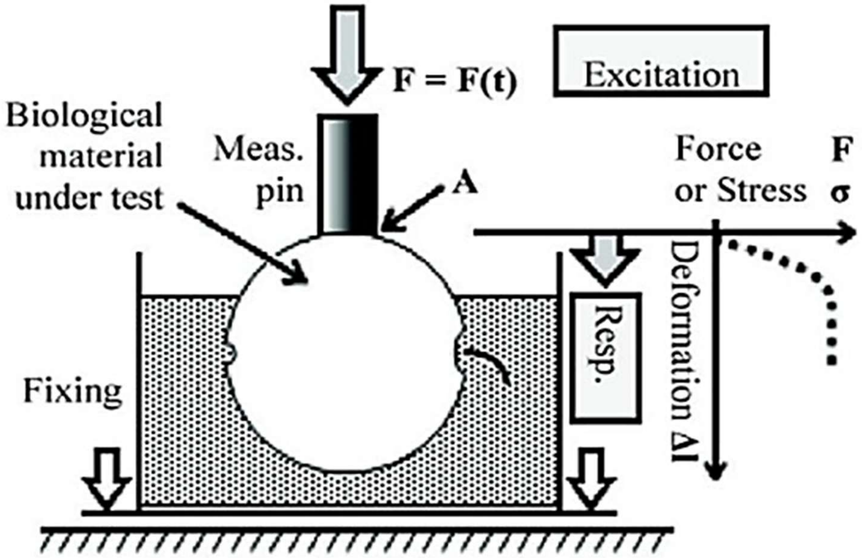

Figure 3. Schematic representation of the application of mechanical load in the DyMa Test (Farkas et al. 2016)

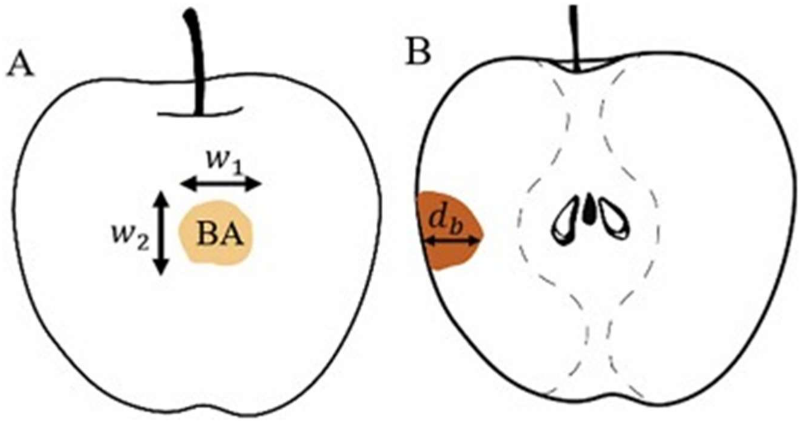

Figure 4. Display of damage measurements on an apple (Fu et al., 2023)

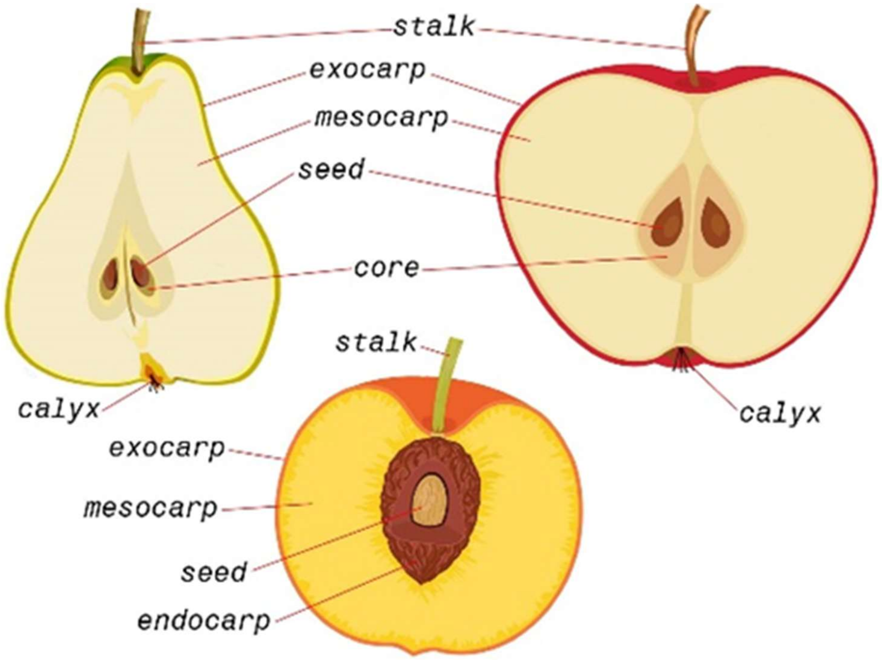

Figure 5. Schematic representation of the structure of a pear, apple and peach

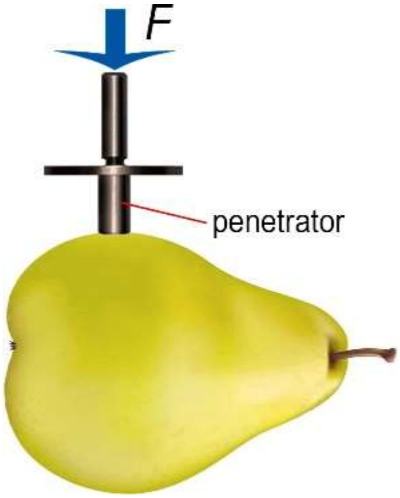

Figure 6. Schematic representation of hardness determination

Figure 7. Analogue, digital, and digital penetrometer on the carrier

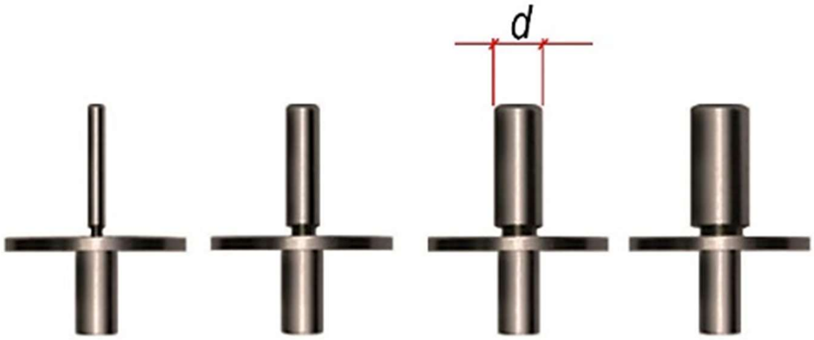

Figure 8. Penetrators with different diameters (Skendrović Babojelić and Fruk, 2016)

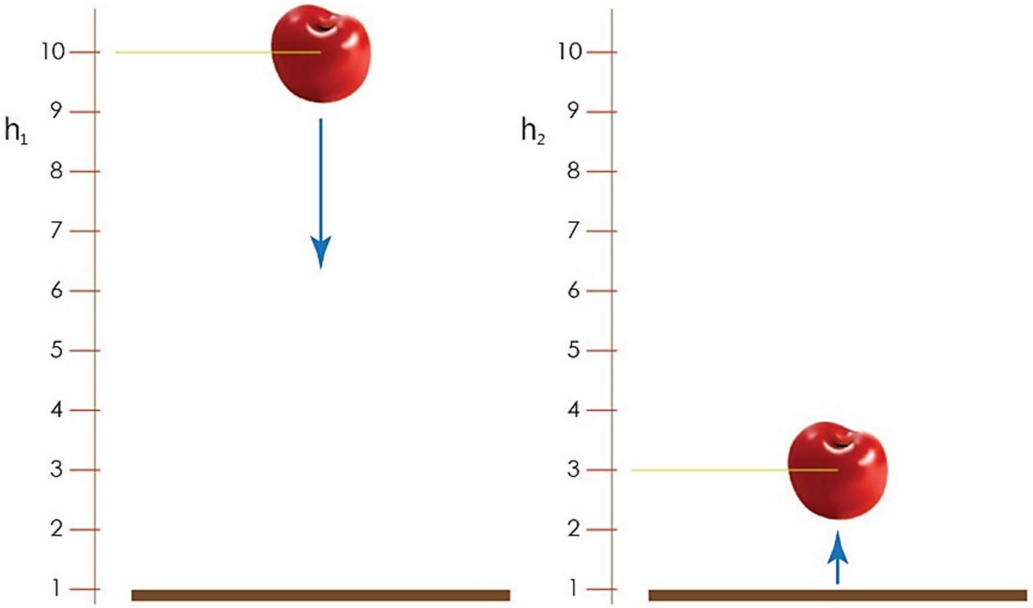

Figure 9. The procedure for determining the elasticity factor

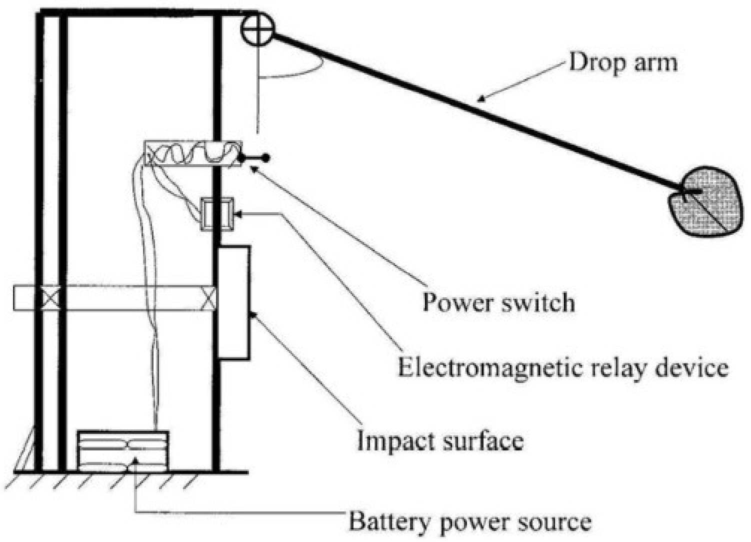

Figure 10. Schematic representation of the components of the new impact testing device (Opara et al., 2007)

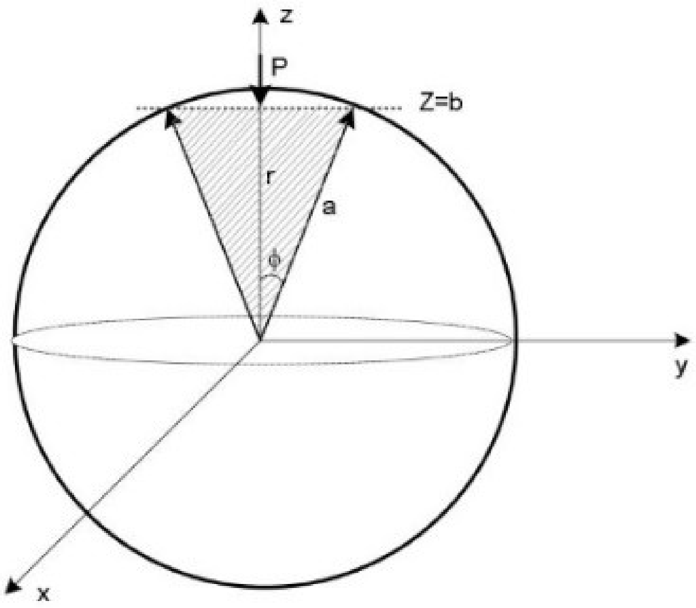

Figure 11. A spherical object subjected to an external point load (Nassiri and Jafari, 2013)