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Bruise Patterns of Fresh Market Apples Caused by Fruit-to-Fruit Impact

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Abstract: Comprehensive understanding of bruise damage caused by apple-to-apple impacts is beneficial to design a low-impact fruit capturing mechanism for mass (shake-and-catch) harvesting, as well as to design other fruit handling devices. This study quantified the bruising severity in 'Jazz' apples induced by different levels of impact upon various fruit surface locations. Impact experiments were carried out to analyze bruising patterns in three zones in a fruit surface, i.e., middle/cheek-to-top/stem, middle-to-middle and middle-to-bottom/calyx. Moving fruit and stationary fruit were impacted using a pendulum-type test device, and an equivalent drop height of fruit was calculated to provide a more practical measure for designing a catching surface. In each impact zone, seven different levels of impacts were applied respectively at seven different locations on the fruit surface. Those locations were evenly distributed along the circumferential direction in each of the three zones, and moving fruit was replaced after each impact test. The United States Department of Agriculture (USDA) standard was then used to estimate percentages of fruit in the *Extra Fancy Class 1* (no bruising), *Extra Fancy* (a bruising area diameter ≤ 12.7 mm) and *Fresh Market* (a bruising area diameter ≤ 19 mm) grades. Results showed that fruit bruising severity increased in a non-linear manner with increasing drop height. It was also found that there existed significant differences in fruit bruising severity between stationary and moving fruit under different fruit-to-fruit impact zones. The bottom zone showed the least bruising sensitivity, followed by the middle zone which was statistically similar to the same in the top zone. The results suggested that the free drop height need to be <3 cm to keep from fruit bruising caused by apple-to-apple impact at a negligible level for 'Jazz' apples.

Keywords: tree fruit; fresh market apple; mechanical damage; bruise patterns; fruit-to-fruit impact

1. Introduction

Statistics from Food and Agriculture Organization of the United Nations (FAO) showed that world apple production exceeded 83 million tons in 2017 [1]. Fresh market apples are harvested manually around the world, which presents challenges due to the increasing labor costs and decreasing availability of the labor-force. These issues could be addressed by developing mechanical harvesting solutions [2]. As one of the most commonly investigated mechanical harvesting methods, mass harvesting (e.g., shake-and-catch harvesting) systems have been successfully used for berries, oranges and other fruits targeted primarily for the processing market [3]. However, limited success has been achieved for fresh market apples as well as berry crops, primarily due to the high level of harvest-induced mechanical damage [4,5].

Bruise damage caused by impacts between apples and their capturing surface, as well as apple-to-apple contacts accounted for in the majority of mechanical damage in mass harvesting [6–8]. Improved understanding of the mechanism of fruit bruising would contribute to designing harvesting systems that can reduce fruit damage. Some studies were performed in this area to evaluate the effect of impact loading conditions on fruit bruising using drop tests [9–14] or pendulum tests [15–18]. The minimum impact conditions corresponding to the initiation of fruit bruising on hard and cushioned surfaces were determined. The factors affecting the bruise susceptibility were also determined, which generally included fruit size and shape (mass, curvature radius), firmness and ripeness [17,18]. The dependence of bruise diameter, bruise area and bruise volume on mechanical parameters such as drop height, impact energy, impact force and absorbed energy was also clarified when apples were bruised by different contact surfaces [17–21]. Since the use of adequate cushions on the catching surface could reduce fruit bruising during mass harvesting, many studies were conducted on the effectiveness of cushions in minimizing fruit bruising [9,11–13,21,22]. Several other studies focused on fruit bruising occurred in stacked columns of fruit during transport or bulk storage [20,23,24]. Past studies on the mass harvesting of apples also demonstrated that a significant amount of bruising is caused by impacts between fruits [6–8,25]. However, few studies were reported on any impact of fruit-to-fruit contacts on apple bruising damage [26–28].

Moreover, past studies [29,30] showed that the mechanical properties of apples were anisotropic, which significantly varied over fruit surface locations. It is, therefore, important to understand how bruising differs at varying locations on the apple surface. Pang et al. [26] characterized impacts onto apples using an Instrumented Sphere (IS). The acceleration during an impact of the IS was measured by an embedded tri-axial accelerometer [31]. The impact conditions corresponding to an initiation of fruit bruising resulting from apple-to-apple impacts were estimated by comparing the results of apple-to-apple and IS-to-apple impacts exerted by dropping one of the two objects from a range of heights. This is because the dynamic response of fruit was different than that of the IS. Pang et al. [27] conducted another study to analyze the impact between a pair of apples in pendulums forms formed by thin nylon threads. The experiment was designed such that each pair of apples impacted each other at different locations on their cheeks by rotating the calyx-stem axis. A video camera was used to record the movement of the two apples during the experiments. They primarily examined relationships between physical parameters, including total bruise volume, contact area, impact energy and energy absorbed during the impact. Subsequently, Studman et al. [28] studied the variation in bruising rate and extent in green and red regions of an apple using fruit cut into green and red halves, and making them impact each other. The above studies showed that when two apples came into contact with each other, one of the two apples and one side of each apple often were more bruised. Also, bruise damage was found to vary over different zones on the apple surface along the stem–calyx axis when different surfaces zones were impacted by aluminum and cushioned surfaces with varying levels of impact exerted at those zones on those apple surfaces [15]. Therefore, it was hypothesized that different zones on the apple surface will bear varying degrees of bruising, depending on the locations of the apple surface impacted by the fruit-to-fruit contacts, which has not been studied in the past.

The major goal of this study was to quantitatively assess the severity of fruit bruising caused by apple-to-apple impacts at different zones on the apple surface. A pendulum-type device was specially designed and fabricated to conduct the experiments with apple-to-apple impact, and equivalent drop height of fruit was also estimated to provide some more practical information for designing an effective and efficient shake-and-catch type of harvester.

The specific objectives of this study were: (1) To estimate the relationship between fruit bruising severity and drop height (estimated using pendulum dynamics) for different fruit surface zones under different apple-to-apple impact zone patterns; (2) evaluate the effect of fruit surface zones/locations on fruit bruising severity; and (3) to determine the minimum impact conditions corresponding to the initiation of apple bruising in different severity.

2. Materials and Methods

2.1. A Pendulum-Type Fruit Impact Device

In past studies [27,28] on fruit-to-fruit impact, researchers generally used two pendulums formed by thin nylon threads to support a pair of apples that can be released from a certain angle to freely impact each other. With this technique, it was difficult to precisely control the specific impact location on the fruit surface. To address this challenge, we designed a special pendulum-type impact testing device (Figure 1) as an improvement over the one used in the past to conduct impact tests between apples and various types of catching surface materials [15]. The test device used in this work was designed in a modular fashion to minimize potential errors/noises. The device primarily consisted of a pendulum arm, an incremental rotary encoder, a set of arm positioning mechanism, an impactor and an aluminum structural frame. The pendulum arm was a 0.9 m long aluminum tube with a 19 × 19 mm cross section. The rotary encoder (E6B2-CWZ3E, YUMO, Yueqing, China) installed at the pivot of the pendulum arm was utilized to measure the angle of swing. The pivot was supported by a pair of ball bearings to reduce the friction. The positioning mechanism included a pair of acrylic sheets (30 cm × 15 cm) with a series of 15 positioning holes at 5° increments, which was used to set the initial position of the pendulum arm. The impactor was attached to a force senor (PCB Piezotronics 208C02, sensitivity: 11.24 mV/N; measurement range: ± 445 N), a rectangular steel tube, and a square aluminum plate (5 cm length × 5 cm width × 0.64 cm thickness) with four pins (2 cm length × 2.8 cm interval). With this mechanism, the impacts between test objects (apples in this case) occurred at the lowest point of swing and in a horizontal direction. Since the impact time was very short (about 5 ms), the friction involved was ignored. Impact force was assumed to be the same as it was applied to the stationary apple. Impact forces and angles of swing were acquired by National Instruments (NI) cards with a sampling frequency of 25.6 kHz and 62.5 Hz, respectively, and were processed using NI Signal Express, 2014.

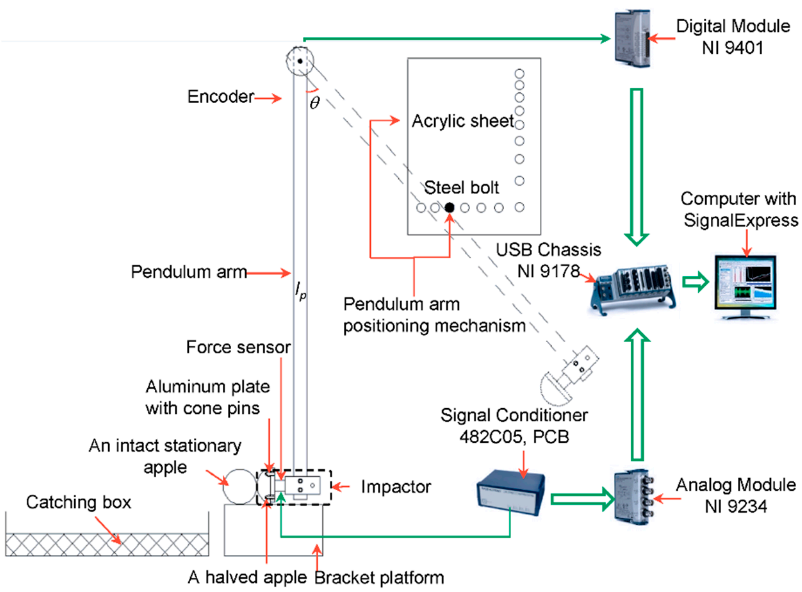


Figure 1. A schematic presentation of the pendulum-type impact test device used in this study. In the diagram, l_p and θ was separately the pendulum arm length and the pendulum's angle relative to the vertical axis. For specification of the test procedures with the impact device, please see Section 2.2.

2.2. Sample Preparation and Experimental Setup

In this study, 'Jazz' apples were used because there were a large number of 'Jazz' orchards available in Washington State (WA) with trees trained to desirable vertical fruiting wall architecture. This commercial planting and management system presents tree canopies with seven horizontal fruiting tiers spaced about 0.5 m apart. This was a particularly suitable canopy system for the subsequent design of a localized shake-and-catch harvesting system for fresh market apple harvesting. In addition, 'Jazz' is a commercially important variety in Washington State, which ranks twelfth by acreage in WA [32]. For this study, apples were picked manually in a random fashion from a commercial orchard near Prosser, WA. The harvesting occurred during the optimal harvest window identified by the grower. Apples were isolated from each other using a molded pulp fruit tray to protect fruit from coming a contact with each other during handling and transportation. Three of those fruit trays were packaged together with a piece of foam separating two adjacent layers, and were placed onto a plastic box. These boxes were carefully transported to the laboratory on a pickup truck with a layer of rubber sheets on the bottom of the boxes. The apples were stored within five hours of picking to minimize any other unwanted stress/impacts on the fruit.

In this study, three apple-to-apple impact zones, i.e., middle/cheek-to-top/stem, middle-to-middle and middle-to-bottom/calyx, were used to study the effect of fruit-to-fruit contact on fruit quality. As described above, a moving fruit (in a pendulum) and a stationary fruit installed at the lowest point of the pendulum swing, were used to cause impact between fruits. A total of 50 stationary fruits (with no existing damage/bruising) were used in the experiment with an average weight of 170 ± 20 g (mean ± standard deviation(SD)). For creating the moving samples, apples were halved along the stem–calyx axis. A total of 525 intact apples were randomly selected from stored apples to prepare the moving samples with an average weight of 90 ± 12 g.

The three impact zones on the fruit surface are shown in Figure 2. To obtain more precise results, each of the three vertical zones (Figure 2a) of the intact stationary fruit was further divided into seven impact locations along the circumferential direction, leading to a total of 21 impact locations on the surface of each stationary fruit. Figure 2 only shows some representative impact locations as the remaining locations would be in the back side of the fruit. By changing the initial angles of the pendulum arm, varying levels of impact were exerted during the fruit-to-fruit contact. To reduce errors caused by variations of specimens, seven different levels of impact were applied respectively at the seven different impact locations within a given fruit surface zone. Each moving fruit was identified as a sample to impact a specific location at the stationary fruit. With this scheme, all moving samples were randomly divided into 21 groups of 50 each, and a group was randomly assigned to a level of impact.

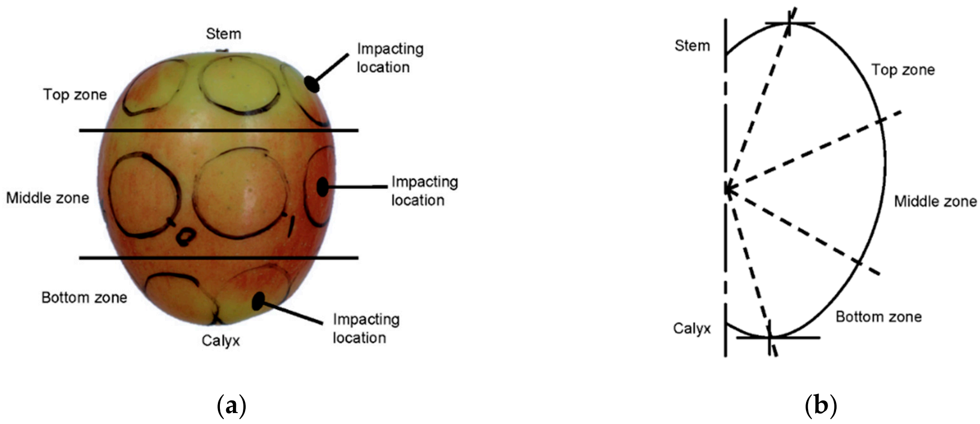


Figure 2. (**a**) Three impact test zones and visible impact locations within each zone on the surface of a stationary apple specimen; (**b**) A fruit section schematic depicting the three impact zones in an apple.

Fruit bruising could be influenced by the radius of curvature on the fruit and flesh firmness under some impact levels [17,18]. To support the subsequent explanation of fruit bruising damage at different locations on fruit surface, the flesh firmness was measured at three test zones using 30 randomly selected fruit specimens from the stored apples. In addition, the harmonic mean of the radius of curvature (refer to R) of the three test zones was calculated using another 72 specimens and Equation (1). The results [15] showed that the bottom test zone had a significantly higher firmness than the other two zones at a 95% confidence level (CL), whereas there was no significant difference in the firmness between the top and middle zones. It was also found that there was a significant difference in the radius of curvature among the three test zones where the middle zone had the largest radius of curvature.

$$R = \frac{2 \times R_1 \times R_2}{R_1 + R_2} \tag{1}$$

where R_1 was the circumferential radius of curvature and R_2 was the meridian radius of curvature.

The apple-to-apple impact experiments were performed at room temperature (about 22 °C, 50% relative humidity (RH)). The height of the apple supporting bracket platform was firstly adjusted to ensure that the moving apple (on a pendulum) would impact the stationary apple at the desired test location on the fruit surface. The impactor with the moving fruit sample was pulled manually to the desired angular position before releasing to exert a certain impact between two apples. To minimize the potential effect of the manual operation of the impactor on the initial speed of the pendulum, an about 1 m long cotton string without elasticity was used. During the individual test, the string was pulled at the tail to move the impactor to the desired angular position set by the steel bolt. Once the impactor reached the desired angular position, the string was pushed and released forward as soon as possible. The moving fruit then impacted (with a specific impact level) a stationary fruit that was freely laying on the bracket platform. This set-up created a normal impact applied at the desired test zone and location on the fruit surface. The contact force and the pendulum's angle (θ) relative to the vertical axis were automatically measured and recorded by the developed computer data acquisition system. After the impact, the stationary fruit flew away from the platform, which was captured on the air by hand to prevent any unwanted fruit bruising/damage. Each moving fruit was used only one time to impact the stationary fruit. Each level of impact was repeated 50 times for each location.

2.3. Equivalent Drop Height

The equivalent drop height for fruit-to-fruit impact was calculated from the pendulum parameters to provide a more practical measure for understanding fruit quality issues caused by fruit-to-fruit impact. According to the law of conservation of energy, the equivalent drop height of stationary fruit was given by Equation (2).

$$h = \frac{E_i - E_f}{mg} = \frac{\left(\frac{m_p g l_p}{2} + m_i g l_p\right) \times \left(\cos\theta_f - \cos\theta_i\right)}{mg} \tag{2}$$

where h was the equivalent drop height; E_i was the initial energy of the impact; E_f was the retained energy of the pendulum; m was the weight of the stationary fruit; g was the gravitational acceleration; m_p was the weight of the pendulum arm; m_i was the weight of the impactor with moving fruit; l_p was the pendulum arm length; θ_i was the initial swing angle relative to the vertical axis; θ_f was the pendulum's angle relative to the vertical axis after impacting.

The angle (θ) of the swing of the pendulum arm was measured using the encoder and was computed using Equation (3).

$$\theta = 360 \times \frac{N_o}{N_b} \tag{3}$$

where N_o is the number of pulses; N_b is pulses per revolution.

The apple drop height was defined to be the mean equivalent height of each moving fruit used to impact a stationary fruit at a specific impact zone with a specific impact level.

2.4. Fruit Bruising Assessment

For assessing the severity/extent of fruit bruising, currently, there is no standard method available. Some reported work in the past used bruise volume as indicator [17,33–35]. However, due to the difficulty in measuring bruise volume, visible bruising, bruise diameter or bruise surface area received greater interests during impact experiments [36,37].

There is a standard provided by the United States Department of Agriculture (USDA) in assessing fruit quality based on the bruise surface area, which has been adopted widely in previous studies [6,38] on harvesting fresh market apples. Using this standard, percentages of apples in *Extra Fancy Class 1* (bruise-free), *Extra Fancy* (with a bruising area diameter ≤ 12.7 mm) and *Fancy* (a bruising area diameter >12.7 mm but ≤ 19.0 mm) grade categories were estimated to quantify fruit bruising severity. The fruit quality standard (with a *Fresh Market* grade being used to include both *Extra Fancy* and *Fancy* grades defined by the USDA) is also used in the fresh fruit packing industry in Washington as well (Karen Lewis, personal communication, July 15, 2015). The diameter of bruised areas of the test fruits were measured after oxidation and discoloration for 24 h at room temperature (about 22 °C with 50% RH). Before skins removal, fruit were first observed visually and evaluated with a slight touch of the fingers to detect whether there was a slight browning or flattening on the impact locations. Non-destructive assessment was then followed by peeling around the impact locations using a 0.4 mm knife to examine the presence of browned tissues. The exposed region around the impact location was then used to measure the latitudinal and longitudinal diameters of the bruised areas, and the larger diameter was chosen to categorize the fruit into different quality grades. Equation (4) was used to calculate the percentage of different grades of fruit at each level of impact.

$$P_n = \frac{N_n}{N} \times 100\% \tag{4}$$

where P_n was percentage of fruit in a certain quality grade; N_n was the number of fruit in certain quality grade; N was the total number of fruits in a sample group.

2.5. Statistical Analysis

Fruit weight is one key factor affecting amount of force exerted during fruit-to-fruit impact. Descriptive statistics and one-way analysis of variance (ANOVA) with Duncan's multiple range test were all performed using IBM SPSS$^{(r)}$ Statistics V21.0 (Armonk, NY, USA) to compare the fruit weight among different groups of fruit samples.

To evaluate the effect of drop height (equivalent drop height in this case) and moving fruit weight on impact force, a multiple, stepwise, linear regression between impact force (peak force) and equivalent drop height and moving fruit weight was analyzed using the SPSS$^{(r)}$ Statistics software. Similar regression was also conducted to determine the effect of moving fruit weight and equivalent drop height of fruit on fruit bruising severity. To help determine the impact condition corresponding to a threshold level of fruit bruising severity, linear and non-linear regression models were respectively built to present relationships between equivalent drop height and percentages of fruit in certain quality grades for stationary and moving fruits. In addition, to further compare the fruit bruising severity between stationary and moving fruits in each fruit-to-fruit impact zone, analysis of covariance (ANCOVA) was respectively performed using SPSS$^{(r)}$ Software. The purpose of selecting ANCOVA was to reduce the effect of variation of fruit on the difference of fruit bruising severity. The regression curves were plotted using Microsoft$^{(r)}$ Excel 2016 (Redmond, WA, USA).

3. Results and Discussion

3.1. Statistical Results of Moving Fruit Weight

Table 1 shows the mean (± standard deviation) weight of 21 groups of moving fruits used to impact stationary fruits at 21 different locations in three different test zones on fruit surfaces. Under the middle-to-top, middle-to-middle and middle-to-bottom impact zones, the greater the impact level, the higher the impact energy it exerted. As seen in the table, there was no statistical difference in moving fruit weight among the most groups.

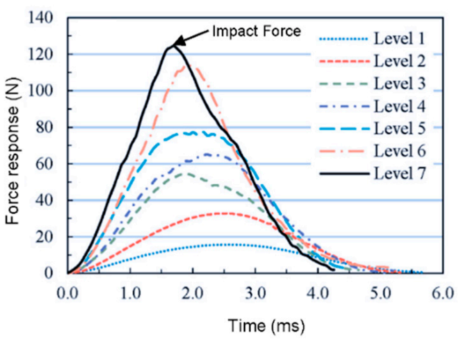
Table 1. Mean (± standard deviation) weights (g) of 21 groups of moving fruits used to impact stationary fruits at 21 different locations in three different test zones on fruit surfaces [i].

Impacting Zones	Impact Levels						
	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7
Middle to Top	92 ± 9 a	93 ± 6 a	97 ± 10 a	92 ± 9 a	94 ± 9 a	95 ± 11 a	95 ± 12 a
Middle to Middle	89 ± 10 a	92 ± 11 a	92 ± 14 a	88 ± 11 a	90 ± 8 a	94 ± 9 a	93 ± 8 a
Middle to Bottom	93 ± 12 a	82± 6 b	90 ± 10 a	82 ± 8 b	85 ± 8 a	90 ± 13 a	82 ± 7 b

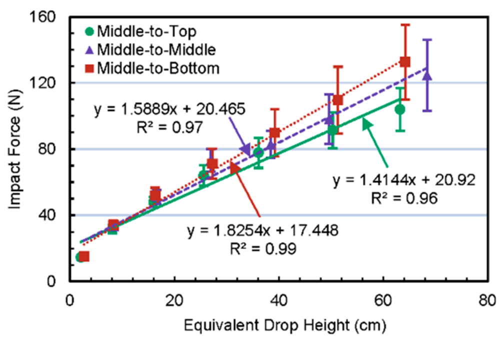
[i]. Different characters ('a' and 'b') next to two numbers indicate that there was a significant difference in fruit weight among the test groups at a 95% confidence level.

3.2. Fruit Impact Responses

Some typical examples of force response during apple-to-apple impact are shown in Figure 3a, which reveal the patterns of impact force (peak force) exerted on a fruit during impact/contact time. Impact forces increased quickly over the first 1.5 ms, and reached their peak around 2 to 3 ms. Instances with relatively larger forces peaked slightly sooner compared to those with relatively smaller forces (Figure 3a). Once peaked, the forces were released as quickly as possible, creating a pattern of forces approximately symmetrical around the peak axis. To provide a more practical parameter for catching mechanism design and for other aspects in mass fruit harvesting, the equivalent drop height of stationary fruit was calculated using Equation (2). The linear regression analysis performed with the "stepwise" method showed that the fruit weight had no significant influence on impact force at a significant level of 0.05. Impact force primarily, therefore, depended on the equivalent drop height of fruit. The potential reason for less influence from fruit weight was the insignificance in fruit weight differences between different test groups. Randomized sampling of moving fruits into various tests led to only three groups with statistically different fruit weighs (Table 1). To evaluate the relationships between equivalent drop height and impact force, a set of linear regression equations were obtained for each test zone: middle-to-top, middle-to-middle and middle-to-bottom (Figure 2), which are shown in Figure 3b. Those equations suggested that the impact force and drop height (equivalent) follow a strong linear relationship in all three impact zones, corresponding to the coefficients of determination (R^2) of 0.96, 0.97 and 0.99 respectively for middle-to-top, middle-to-middle and middle-to-bottom zones. In addition, Figure 3b shows that the slope of the fitted lines increases sequentially from middle-to-top to the middle-to-bottom zone, and the extent of impact force is very close to each other for all three impact zones at lower drop heights. The potential reason for this result is that the bottom zone had a significantly larger flesh firmness than the other two zones as measured by Fu et al. [15], and the harder fruit surface bruised later during impact and absorbed less energy to cause a larger impact force.



(a)



(b)

Figure 3. (**a**) Typical force response-time curves for different impact levels in the same impact zone (middle-to-middle); the greater the impact level, the higher the impact energy it exerted. (**b**) The linear regression equations between equivalent drop height and impact force for the three impact zones.

3.3. Fruit Bruising Severity Assessment

The percentages of both *Extra Fancy Class 1* grade fruit and *Extra Fancy* grade at each impact level were calculated using Equation (4). These measures were calculated separately for stationary fruits and moving fruit involved in the apple-to-apple impact. Past studies have shown that fruit impact-induced bruising is dependent upon fruit weight [39] and drop height [22]. In this study, the fruit weight had no significant influence on impact force at a significant level of 0.05, primarily because this fruit weight itself was mostly uniform (statistically). The fruit bruising severity was, therefore, primarily determined by the equivalent drop height of the fruit, which was confirmed by a multiple stepwise linear regression.

Figures 4 and 5 present scatter plots between the equivalent drop heights and percentages of both *Extra Fancy Class 1* grade fruit and *Extra Fancy* grade fruit. The results showed that no apples were bruised within some level of drop height. As expected, the tolerance on drop height was slightly higher for the *Extra Fancy* grade compared to the same with the *Extra Fancy Class 1* grade (Figures 4 and 5). For stationary fruit, the threshold drop height for retaining *Extra Fancy Class 1* grade was around 3 cm. When the drop height rose to about 8 cm, only 85% fruit remained in the *Extra Fancy Class 1* grade. When the height was further raised to 16.0 cm, the percentage of *Extra Fancy Class 1* dramatically dropped to 40%. It was found that fruit bruising effects were similar (in terms of *Extra Fancy Class 1*) for moving fruit (which was attached on the pendulum impactor) when it comes to middle-to-middle impacts in most impact levels. However, extent/severity of bruising was slightly higher for moving fruit than those in stationary fruit for middle-to-top impact cases whereas the same was substantially lower for middle-to-bottom impact cases.

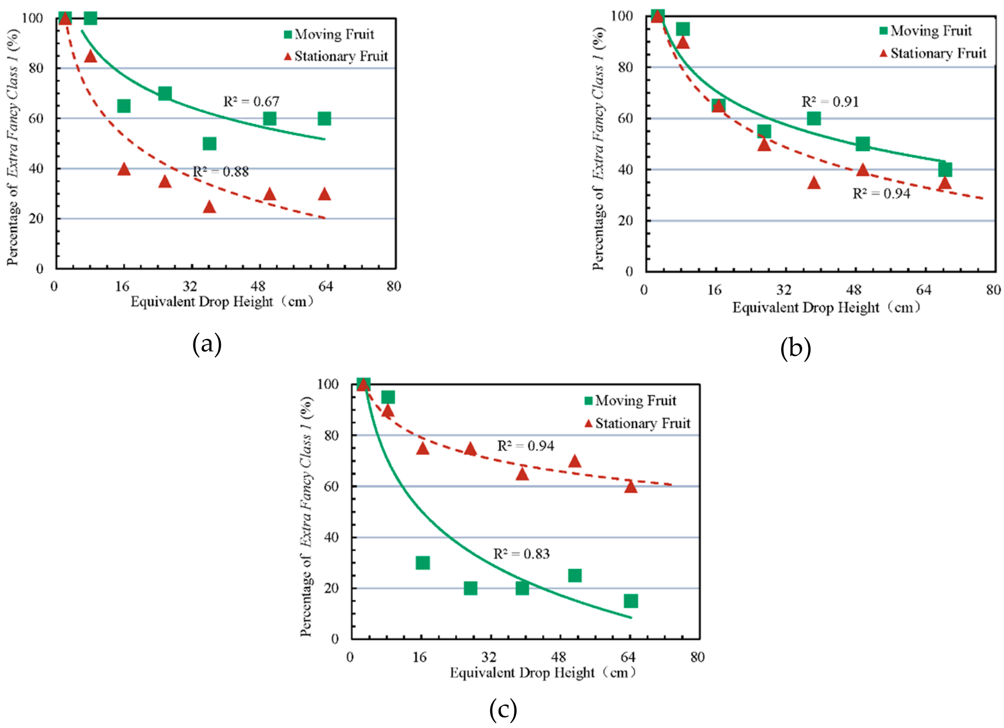


Figure 4. Percentages of *Extra Fancy Class 1* grade fruit with increasing equivalent drop height for free apple-to-apple impact in (**a**) middle-to-top, (**b**) middle-to-middle, and (**c**) middle-to-bottom impact patterns. Logarithmic curves were fitted separately for stationary and moving fruit samples.

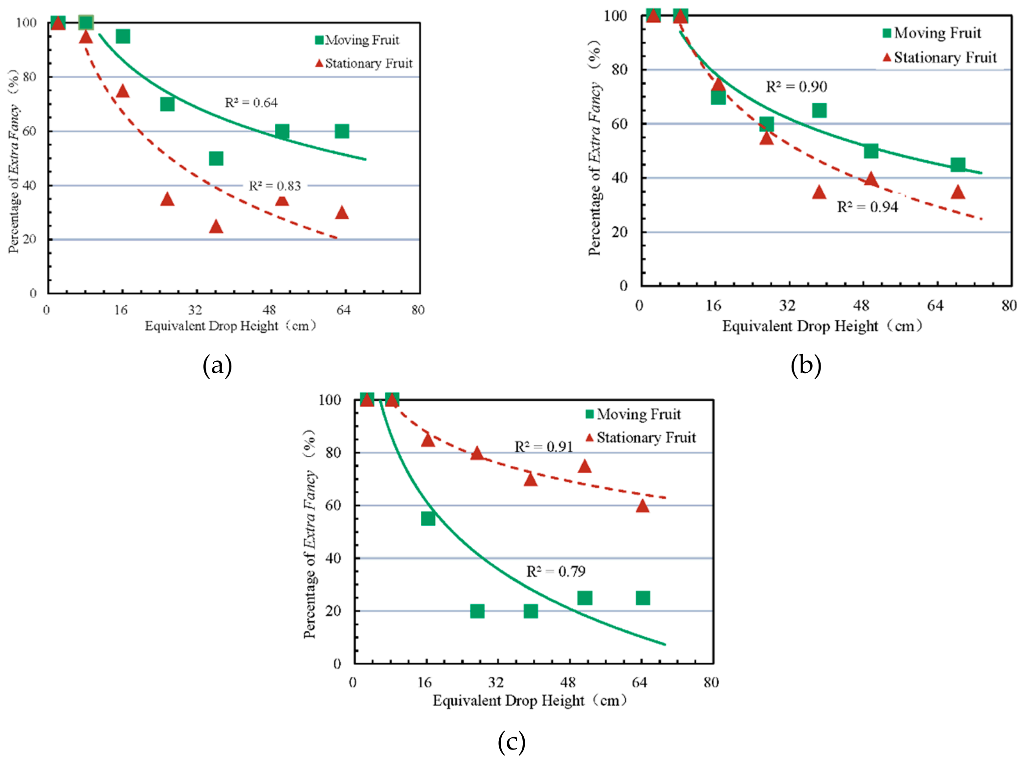


Figure 5. Percentages of *Extra Fancy* grade fruit with increasing equivalent drop height for free apple-to-apple impact in (**a**) middle-to-top, (**b**) middle-to-middle, and (**c**) middle-to-bottom impact patterns. Logarithmic curves were fitted separately for stationary and moving fruit samples.

As seen in Figure 5, it was found that the threshold drop height for retaining *Extra Fancy* grade fruit is around 8.5 cm. When the drop height was increased further, the percentages of *Extra Fancy* fruit decreased rapidly, expect for stationary fruits under the middle-to-bottom impact pattern. The percentages of *Extra Fancy* fruit, as anticipated, were similar to those of *Extra Fancy Class 1* fruit. This is because a previous finding [27] showed that the first bruised fruit between two contacted apples would absorb more energy to cause a larger bruise area. In addition, the *Fresh Market* (a bruising area diameter ≤ 19.0 mm) grade quality was also estimated in this study. Since most of the tested fruits could retain *Fresh Market* grade at most impact levels, no plots were presented. For stationary fruit, the threshold drops heights for maintaining *Fresh Market* grade were around 25.6, 27.0, and 27.3 cm for middle-to-top, middle-to-middle and middle-to-bottom impact patterns, respectively. When the drop height was raised to the largest 63.2, 68.4 and 64.2 cm, respectively, the corresponding percentages of fruit in *Fresh Market* grade decreased to 55%, 40% and 70%. For moving fruit, the threshold drop heights to retain *Fresh Market* grade were around 36.1, 27.0 and 27.3 cm from the three impact zones, respectively. With the largest impacts, the percentages of *Fresh Market* fruit dropped to 60%, 60% and 50%, respectively.

As discussed before, regression analyses were carried out between equivalent drop height and percentages of *Extra Fancy Class 1* and *Extra Fancy* grade fruit for stationary and moving fruits, which helped to determine the impact condition corresponding to a threshold level of fruit bruising severity. Compared to linear modeling, logarithmic modeling was preferred with a relatively high R^2, which was found to be more suitable for the trends observed (Figures 4 and 5). As seen in these curves, fruit bruising severity is increased quickly once the drop height exceeded some threshold, and then tended to stay flat with increasing drop height for the range tested in this study. It was also seen that the rate of increase of fruit bruising gradually decreased from the top zone to the bottom zone. The sharp change in the slopes of the plots could be treated as the indicator of drop height thresholds that would keep the bruising at a reasonable level while optimizing the drop height for practical use in fruit harvesting. Since fruit bruising occurs when impact-induced stress exceeds tissue failure stress [40], increased bruising severity with increasing drop height was expected as the impact-induced stress is positively correlating to the impact force exerted on the apple surface [41].

To examine the differences in bruising severity between stationary and moving fruits, analysis of covariance (ANCOVA) was performed at a significance level of 0.05. Results showed that differences in bruising severity between stationary and moving fruits were significant on the middle-to-bottom impact zone. These results indicated that the bottom zone is the least sensitive to bruise in apple-to-apple impact, followed by the middle zone. However, the difference between middle and top zones in terms of their bruise sensitivity was not statistically significant. In general, a fruit with a larger radius of curvature would result in a lower contact-induced stress, and with a larger flesh firmness, this would also cause a smaller bruise size during impact [17,40,42,43]. Radius of curvature of the middle zone was significantly larger than that of the bottom zone, while the flesh firmness was significantly higher in the bottom zone than the same in the other two fruit zones [15]. Therefore, the results indicated that the flesh firmness of the apples attributed the most in fruit bruising during fruit-to-fruit impact.

The fruit bruising severity in the top zone was slightly higher than that in the middle zone (Figures 4a and 5a), which might be because of the relatively smaller flesh firmness in the top zone of an apple than that in the middle zone [15]. However, the difference in fruit bruising severity between the top and middle zones, when tested with ANCOVA, was statistically insignificant [15]. Due to the similarity of the flesh firmness in the same zone, the bruising severity was also found to be similar over different impact locations within a specific fruit surface zone (Figures 4b and 5b). Based on the results, when fruit-to-fruit impacts are unavoidable, it could be beneficial to alter fruit falling angles such that the harder zone of an apple impacts other apples. Such a contact between two fruits would help keep at least one fruit intact as the other fruit would act as a cushion. Another important finding of this study was that the threshold drops heights for fruit to retain *Extra Fancy Class 1*, *Extra Fancy*, and *Fresh Market* grade quality were respectively around 3.0 cm, 8.5 cm and 27.0 cm. In other words, if apple drop height is kept at 3 cm or less (which is possible in some of the stages of fruit handling during harvesting and in the post-harvest environment), no bruising of any size might occur. This is also important to note that the threshold drop heights during apple-to-apple contact is much lower than the same with fruit-to-cushioned surface contact [15,44]. That is the reason why bruising damage caused by apple-to-apple impacts accounts for the majority of fruit damage during shake-and-catch harvesting tests [6–8].

4. Conclusions

For 'Jazz' apple, the degree/ severity of fruit bruising increased in a fairly logarithmic manner with increasing drop height when two apples impacted each other freely. The rate of increase of bruise damage was highest when the fruit were impacted in the top/stem zone, followed by the middle/cheek and then the bottom/calyx zones. The bottom zone in the tested apples was found to show the least bruising sensitivity, followed by the middle zone which was statistically similar to the same in the top zone. The bruising sensitivity of different zones on the apple surface primarily determined their flesh firmness. To retain 'Jazz' apples in *Extra Fancy Class 1*, *Extra Fancy* and *Fresh Market* grades, the free drop heights for apple-to-apple impact need to be minimized to below 3.0, 8.5 and 27.0 cm, respectively.

The findings from this study provided some basic information for the design of low-energy impact-capturing devices for bulk (shake-and-catch) mechanical handling systems and potentially for other fruit handling devices. It is noted that these findings were just based on the 'Jazz' variety of apples and may not be translated to other varieties of apples without more experiments. Since the fruit/flesh firmness is a very important parameter affecting fruit bruising severity, a more precise bruising patterns and more accurate estimation of its effect on fruit bruising could be obtained if the firmness could be measured with a non-destructive method. Future studies could focus on addressing these challenges.

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