Measure of mechanical impacts in commercial blueberry packing lines and potential damage to blueberry fruit

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\begin{abstract}
Blueberry fruit is susceptible to bruising from mechanical impact. Bruised fruit has shorter postharvest shelf life and softens rapidly in cold storage than non-bruised fruit. A blueberry packing line consists of a hopper for transferring fruit in field containers onto a conveyor line that moves fruit into trash removal equipment, electronic sorter, inspection line, and finally onto clamshell-filling equipment. Blueberry fruit drops as it is transferred from one equipment to the next on the packing line. The mechanical impacts that occur on blueberry packing line equipment were measured quantitatively with a miniature, instrumented sphere called the blueberry impact recording device (BIRD) at 11 packing houses in the United States in 2013 and 2014. The BIRD sensor recorded impacts at transfer points or wherever there was a vertical drop on the packing line. The potential for impact damage was determined in four cultivars ('Farthing', 'O'Neal', 'Reveille' and 'Star') by dropping fruit from different heights. The measured data revealed that the largest impacts (~230 g) were recorded when the sensor dropped into the hopper above the clamshell filler on eight empty lines. The cumulative peakG data showed strong correlation with overall drop height, indicating that reducing the overall drop height on a packing line could reduce the impact level. When the transfer points were padded with Poron foam sheet, significantly lower levels of impact were recorded by the sensor. The BIRD sensor also recorded lower impacts when it was run with fruit on the packing line. The severity of bruise damage resulting from fruit being dropped was related to the impact data recorded by the BIRD sensor. Using peakG-velocity change plot and the fruit bruising rate, several large impacts sufficient to cause bruising were identified, (e.g., >20% of cut surface area indicating bruise damage in 76% of ‘Reveille’ fruit). This paper quantitatively measured the mechanical impact on blueberry packing lines for the first time and the information will assist in improving the design and configuration of blueberry packing line equipment. These changes should result in reducing the magnitude and frequency of mechanical impacts and bruise damage in blueberry fruit.
\end{abstract}

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1. Introduction

The United States is the largest producer of blueberries in the world. In 2013, U.S. produced around 400 million kilograms (881 million pounds) blueberries with an estimated total farm gate value of $988,435,000 (USDA, 2014). Due to the high market value of fresh blueberries (2.639 dollar per kilogram compared to 1.484 dollar per kilogram for processed blueberries in 2013), nearly 41% of the US blueberries were packed for the fresh market (USDA, 2014).

Mechanization is used in fruit harvesting and postharvest handling to increase capacity and efficiency, and to reduce labor cost. In fruit harvesting, machines are used to harvest much of the fruit designed for processing. The use of machines to harvest blueberries that will be packed for the fresh market is limited because machine harvesting produces an unacceptable amount of fruit that cannot be packed for the fresh market. The short shelf-life of machine harvested fruit is the result of excessive bruising which contributes to rapid decline in fruit firmness, loss of intact cuticular wax on the skin, and oxidative browning of fruit tissues. Excessive mechanical impacts during harvesting have been attributed to bruising damage in blueberries (Brown et al., 1996). Fruits can also become bruised during transporting fruit-filled containers from the field to the packing house and during packing when the fruits...
collide with hard surfaces. In the transporting process, for instance, both vertical and horizontal movements occur as stacked containers are carried over uneven surfaces or with sudden acceleration or deceleration of the carrier vehicle.

Impact damage results in loss of fruit firmness leading to reduced fruit quality and shelf life. In the process of handling blueberries from the field to the market, machine harvesters and packing lines are the two main sources that produce large mechanical impacts to blueberries. Brown et al. (1996) estimated that 78% of the blueberries were bruised during the harvesting process when fruit was harvested with commercial machine harvesters. In addition, blueberries had a bruise rate of 0 to 50% when the fruit were dropped from 150 mm to 300 mm heights onto hard surfaces such as fruit catcher plates made of polycarbonate and steel on commercial berry harvesters and stainless steel surfaces on many of blueberry packing lines. The probability that a blueberry can be damaged by the packing line surfaces is high. However, these potential damages have not been systematically evaluated by quantitatively measuring the impact created by the hard surfaces on the packing lines using the instrumented sphere technology, which was widely used for other fruits and vegetables (Bajema and Hyde, 1995; Brown et al., 1990b; Desmet et al., 2004; García-Ramos et al., 2004b; Herold et al., 1998; Hyde et al., 1992; Miller et al., 1995; Timm and Brown, 1991).

Instrumented spheres (IS) are in essence data loggers that are used to detect and quantify mechanical loads of fruits and vegetables during handling chain. The commonly used ISs in the literature include the Impact Recording Device (IRD) (Zapp et al., 1990), Pressure Measuring Sphere (PMS-60) (Herold et al., 1996) and Potato-shaped Instrumented Device (PITR-200) (Canney et al., 2003). Other instrumented spheres such as Mikras, Smart Spud and TuberLog are commercially available but not commonly used in the literature (Praeger et al., 2013). Several key factors were found to affect the level of mechanical impacts in previous studies. Directly dropping on machine parts with hard contact materials (e.g., singulator, size cup, clamshell filler) were found to be one key factor that could induce high level of impacts. Therefore, cushioning these hard contact surfaces can dramatically reduce the impact damage (Bajema and Hyde, 1995). High elevation change was another key factor that induces large impacts (Brown et al., 1990a). Accordingly, reducing elevation changes, such as adjusting the machine alignment and installing ramps at transfer points to reduce the drop heights, was suggested to growers to reduce impact damage (Sargent et al., 1990; Timm and Brown, 1991). Other factors such as conveyor speed, flow of fruit, deceleration elements, and even the harvesting condition can affect the impact level (Bentini et al., 2006; García-Ramos et al., 2004a). Recent studies focused on evaluating the impact damage due to different harvest machine types (e.g., electronic sorters, filling equipment) and packing line settings (e.g., line speed, elevation height, decelerators, paddings), which can be used to optimize the packing line design (García-Ramos et al., 2003a,b; García-Ramos et al., 2004b).

Although the packing line for various types of fruits and vegetables have been evaluated using instrumented spheres, no study was reported for blueberries because no IS was available to resemble small fruits like blueberries. For example, the sizes and shapes of IRD, PMS-60, and PTR 200 are 57-mm sphere, 62-mm sphere and 53 × 53 × 83 mm semi-ellipsoids which are several times larger than a typical blueberry (7–23 mm in diameter), making it unsuitable for blueberry packing line evaluations. IrDAN data-logger (Elektronische Systemtechnik, Berlin, Germany) is a small acceleration measurement cube with size of 31 × 31 × 31 mm³, but the sensing range (27 g) was not large enough for measuring large impacts. Our research group developed the Berry Impact Recording Device to measure the mechanical impacts for small fruits and vegetables (Yu et al., 2011a,b). The BIRD sensor is a sphere with a size of 25.4 mm in diameter, providing a close approximation to a large-size blueberry fruit. The BIRD sensor has been used in the field to assess the mechanical impact created by three commercial blueberry mechanical harvesters (Yu et al., 2012, 2014a). The sensing range of the BIRD sensor (866 g) is adequate to measure the impacts generated on the packing lines, given that the drop heights of the transfer points range from 10 cm to 40 cm.

The primary goal of this study was to quantitatively measure the mechanical impacts on 11 commercial blueberry packing lines in the United States, using an in-house built miniature instrumented sphere. Specific objectives were to

1) quantitatively measure the impacts created by each packing line and each transfer point;  
2) compare the impact level on packing lines with and without fruit;  
3) evaluate the effect of impact reduction by padding the surface of the packing line;  
4) relate the sensor data to the fruit bruising rate.

Table 1

<table>
<thead>
<tr>
<th>Line number</th>
<th>Location</th>
<th>Time</th>
<th>Replicates</th>
<th>Transitions</th>
<th>Total drop height (cm)</th>
<th>Test condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>GA</td>
<td>June, 2013</td>
<td>5</td>
<td>6</td>
<td>~155</td>
<td>Fruit</td>
</tr>
<tr>
<td>2</td>
<td>GA</td>
<td>June, 2013</td>
<td>5</td>
<td>7</td>
<td>107</td>
<td>Fruit</td>
</tr>
<tr>
<td>3</td>
<td>MI</td>
<td>August, 2013</td>
<td>4</td>
<td>4</td>
<td>47</td>
<td>Empty</td>
</tr>
<tr>
<td>4</td>
<td>MI</td>
<td>August, 2013</td>
<td>6</td>
<td>4</td>
<td>~56</td>
<td>Empty</td>
</tr>
<tr>
<td>5</td>
<td>MI</td>
<td>August, 2013</td>
<td>6</td>
<td>4</td>
<td>~61</td>
<td>Empty</td>
</tr>
<tr>
<td>6*</td>
<td>MI</td>
<td>August, 2013</td>
<td>5</td>
<td>5</td>
<td>80</td>
<td>Empty</td>
</tr>
<tr>
<td>7</td>
<td>NC</td>
<td>May, 2014</td>
<td>6</td>
<td>7</td>
<td>~79</td>
<td>Empty</td>
</tr>
<tr>
<td>8</td>
<td>NC</td>
<td>May, 2014</td>
<td>6</td>
<td>6</td>
<td>~134</td>
<td>Empty</td>
</tr>
<tr>
<td>9</td>
<td>NC</td>
<td>May, 2014</td>
<td>6</td>
<td>6</td>
<td>117</td>
<td>Empty</td>
</tr>
<tr>
<td>10</td>
<td>NC</td>
<td>May, 2014</td>
<td>6</td>
<td>7</td>
<td>92</td>
<td>Empty</td>
</tr>
<tr>
<td>11</td>
<td>FL</td>
<td>April, 2014</td>
<td>6</td>
<td>7</td>
<td>187</td>
<td>Empty</td>
</tr>
</tbody>
</table>

* Only part of the complete line was tested.
the tray. Therefore, packing line 1 and 6 were tested without the last section of the operation (clamshell filler). The information of each packing line test is summarized in Table 1.

Fig. 1 illustrates the layout of the tested lines. These 11 packing lines, along with other typical commercial blueberry packing lines in the U.S., have five main components: trash removal devices to remove leaves and other trash, the color sorter to sort out immature (red and green) berries, the soft-fruit sorter to remove soft and defected berries, the clamshell filler with a hopper to temporarily store and pack berries into clamshells, and conveyor belts (including inspection belt) that allow fruit to be moved from one component of the packing line to the next. Although the packing lines tested share these common components, they differ because of various combination and alignment.
of these components that create different impact damage to the fruits.

The impact damage usually occurs at transfer points where the berries drop and collide with the ramp and conveyor belt during the transfer and the magnitude of the impact is directly related to the drop height. Therefore, drop heights from one conveyor belt to another at the transition points were measured using a ruler. Some drop heights were estimated based because they were difficult to measure due to the structure of those transfer points.

The packing process starts from dumping the berries onto the packing line. Then the berries are moved to a trash removal through a lifting conveyor. The trash removal blows out small blueberries, leaves, and other trash by a strong squirrel cage fan. Because of the wind from the fan, the berries bounce several times and impacts may have occurred in this section. After the trash removal, the blueberries go through the color sorter and soft-fruit sorter to remove immature, soft and defect berries. Then the berries roll onto a grading/inspection belt where workers remove additional immature and soft or other unqualified fruit missed by the electronic color and soft-fruit sorters from the lines. These workers usually use palm of their hands to roll the fruit to inspect all fruit surfaces which could damage the cuticular wax on the skin. The blueberries are then transferred through one or multiple conveyors before they dropped into a hopper atop of a single-clamshell filler or a slopped fruit distribution unit atop a multi-clamshell filling machine.

2.2. BIRD sensor and data recording

The BIRD sensor is a miniature instrumented sphere designed for small fruits and vegetables. It is designed to record the time and x, y and z acceleration (in gravity units, \( g = 9.8 \text{ m/s}^2 \)) of the impact events using a trial-axis accelerometer. The sensing range of the BIRD sensor is 866 g, which is adequate to record most impacts occurred on the packing lines. The sensor can operate at a frequency of 2 KHz. A user-defined threshold was used to prevent recording trivial impacts.

For each packing line test, the BIRD sensor was gently placed on the conveyor belt at the beginning of each line and was allowed to go through the complete line with or without fruit. After the sensor went through the complete packing line, the sensor was connected to a laptop and the data were downloaded to the computer. Based on the preliminary test, the BIRD sensor was set to record impacts greater than 25 g (to avoid trivial impacts) at a frequency of 2 KHz. Each packing line was tested at least 4 times in order to obtain a reasonable estimation of the impacts given the variation of the impact events.

During each test, a video camera (HDR-CX380, Sony) was used to record and track the motion of the BIRD sensor. Before each test, the clock of the video camera and the sensor were synchronized with the laptop clock to keep the time consistent for all three devices, which was important for further data analysis. The video camera followed the movement of the sensor and kept the sensor within the view of the camera especially at the transfer points. However, because of the fast speed of the conveyor belts at certain stage (for example, conveyor belts of the color sorter and soft-fruit sorter), the movements of the sensor at these transfer points were not recorded by the video. Therefore, the time when the sensor dropped at each transfer point was also recorded manually using a timer.

2.3. Padding sheet and line modification

In order to test the efficacy of reducing the impacts by padding the hard surface of the packing line, one packing line (No. 11 in Fig. 1) was modified by covering the stainless steel ramps at the transition points (with red circles in Fig. 1) using a closed cell padding sheet (Poron “No-Bruise”, A&B Packing Equipment Inc., Lawrence, MI). In the hopper only the surface which the fruit made the contact was covered with the padding. The line was tested before and after modification using the BIRD sensor and each condition was tested 6 times.

2.4. Data processing and analysis

The raw data recorded by the BIRD sensor were processed by the following procedure (Fig. 2). First, the physical location of the impacts occurred on the packing line was identified from the video.
using a LabVIEW-based program. The video displaying window of the program shows the sensor moving along the packing line, while simultaneously the impact curve displaying window shows a moving cursor that is synchronized with the sensor movement on the impact curve so the physical location of the sensor in the video and the impacts can be related. Second, only the impacts that occurred on transfer points were considered while other impacts were removed (e.g., when the sensor hit the side wall of the conveyor belt). Third, the impact data recorded from the beginning to the end of the packing line were separated based on transfer points. Fourth, the raw data were converted to real acceleration values (for each axis and summation) and the ‘peakG’ (the largest summation acceleration in one impact curve) and ‘Velocity Change (VC)’ (the area under impact curve) was calculated from the acceleration. PeakG directly reflects the magnitude of the impact. VC indirectly reflects the hardness of the contact surface by taking the impact duration into consideration. Therefore, soft surfaces have longer impact duration and larger VC than hard surfaces given the same impact magnitude. Last, the average impact values for each packing line and transfer point were calculated. Since the surface property of the BIRD sensor is different from that of blueberries, the sensor tends to have more bounces than the blueberry when they hit on a hard surface. To reduce this potential bias from the sensor, only the maximum impact (usually happened at the first impact) of each transfer point was used in data analysis. For each line, the impact level was described by the average, maximum and cumulative peakG. Only the average peakG was used for each transfer point to evaluate the impact level. For line 11, t-test at significance level of 0.05 was performed to compare the impact level of the transfer points before and after the padding. Mean separation test (least significant difference) was performed on line 1 to 10 to compare the impact level of each line.

2.5. Fruit bruise assessment

To simulate what could happen to blueberry fruit on the packing line, fruit drop tests were conducted in which blueberries were dropped onto a hard plastic surface from 15 cm (6 in), 30 cm (12 in) and 60 cm (24 in) height. In North Carolina, four blueberry genotypes, ‘Farthing’, ‘O’Neal’, ‘Reveille’ and ‘Star’, were used. A total of 100 hand-harvested bruise-free fruit of each cultivar were used for the three drop heights, as well as for the control group with no drop. Every 25 dropped berries were used as one replicate for estimating the bruising rate and they were placed in 0.5 L (1 pt) clamshells and held at 21 °C. After 24 h, the dropped and control berries were sliced along the equator and photographed. The images were used to estimate the discolored area (% of cut surface area with bruise damage) and berries with discolored area larger than 20% of sliced surface were rated as bruised. The bruising rate for one replicate was calculated as the percentage of the bruised berries to the total berries in one replicate (25 berries) (Yu et al., 2014b).

To relate the sensor data with fruit bruising rate, the BIRD sensor was dropped onto the same contact surface from the three drop heights used for blueberries. The BIRD sensor was dropped from each height for 20 times and only the first impact of each drop was collected for further data analysis (the recording resulting from subsequent bounces were removed). PeakG and VC of each impact was calculated and the average values of the 20 replicates at each drop height were used to evaluate the impact level. Bruise probability regions on the peakG-VC plot were defined for the four blueberry cultivars using the method developed by Yu et al. (2014b).

3. Results and discussion

3.1. Impact data on the packing lines

The BIRD sensor recorded impacts occurred during the packing process and almost all the impacts occurred at transfer points (Fig. 3). Video record showed a few impacts occurred when the sensor hit on the sidewall of the conveyor belts. However, these impacts were excluded from the data analysis since they are insignificant and rarely happened in normal operations with fruit. At transfer points, the sensor recorded a big impact at the initial drop followed by several small impacts due to the bounce of the sensor. The number of bounces also depended on the contact material where it tended to bounce more on hard surfaces than soft surfaces. The sensor also bounced less on the lines with fruit than on empty lines because the fruits can prevent the sensor from moving freely, and thus fewer impacts were recorded on the lines with fruit than on the empty lines. For this particular line (line 8), the BIRD sensor recorded two largest impacts (~370 g) on the transfer points from the color sorter to the soft-fruit sorter and

![Fig. 3. Impacts versus time recorded by the BIRD sensor on line 8.](image-url)
from the soft-fruit sorter to the inspection belt. This was mainly due to the large drop heights (36 and 35 cm) and the fast speed of the conveyor belt within the color sorter and soft-fruit sorter. The speed of the conveyor belt for color sorter and soft-fruit sorter are normally faster than other conveyor belts, which was illustrated by the short time period between two successive big impacts in Fig. 3. Therefore, big impacts can occur at the transfer points from color sorter or soft sorter. Large impacts (~359 g) were also recorded when the sensor dropped into the hopper due to the hard contact surface (stainless steel) and high drop heights.

When comparing the impacts between the lines with fruit (line 1 and 2) and lines without fruit (line 3–10), the BIRD sensor recorded smaller impacts (average and maximum peakG) on line 1 and 2 than on line 3-10 mainly because the fruit on the packing line provided cushion while the empty lines had harder surfaces (Fig. 4). The peakG-VC plot (Fig. 5) also showed that the impact on the lines with fruit are concentrated at the lower left corner while there are many large impacts on empty lines at the upper right corner which means that the peakG and VC of some impacts were both reduced by the fruit. In addition, there are some impacts overlapping with each other between lines with fruit and without fruit, meaning that the fruit may not affect those impacts. When the last transfer point was considered for all the packing lines, lines 1 and 2 had much smaller average impacts than the rest packing lines without fruit (Fig. 6) even line 1 and 2 has larger drop heights than other lines. The video revealed that the sensor dropped on top of fruit stacked in the hopper on packing lines 1 and 2, whereas the sensor directly landed onto the stainless steel surface of the hopper on other empty lines. It is noticeable that factors (such as drop height and velocity) other than the fruit may also affect the difference of the impact level, but the effect of these factors are insignificant since all the packing lines had similar settings. A more accurate evaluation of the fruit effect could be done by running the sensor on the same line with and without fruit. Similar results were observed on apple packing lines. Smaller impact readings were recorded on lines with flow of fruits compared to empty lines (Garcia-Ramos et al., 2004b). The difference in the sensor reading on lines with fruit and lines without fruit suggested that the real damage that the packing line produced at certain transfer points during the normal operation (when there were fruit on the lines) may be smaller than what the sensor measured on empty lines. Therefore, the sensor data from the empty lines could over-estimate the impact damage created by the packing lines.

An average peakG of 118 (in line 3) to 200 g (in line 8), maximum peakG of 230 (in line 4) to 402 g (in line 5), and cumulative peakG of 474 g (in line 3) to 1198 g (in line 8) were recorded on empty lines (line 3–8). Among the empty lines, line 3 had the smallest average and cumulative peakG because of its smallest number of transfer points (only four) among all the lines. Line 5 had the largest maximum peakG because of the large drop height (28 cm) in the last transfer point. The largest average and cumulative peakG was found on line 8 because of the large number of transfer points (6) and total elevating height (~114 cm).

The packing lines were further assessed and compared by looking at the impacts at each individual transfer point (Fig. 6). Among all the transfer points on the empty lines, the last transfer point had the largest impact for almost all lines except line 6, which is expected because the sensor directly landed onto the hopper made of stainless steel or hard plastic from a relatively large drop height (15 to 28 cm). Line 6 recorded less impact level at the last transfer point due to the plastic tray that was used to catch fruits and small drop height. However, we only tested the first part of line 6 without the part that the fruit was packed into the clamshell and thus the fruit could experience more impacts for the complete line.

Theoretically, the mechanical damage created by the packing line is mainly determined by the drop height at each transfer point, speed of the conveyor belt, and the surface properties of the contact material. Among the tested lines, we found that most of the lines had one or more transition points where drop heights were greater than 30 cm (Fig. 1). These large drop heights contributed to the total drop height which was found to have a strong linear correlation (r² = 0.8406) with the cumulative peakG (Fig. 7). The drop height can be reduced by reducing the vertical distance between two conveyor belts. However, there are certain line components in which drop heights cannot be reduced. For example, most early models of soft-fruit sorter were designed based on the principle of impact force response. This type of soft-fruit sorter has an array of sensor fingers that can detect the force response when the fruit hit on them. Based on the force response, the machine senses the firmness of the fruit and rejects the soft fruit. Therefore, a minimum drop is required for the sorter to let the fruit drop on the sensor finger. However, as the technology has advanced, some latest models, BEST Primus optical sorter (Tomra Systems, Askler, Norway) for instance, use optical principles to measure the fruit firmness and thus the color and soft-fruit sorter can be integrated into one machine unit. In this case, they can use one conveyor belt so that no drop for the soft-fruit sorter is needed. Three packing lines (line 3 to 5) were equipped with optical sorters and thus they have less transition points than other lines.

![Fig. 4](image_url) Overall impact level for 10 packing lines. The white bars indicate the lines that were tested with blueberries. Lines with the same letter did not show significant difference. The error bars represent the standard deviation.
The contact materials are mainly determined by the material of the conveyor belt since the fruit are moved by conveyor belts. The material of the conveyor belts are food grade and are usually made of USDA certificated plastic or metal mash. We observed that some transition points used ramps made of stainless steel or plastic to reduce the speed of fruit as they rolled down to the following conveyor belt. In this case, the fruit would hit on the ramp first and then roll or bounce to the conveyor belt. Hoppers on the tested lines were made of plastic for line 4 and stainless steel for other lines. In summary, based on the material of the machine parts, the contact surface can be roughly classified into steel, hard plastic and soft padding. Padding the hard surface using soft materials could avoid the fruit from directly contacting with the hard surface and this practice was shown to be effective based on the experimental data to be discussed in Section 3.2.

**Fig. 5.** PeakG-VC map of the impacts on lines with fruit (line 1 and 2) and lines without fruit (line 3–10).

**Fig. 6.** Bubble plot of the average impact level at the transfer point when transferred onto indicated component. The peakG value is proportional to the area of the circle. Line 1 and 2 under the dashed line were tested with fruit.
To reduce the speed of the fruit at the transfer points, ramps were used at many transfer points on the tested lines. However, inappropriate installation (e.g., large ramp angle, hard surface) of the ramp may not decrease the velocity at the end of the ramp efficiently, resulting in significant impacts at the end of the ramps (García-Ramos et al., 2003a,b). For example, the drop heights between the trash removal and color sorter on line 3 and 4 were similar. However, the sensor recorded higher impacts at this transfer point on line 4 (193 g) than on line 3 (67 g). The video revealed that the sensor dropped on the stainless steel ramp and bounced to the color sorter on line 4 while the sensor directly dropped on the color/soft-fruit sorter on line 3. Because stainless steel is much harder than the conveyor belt on the color sorter and creates large impacts, it would be more desirable to use soft materials to replace the stainless steel ramp or cover it with paddings. An additional decelerator could reduce the speed of the fruit at the end of the ramp. For example, using blanket and curtain above the ramp can increase the length and friction of the ramp and subsequently decrease the speed of the fruit (García-Ramos et al., 2003a,b).

Fig. 7. Linear regression of the cumulative peakG and the total drop heights from the eight packing lines (line 3 to 10). The error bars represent the standard deviation.

Fig. 8. Comparison of the average impact at the transfer points before and after padding the surfaces. The error bars represent the standard deviation.
3.2. Effectiveness of the padding

The BIRD sensor recorded different impact levels at the transfer points before and after padding the surfaces (Fig. 8). The T-test showed that the difference was significant (P-value < 0.001). The average impact level of the transfer points to the inspection table, the first conveyor, the second conveyor, and the hopper were reduced by 67%, 56%, 64% and 61%, respectively. Similar results were obtained on a peach packing line where the mean peakG was reduced almost 30% from 75.2 g to 54.5 g by the presence of padding. Another study demonstrated that padding the transfer points reduced the impact level by 90 g and the apple bruising rate from 88% to 12% (Garcia-Ramos et al., 2003a). Comparing the data points in the peakG-VC plot between padded and unpadded line, most of the data points moved to the lower left part of the plots after padding the line, meaning that both peakG and VC of these impacts reduced (Fig. 9). The padding avoided the direct contact of the sensor with the hard surface, and thus reduced the impact level. Therefore, providing cushion to the transfer points was proven to be effective for reducing the impact damage.

3.3. Relating fruit bruising and impact data

The development of bruise damage caused by mechanical impacts was evident 24 h after the drop test (Table 2). ‘Farthing’ showed more resistance to impacts than other genotypes because it did not show significant bruising increase from the control samples until at the 60 cm drop height and the bruising rate was much lower than other genotypes. ‘O’Neal’ started to show significant bruising increase at 15 cm drop. ‘Reveille’ showed to be more susceptible to impacts. Significantly higher bruising rates occurred for the 30 cm and 60 cm drop heights when compared to the other three genotypes. However, the initial bruising rate (corresponding with the ‘No drop’ bruising rate) for ‘Reveille’ was also higher than the control bruising rate of the other genotypes which could contribute to the bruising rate for the dropped fruit. Increasing the drop height for ‘Star’ did not increase the bruising rate significantly, indicating that ‘Star’ is also more resistant to impact damage. The susceptibility of different genotypes to mechanical impacts has been investigated by previous researchers and the concept of Damaging Impact Energy Threshold (DIET) was established to characterize the critical energy level that causes fruit bruise (Desmet et al., 2003, 2004; Molema, 1999). In this study, the impact energy level was dictated by the drop height and our results showed similar pattern as those found in the above studies.

The BIRD sensor measured average peakG values (Table 2) of 226 g, 366 g, and 550 g at 15, 30 and 60 cm drop heights, respectively. These impacts correspond to bruising rates of 4% to 86% depending on the drop height and the blueberry genotype. For instance, 366 g could indicate 76% bruising rate for ‘Reveille’ for hard plastic surface. However, the relationship between bruise rate and impact reading were not simple linear relationship and only peakG values can not be used to evaluate the bruise rate accurately (Yu et al., 2014b).

Brown et al. (1990a) have shown that the plot of peakG and velocity change (VC) can be used to compare impacts on different contacting surfaces with known characteristics. This relationship is based on the fact that harder materials create larger peakG and smaller VC than soft materials. Therefore, peakG-VC plot was used to compare the impacts recorded on the packing lines with the impacts recorded on a plastic plate (Fig. 10). The plastic plate was used as the reference because the plastic plate was used in multiple transfer points on the packing lines and its surface characteristics are similar to stainless steel—another common type of contacting material used on packing lines. Using the plastic plate as a reference, we can estimate bruising rate for the impacts recorded on the packing lines based on the cultivar and the region (region 1–3) on the peakG-VC plot. Taking ’Reveille’ as an example, about 14%
of the total impacts are located in region 1 which can create bruising rate larger than the bruising rate dropped from 15 cm onto the plastic plate (21%). High bruising rate (76%) can be produced by the impacts in region 2 (6% of the total impacts) when the fruit dropped from 30 cm onto the plastic plate. No impacts were located in region 3, suggesting that no impact can create bruising rates higher than 86%. However, since the bruising rate started to increase from 30 cm drop for ‘Reveille’, only the impacts in region 2 can give rise to bruise damage to the fruit. Although the remaining impacts located below region 1 may not lead to bruise damage to the fruit individually, the cumulative effect of these multiple small impacts could lead to significant bruising to fruit. Our preliminary test of other genotype showed that five repeated drops on plastic from 15 cm and 30 cm created larger bruising rate of 8.7% and 34.2% comparing to one single drop from 60 cm (5%) and 120 cm (31.6%), respectively. Therefore, these impacts can not be neglected. It is also noteworthy that since only one reference surface (hard plastic) was used in the peakG-VC plot, only the bruising rate of the impacts in region 1, 2, 3 can be ensured. No confident interpretation can be made for these impacts located outside the three regions and more bruising boundary lines using different contact surfaces are needed to determine the bruising rate for these impacts.

4. Conclusion

The mechanical impacts created by typical commercial blueberry packing lines in the U.S. were measured quantitatively using the BIRD sensor for the first time. The data provided by the BIRD sensor revealed that most impacts occurred at the transfer points and the high impact happened when the sensor dropped on hard surfaces such as the stainless steel and the hard plastic. The presence of the blueberry fruit on the packing line lowered the impact compared to those packing lines without fruit. Padding the transfer points was proven to be effective to reduce the impacts. Several large impacts were identified to cause bruise damage to the fruit using peakG-VC plot. Most of the individual small impacts at the transfer points may not cause bruise damage, but the cumulative effect of these impacts may cause fruit bruising and increase the bruising rate significantly.

Future studies will focus on evaluating the fruit bruising from the packing line and developing a more accurate relationship between the impacts recorded by the BIRD sensor and the fruit bruising rate by considering multiple contact materials.

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