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An Integrated Experimental and Numerical Approach to Develop an Electronic Instrument to Study Apple Bruise Damage

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***Abstract*—**Apple bruise damage from harvesting, handling, transporting and sorting is considered to be the major source of reduced fruit quality, resulting in loss of profits for the entire fruit industry. The three factors which can physically cause fruit bruising are vibration, compression load and impact, the latter being the most common source of bruise damage. Therefore, prediction of the level of damage, stress distribution and deformation of the fruits under external force has become a very important challenge. In this study, experimental and numerical methods were used to better understand the impact caused when an apple is dropped from different heights onto a plastic surface and a conveyor belt. Results showed that the extent of fruit damage is significantly higher for plastic surface, being dependent on the height. In order to support the development of a biomimetic electronic device for the determination of fruit damage, the mechanical properties of the apple fruit were determined using mechanical tests. Preliminary results showed different values for the Young's modulus according to the zone of the apple tested. Along with the mechanical characterization of the apple fruit, the development of the first two prototypes is discussed and the integration of the results obtained to construct the final element model of the apple is presented. This work will help to reduce significantly the bruise damage of fruits or vegetables during the entire processing which will allow the introduction of exportation destines and consequently an increase in the economic profits in this sector.

***Keywords*—**Apple, fruit damage, impact during crop and post-crop, mechanical characterization of the apple, numerical evaluation of fruit bruise damage, electronic device.

I. Introduction

ONE of the main problems of fruit distributors and sellers is related to the bruise damage, which contributes for a production loss around 25%. Fruit damage is often caused by vibrational, compressive and impact forces between the fruit and the equipment used during the several steps of fruit processing, which comprise harvesting, handling, transportation, and sorting [1]. It also usually leads to dramatic alterations in the visual aspect and reduced shelf-life, which restricts the exportation destination and has a tremendous economic impact. In addition, fruit damage is also associated to a significant increase in the risk of bacterial and fungal contamination, raising healthcare concerns [2]-[5]. To overcome these problems, companies have been investing in novel processes and technologies to determine the damage sources during the fruit processing [6]. This approach affords the introduction of modifications in the equipment used during crop and post-crop operations in order to reduce the fruit damage, which is essential for the global competitiveness of this sector.

In this work, we present a technological device, called "electronic elastic sphere (EES)" to evaluate apple bruise damage caused by impact during the different stages of the crop and post-crop. This electronic device will pass through the entire path of the apple and will allow to study in detail the impact, which is the main source of bruise damage [7]-[10]. The severity of the impact is closely related to the principle that "the bigger it is the higher the drop is". The energy (E) involved on the impact of the fruit is given by $E = m \times h \times g$ where m is the mass of the fruit, h is the high of the drop and g is the earth gravity. If the energy of the impact absorbed by the apple causes an effort of its internal tissues beyond its initial bruise damage, that will be the main cause of a financial loss. Therefore, prediction of the level of damage, stress distribution and deformation of the apple under an external force has become a very important challenge.

In order to develop an electronic device that mimics the main properties of the apple, different studies need to be performed: 1) determination of fruit's damage curve; 2) mechanical characterization of the apple fruit; 3) design the EES device by choosing the best material, dimensions, type of sensors and shape. This information will allow the development of a biomimetic EES device that allows the determination of the impact of the apple fruit with the different surfaces that apples pass through, such as boxes, buckets and pallets. Additionally, the results obtained will be essential to create a more realistic viscoelastic model that will mimic the impact caused by the apple when it is released from different heights onto different materials. The comparison between the experimental and numerical results will allow the validation of the apple bruise damage caused by impact obtained using the EES device. Our results will allow the development of mechanical systems and re-designing of all crop and post-crop instruments used to minimize the impact zones that caused apple bruise damage.

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II. METHODS

A. Determination of Apple Fruit's Damage Curve

In this study, we considered apples (Royal Gala) with any type of damage (case I) and apples where its bruise damage inhibits its commercialization (case II). We evaluated the level of the impact that causes bruise damage in the apple because it is very important to understand which is the value of the threshold that lower than that the impact will not damage the fruit. All the different values of impact over the threshold need to be study subsequently. In order to calculate this threshold, it was necessary to perform experimental studies to determine the fruit's damage curves. Forty (n=40) apples were dropped from eight different heights (1, 3, 5, 9, 13, 17, 21 and 40 cm) onto two different surfaces (plastic and the conveyor belt), both frequently present during fruit processing. Three repetitions were performed. The apple was dropped using a vacuum pump. After predetermined periods of time, both interior and exterior areas were subsequently analyzed regarding the existence of bruise damage. Each surface was identified using a specific dust of different colors that helped to measure the precise area of the impact caused by the apple drop (see Fig. 1). The results allowed the identification of the threshold over which the impact would cause bruise damage. Fruit's damage curves were then performed.

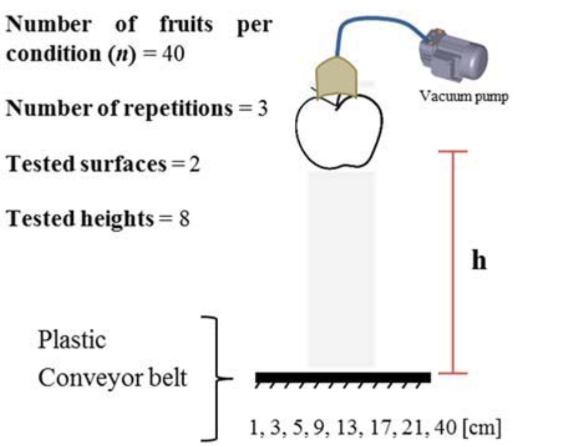

Fig. 1 Schematic representation of the experimental setup used to determine the apple damage due to the impact with two common surfaces (plastic and a conveyor belt) at different heights.

B. Mechanical Characterization of the Apple Fruit

In order to create a finite element model of the apple fruit to study numerically the impact of the apple into a certain material, the mechanical characterization of the apple fruit is needed. There is no data available on the literature regarding the variation of apple fruit's mechanical properties that consider in detail the anatomy of the apple. Apple is usually modelled computationally as an isotropic material which can cause significant errors when predicting apple's bruise damage. Apple is composed by epidermis, pericarp and seeds [11]-[14], which suggests that an anisotropic model would be better to study the damage caused by impact. In this work, a Royal Gala apple was used as the sample organic material to investigate deformation in the drop case scenario. These apples came from Frutus cooperative in Cadaval, Portugal. Compression tests were performed on geometrically cut specimens of apple parenchyma in a Zwvick testing machine. This machine was equipped with load cell of 5kN and two parallel plates that one is fixed and the other is versatile and moves at a compressive rate of 1mm/min. The apple was cut in layers with 5 mm and cubic specimens along the apple flesh were obtained (see Fig. 2).

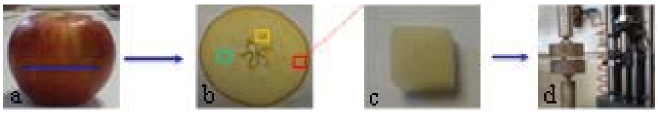

Fig. 2 Compression tests were performed cutting horizontal layers (a) of 5 mm from different Royal Gala apples. Different zones of the apple were studied (b) Cubes with 5mm were obtained and used to perform the compression tests

C. EES Sphere Characterization

An electronic fruit called EES sphere was made to measure the impact in 3-axis (x,y,z) of the apple when it was dropped from different heights and into different materials (plastic and a conveyor belt). The device is portable, with a high autonomy and easy to use. It has USB connection to a PC for data transfer and battery charge and also a microprocessor. The first prototype was constructed in silicone using additive manufacturing, coupled with multiple electronic sensors (temperature, triaxial acceleration sensor and force sensors) to better simulate the apple path from crop to post crop different stages. This device allows the registration of the time and acceleration of the impact of the apple through the processor lines. Data is registered as peak acceleration in Gs and speed variations (dv) in meters per second. The results obtained are related to the absorbent capability of the impact force and the speed achieved when the EES touches the surface can be seen graphically. Each surface presents a specific feedback given by the EES which is represented by a line, function of the acceleration speed values and the speed captured by the EES. The combination of these results will allow to define the level of the impact that can cause a bruise damage in the apple. When the zones are identified some changes can be done in order to minimized the bruise damaged caused by impact.

III. RESULTS

A. Determination of Apple Fruit's Damage Curve

In order to better understand the extent of damage caused by the impact in the apple (Royal Gala), fruits were dropped from several heights onto different type of materials (plastic and a conveyor belt) and the damage curves determined for two different situations: Case I, which comprises all apples with damage and case II, where their bruise damage inhibits the commercialization (Fig. 3). The results for case I, shows that when the apples are dropped onto a plastic surface there is always a bruise damage, which increase to 40% and 80% when the apple is dropped of a 3 cm and 5 cm height, respectively. When the apple is released from a height of 9 cm or more onto a plastic surface, the damage caused is always around 100%. Case II presented different results. A damage percentage more or equal than 5 was observed only after the apple was dropped from a height of 13 cm. When the impact height was 40 cm the correspondent percentage of damaged fruit was 25%. When the apple was released onto a flat conveyor belt the results were different. Apple bruise damaged, in case I, was around 20% when the apple was dropped from the eight different heights explored. Whereas in case II, the results showed no consequences on apple bruise damage when it was released from any of the eight different heights studied.

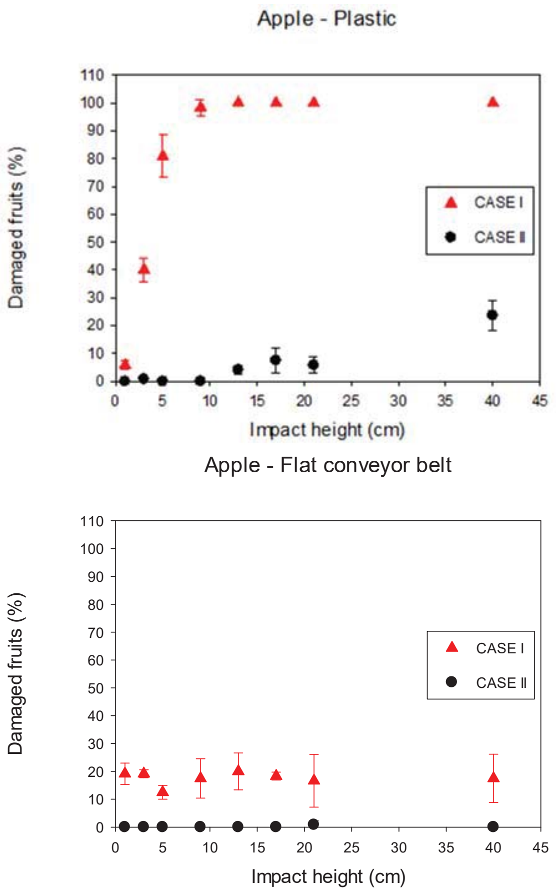

Fig. 3 Determination of fruit's damage curves (in %) when the apple is dropped from eight different heights (1, 3, 5, 9, 13, 17, 21 and 40 cm) onto two different surfaces like plastics and a conveyor belt

B. Mechanical Characterization of Apple Fruit

Compression tests were performed by cutting horizontal layers of 5 mm from different Royal Gala apples (see Fig. 2). The results of the compression tests performed can be seen in Fig. 4 where the average of the Young's modulus was obtained. Different values of the elasticity modulus were obtained which was consistent with the hypothesis that the isotropic model is not the best model to characterize the apple fruit. The results showed that different results were obtained for the different layers studied and they could be grouped in to three distinct zones 1, 2 and 3. An average of the higher value, E≅2.36 MPa, was obtained at zone 1, whereas the lower E≅1..60 MPa, was obtained at zone 3 (see Fig. 4).

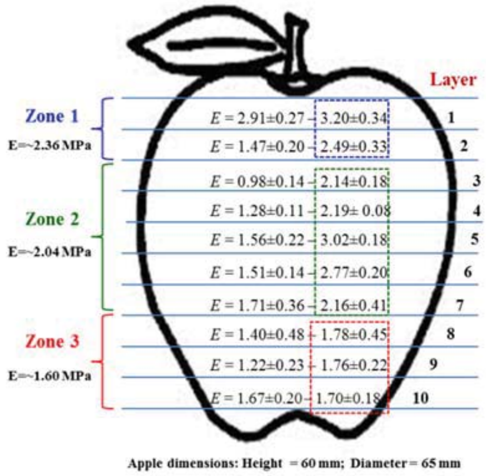

Fig. 4 Mechanical characterization of the fruit using compression tests to calculate the Young's modulus in ten different layers obtained by cutting the apple in layers of 5 mm and -1q \cubic specimens from different along the apple flesh. Different results were obtained and three distinct zones 1, 2 and 3 were identified

C. EES Sphere Characterization

The innovative electronic fruit, EES, has several requirements. It measures the impact in 3-axis (x,y,z) and also the compression loads which allows the identification of the precise location (x,y,z) of impacts and loads. It is portable, has a high autonomy and it easy to use. The USB connection to a PC for data transfer and battery charge is also available. Different engineering and development phases were considered. First, the 3D modelling is used to find out which was the best geometry. Second, the prototype materialization with the different materials and type of sensors are used and third, different tests were conducted and therefore, the device was optimized and validated. The results presented in this section consist of the 3D CAD model (see Fig. 5) and also the prototype materialization. Two different models were made. The first one, prototype V1.0 had the sensor located at the edges, whereas the second one, prototype V2.0 was round and kept the same pentagonal regions well distributed around the sphere (see Fig. 5). The latter was made using silicone. Both prototypes were constructed using additive fabrication. Firstly, using ABS, and then a silicone which better integrate the electronic control developed, which contained, a temperature sensor, a triaxial acceleration sensor and forces sensors to analyze the mechanical loads.

IV. Discussion

In this work, we report a methodology for the design of an electronic device to be used in the determination of damage sources of the apple fruit. Fruit damage during crop and post-crop operations is a major source of fruit waste and economic loss. During the processing, fruit is permanently in movement and in contact with numerous surfaces. The interaction between the fruit and such surfaces subject fruits to a wide range of mechanical loads from vibrational, compressive and impact forces. Among them, impact and compressive forces are frequently experienced by the fruits throughout the processing stages, which depending on the distance between the fruit and the receiving subtract, might lead to bruise damage. In addition to the distance, the surface properties of receiving substrate also play a key role in the extent of the damage. It is widely recognized that rigid surfaces like plastic, for example, increase the area and depth of the damaged area compared to soft surfaces with high energy absorption capacity. The extent of fruit damage determines the shelf-life and ultimately restricts the commercialization window and destination.

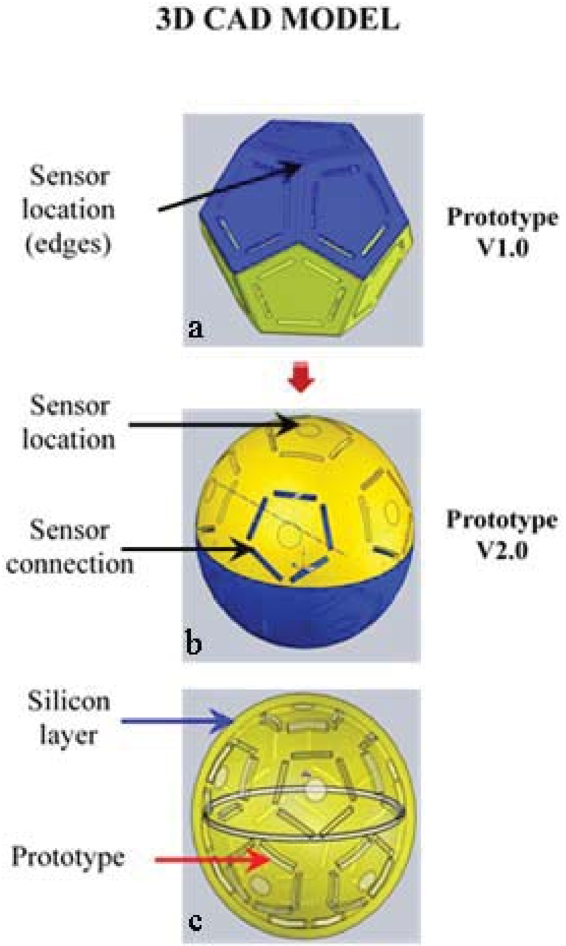

Fig. 5 The 3D CAD model of the innovative electronic fruit called EES sphere. It was made to measure the impact in 3-axes (x,y,z) of the apple when it is dropped from different heights. Two different prototypes were constructed. The prototype V1.0 (a) had pentagons at each face and the sensors were located at the edges of the polygon, whereas the prototype V2.0 (b) has a round shape and the sensors localization. The silicon layers can also be in (c)

In order to identify and reduce the fruit damage during the processing operations, we developed a methodology to design an electronic device that measures impact and compression loads in space and time. This, combined with information about the exact location of the experienced forces, allows us to identify critical areas that are involved in fruit damaging towards subsequent modification. To allow the development of an electronic device for the determination of damage in apple fruit, we started by performing experimental assays to access the apple damage curves using two common impact substrates – plastic and conveyor belt. A significant number of fruits were left from different weights onto the substrates and the extent of damage (surface area and depth) analyzed according two classifications: (1) case I, fruits exhibiting visual damage and (2) case II, fruits exhibiting damage that prevents commercialization. In the case of plastic substrate, it was found that the percentage of fruits with visual damage significantly increased from 1 to 3 cm of height. About 40% of apples presented visual damage when left from a distance of 3 cm, but this height does not lead to damage that prevents commercialization, as can be seen in Fig. 3. When the height was increased to 21 cm, more than 10% of the fruits cannot proceed for commercialization. In contrast, when the fruits were tested with conveyor belt, a significant reduction on the number of fruits presenting visual damage was observed. Notably, for all tested heights, the percentage of fruits with visual damage was less than 25%, whereas the percentage of fruits that cannot be commercialized was negligible. This information, correlating the effect of substrate and the percentage of damaged apples, allows us to define the threshold in the electronic device for which the percentage of fruits that cannot be commercialized is higher than a determined value defined by the user. Experimentally, this is done by dropping the EES from the same heights used to determine the apple's damage curves onto the same surfaces. For each drop, the EES registers peak acceleration of the impact in Gs, which is subsequently attributed to the corresponding height and surface. Based on the damage curve results, we are able to determine in the EES corresponding value of peak acceleration that prevents the fruit damage.

After analyzing the effect of receiving substrate on the fruit damage, we moved to the design of the electronic device for the determination of apple damage. The device is composed of robust and rigid polymeric structure that accommodates the electronic components, which is covered by a silicone layer for impact absorption and damage prevention during the utilization. The base structure of the prototype was fabricated by additive fabrication, while a custom-made electronic board was designed to accommodate a chargeable battery and a triaxial acceleration sensor for impact measurements. Load sensors are distributed throughout the surface of the base structure, covering the maximum available area. Sensors with different areas and loads were tested along silicon layers of variable thicknesses (data not shown). Although silicone was selected as the base material to cover the electronic device, the type, composition and viscoelastic properties of the cover layer should be selected in order to closely resemble the fruit properties. To this end, we collected cubic samples from different regions of the apple and performed compression mechanical tests. The results show that the mechanical properties of the apple varied according to the layer of the apple in study, being the Young's modulus lower in layers 8-10 (see Fig. 4). These data allow a better characterization regarding the mechanical properties of the fruit, which is relevant not only for materials selection, but also for computation modelling and simulation. Conventional engineering approaches to design electronic devices for agricultural applications assume that fruits are isotropic materials and not consider neither viscoelastic properties nor fruit shape. To develop a biomimetic electronic fruit that better replicates the anatomic and biomechanical properties of the apple, we are implementing an integrative approach involving image acquisition and segmentation, biomechanical data, computer modelling and simulation. The first two prototypes are already built. Future work will focus in the validation of the first preliminary optimization tests made to evaluate the performance of different type of sensors regarding the silicone thickness and to determine the sensor response to mechanical loads. Additionally, the validation of the software and the data obtained when the sensor mimics an apple during all the procedures of crop and post-crop will also be performed. The data obtained experimentally will be compared with the numerical results obtained using a computer model where a biomimetic approach replicating biomechanical properties of the Royal Gala apple is considered which will allow to predict more accurately the bruise damage of this fruit.

Using this approach, it will be possible to acquire the shape of the fruit (vegetable) using low cost technologies for subsequent segmentation, virtual modelling and fabrication of mimetic electronic devices. In combination with the organic shape, biomechanical data will be useful in the selection of suitable cover materials that better represent the fruit-fruit (vegetable-vegetable) and fruit-substrate (vegetable-substrate) mechanical interactions. Together, this approach will be very useful in the design of more realistic electronic devices that could be easily applied in industry to optimize processing lines, reduce food waste and costs.

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