Evaluation of Shock-Proof Performance of New Cushioning System for Portable Packaging of Apples

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Mechanical damage due to vibration and/or shock during transport is a primary factor in inducing disorder in appearance of fresh produce. Thus, designing of cushioning packaging for fresh produce is necessary. As cushioning materials, paper- and/or plastic-based materials are usually used for fresh produce. Especially, plastic-based materials possess suitable cushioning properties to reduce the damage due to shock and vibration. However, it is difficult to recycle these materials compared with paper-based ones. Therefore, it might be ideal to reduce the use of plastic-based materials as much as possible.

Based on the aforementioned information, for apple fruit, we evaluated the shock-proof performance of a new cushioning system for portable packaging using a two-ply pulp molded tray instead of the conventional foam net. The results of measurements of peak acceleration ($P_{acc}$) and velocity change ($V_c$) with the drop height of 0.2 m and 0.4 m using a dummy fruit, and shock test using various $P_{acc}$ and $V_c$ with apple fruit suggested that the proposed cushioning system exhibits superior cushioning performance than that of the conventional packaging system using foam net.

Keywords: damage control, handling, peak acceleration, shock test, transportation, velocity change

INTRODUCTION

Fresh produce deteriorates due to various factors such as stress during transportation. It is necessary to control temperature and humidity to avoid the deterioration of fresh produce caused by physiological changes and microbial activity. In addition, controlling the environment of gases such as oxygen and carbon dioxide is important. Considering these factors, modified atmosphere packaging has been developed (Caleb et al., 2013).

Further, mechanical damage due to vibration and/or shock during transportation is a primary factor in inducing disorder in the appearance of fresh produce (Opara and Pathare, 2014). Thus, theories for cushioning packaging have been constructed and then, cushioning packaging has been designed considering such theories. For example, Nakamura et al. (2007) demonstrated that the accuracy of the prediction of damage occurrence in the case of strawberries due to vibration would be improved via the use of the S-N curve theory considering the transmissibility of acceleration of each vibration frequency. In addition, the authors have constructed a new theory for evaluation of the damage to products caused by repetitive shock considering three factors of peak acceleration ($P_{acc}$), velocity change ($V_c$) in shock pulse, and times of shock to obtain damage; the theory could be used for damage evaluation in the case of strawberries (Kitazawa et al., 2014). Based on the theory, for strawberries, a method of cushioning packaging to avoid the damage due to repetitive shock has also been proposed (Kitazawa et al., 2015).

For such cushioning packaging for fresh produce, paper- and/or plastic-based materials are generally employed. Notably, plastic-based materials such as foamed net, sheet, or brock possess suitable cushioning properties to reduce the damage due to shock and/or vibration. Further, it is difficult to recycle these materials compared with paper-based materials. Therefore, in the situation of country-to-country transportation, i.e., export, it might be ideal to reduce the use of plastic-based materials as much as possible. However, few reports exist regarding the evaluation of cushioning performance of paper-based materials compared to plastic-based ones, except a report on the relationship between apple damage and shock energy (Jarimopas et al., 2007).

Consequently, in this study, for apple fruit, the shock-proof performance of a cushioning system using a pulp-molded material instead of the conventional foam net (Ishi-
kawa et al., 2014) was investigated. In the above-mentioned situation regarding the export of fresh produce, it is suggested that it would be transported as a souvenir. Therefore, the packaging we investigated was a portable type.

For the estimation of damage due to shock to fresh produce, it was suggested that the consideration of both \( P_{\text{Ace}} \) and \( V_c \) of shock pulse was important (Schulte et al., 1994; Matthey and Hyde, 1997). In addition, our previous study demonstrated that the degree of damage caused by shock to apples was affected by both \( P_{\text{Ace}} \) and \( V_c \) (Kitazawa et al., 2016). Thus, we estimated the relationship between \( P_{\text{Ace}} \) and \( V_c \), and the bruise area of the apples.

**MATERIALS AND METHODS**

*Fruit material*

We used a red apple cultivar “Fuji” to evaluate the relationship between the bruise occurrence of apples and the differences of shock condition. The mean fruit diameter was 83.4 mm in the vertical direction and 91.2 mm in the horizontal direction, and the weight was 354.6 g. The firmness around the calyx end of each fruit measured using a fruit firmness tester with a 5-mm-diameter plunger (KM-5, Fujiwara Scientific, Tokyo, Japan) was 32.3 N.

*Details of packaging and cushioning system*

The box was constructed with a 1.0-mm-thick corrugated fiberboard (Fig. 1a). The internal dimensions of the box were 210 mm (length) × 108 mm (width) × 110 mm (depth). A piece of foam net sheet (5 mm thickness) was laid on the bottom surface inside the box (Fig. 1b). It was ideal if certain paper-based materials were used instead of the foam net sheet. However, we focused on the evaluation of the performance of the under-mentioned cushioning system. A pair of apples was wrapped in foam nets (FN. Fig. 1c) and placed in a package next to each other. Each foam net was composed of foamed polyethylene. We assumed this to be the control.

We prepared two other types of packaging conditions using pulp-molded trays. One type of packaging was that a pair of apples was placed into the pair of hollow space of a pulp molded tray instead of wrapping with foam nets (Pulp-1. Fig. 1d).

The other was also that a pair of apples was placed into the pair of hollow space of a two-ply pulp molded tray (Pulp-2. Fig. 1e). For Pulp-2, the size of the hollow spaces of the tray at the top layer was slightly smaller than those of the apples and the tray at the bottom layer. Thus, for Pulp-2, a pair of apples was suspended; a 3–5 mm space existed between the fruit and the inside surface of the hollow of the top layer. A 3–4-mm space also existed between the inside surface of the hollow of the bottom layer and the outside surface of the hollow of the top layer. Thus, it was expected that the transmissibility of shock acceleration from the bottom direction of the box would be reduced, which was assumed to be the newly proposed cushioning system. The head space of the box under each cushioning condition was filled with crushed paper to suppress the rebound of the apples (Fig. 1f). The total weight of each box was 810–840 g.

*Measurement of \( P_{\text{Ace}} \) and \( V_c \) when dropping the box (Experiment 1)*

We assumed that the primary source of shock occurrence during transport would be drop caused due to handling. The maximum drop height \( (h, \text{m}) \) in delivery services has been estimated to be 0.2–0.6 (Saito et al., 1998; Singh et al., 2009). Further, previous observations also suggested that the height, \( h \) of 0.6 m seemed to be unusual during transportation of fresh produce (Ishikawa et al., 2009; Nakanishi et al., 2015). Therefore, based on these studies, the box was freely dropped from the \( h \)s of 0.2 and 0.4 using a drop tester (DTS-50, Shinjyu Testing Machinery, Tsukuba, Japan). Each \( h \) was the same as the distance between the bottom surface of the box and the surface of the counterface of the drop tester. Subsequently, the values of \( P_{\text{Ace}} \) were measured for each \( h \).

A three-dimensional accelerometer (2366AWS, Showa Sokki, Tokyo, Japan) was connected to the shock analysis system consisting of a device (SMH-12, Shinjyu Testing Machinery, Tsukuba, Japan) and software (SMS-500M, Shinjyu Testing Machinery, Tsukuba, Japan). The following measurement conditions were used for the accelerometer: a sampling duration of 5–10 \( \mu \text{s} \), 8000 data points.

For all cushioning conditions, we used a pair of dummy fruit composed of clay (weight: 350 g) instead of apples. Regarding the control, the accelerometer with a plastic attachment (Fig. 2) was attached on the bottom of the dummy fruit wrapped using the foam net. For Pulp-1 and Pulp-2, the accelerometer with the plastic attachment was attached on the bottom surface of the inside of the hollow of the mold tray using a double-sided tape.

The box did not drop completely perpendicularly because the center of gravity of the box was not always located at the geometric center. Thus, to calculate \( P_{\text{Ace}} \), the shock accelerations (m s\(^{-2} \)) in the horizontal (right-left, \( x \),
horizontal (front-back, y), and vertical (z) directions were assigned in the following equation:

\[ P_{\text{acc}} = (x^2 + y^2 + z^2)^{0.5} \]  

(1)

The \( V_c \) in the x, y, and z directions were also synthesized using the above-mentioned software. The test was conducted three times for replication.

**Estimation of bruise occurrence due to shock (Experiment 2)**

**Generation of shock pulse**

Half-sine shock pulses were generated by a shock tester (SDST-300, Shinyei Testing Machinery, Tsukuba, Japan) with a cushioning adjuster (SVS-300, Shinyei Testing Machinery). The \( P_{\text{acc}} \) of the shock pulse was determined based on the results of Experiment 1. When packaged objects are dropped perpendicularly, \( V_c \) is determined using the following equation:

\[ V_c = (1 + e) \times (2 \times g \times h)^{0.5} \quad (0 \leq e \leq 1) \]  

(2)

where \( e \) and \( g \) denote the coefficient of restitution and the acceleration of gravity (9.80665 m s\(^{-2}\)), respectively. Accordingly, when the box was dropped from the \( hs \) of 0.2 and 0.4 m, the \( V_c \)s were within the ranges of 1.98–3.96 and 2.80–5.60, respectively. Based on these conditions, thus, the \( V_c \) was set to 3.0, 4.0, and 5.0 m s\(^{-1}\), respectively.

These adjustments were conducted using an accelerometer (2351AW, Showa Sokki, Tokyo, Japan) attached on the table of the shock tester and connected to the same shock analysis system, device, and software that were used for Experiment 1. The measurement conditions for the accelerometer were also the same as Experiment 1. The total number of shock conditions we tested was nine.

**Bruise measurements**

Shock pulses were applied once to the box that contained a pair of apples. One day later, the skin of the fruit was peeled and subsequently the widths (in mm) of the bruised portions along the calyx end (Fig. 3) of each apple were measured using a digital caliper (CD-20CX, Mitsutoyo, Kawasaki, Japan). The value of the bruise areas (\( B_s \), mm\(^2\)) of each fruit corresponding to each set of shock conditions were calculated using the equation obtained by Lu et al. (2010):

\[ B_s = (W_1 \times W_2 \times \pi) / 4 \]  

(3)

where \( W_1 \) and \( W_2 \) represent bruise widths along the major and minor axes, and \( \pi \) the circle ratio. The values of \( B_s \) obtained from two fruits in each box were averaged. When two or more bruised portions were observed within a fruit, the values of each \( B_s \) were summed up. For each shock condition, 10 replications were conducted.

**Statistical analysis**

For the measurements of \( P_{\text{acc}} \) in the drop test, we used Student’s t-test with Bonferroni correction for control-to-others comparison because the homogeneity of variance could be assumed. Further, for the evaluation of apple bruise, the homogeneity of variance could not be assumed for comparisons between the control and other two cushioning systems. Thus, we used Welch’s t-test with Bonferroni correction for control-to-others comparison. For each statistical analysis, the family wise error rate (\( \alpha \)) was controlled strictly to 0.05 using a spreadsheet (Excel 2013, Microsoft Japan, Tokyo, Japan).

**RESULTS AND DISCUSSION**

**Measurement of \( P_{\text{acc}} \) and \( V_c \) when dropping the box (Experiment 1)**

When \( hs \) were 0.2 and 0.4, the \( P_{\text{acc}} \)s for Pulp-1 were significantly larger than that of the control (Table 1) while the \( P_{\text{acc}} \)s for Pulp-2 was not different from the control. Regarding the control, the value of \( P_{\text{acc}} \) was reduced due to the foam net, which was used for wrapping the dummy fruit. In addition, for Pulp-2, it was suggested that the value of \( P_{\text{acc}} \) was reduced. As the reason, two factors were considered: one was because of the space between the inside surface of the hollow of the bottom layer and the outside surface of the hollow of the top layer. The other was that the pulp-molded material was twice as thicker than that used for Pulp-1; we assumed the above-mentioned space between each molded tray was compressed due to shock. Further, for Pulp-1, it was suggested that cushioning performance against acceleration was less than those of other cushioning conditions. The values of \( P_{\text{acc}} \) for Pulp-1 seemed to reflect the acceleration that was delivered from the bottom of the box mostly among all cushioning conditions because the attenuation of shock acceleration was
less than that of other two conditions.

The $V_C$ for Pulp-1 were not different from the control (Table 2). For Pulp-2, the $V_C$ for $h$ of 0.2 was significantly larger than that of control while the $h$ of 0.4 was not different from the control. According to Eq. 2, the increase in $V_C$ was caused due to the increase in coefficient of restitution. However, it could not be assumed that the inside surface of the hollow of Pulp-2 was more solid than that of Pulp-1. Thus, this might be caused due to the extension of time of shock because the accelerometer was suspended when $P_{acc}$ was measured.

*Estimation of bruise occurrence due to shock (Experiment 2)*

Based on the results of Experiment 1, we set $P_{acc}$ to 490.3, 735.5, and 980.7 m s$^{-2}$ (i.e., 50, 75, and 100 G) (Fig. 4), considering the design of the shock tester and the cushioning adjuster. When $P_{acc}$ was 490.3 m s$^{-2}$, the values of $B_A$ for Pulp-1 were not different from the control even if $V_C$ were different; the values of $B_A$ for the control and Pulp-1 in order from the bottom of $V_C$ were 63.1, 123.6, and 69.3, and 93.9, 249.7, and 141.9, respectively (Fig. 5). Similar tendencies were observed in other two $P_{acc}$ conditions although a significant increase in $B_A$ was observed in the condition of 735.5 m s$^{-2}$ of $P_{acc}$ and 4.0 m s$^{-2}$ of $V_C$. The values of $B_A$ for 735.5 m s$^{-2}$ for the control and Pulp-1 in order from the bottom of $V_C$ were 148.1, 211.7, and 184.3, and 171.6, 367.6, and 286.1, respectively. The values of $B_A$ for 980.7 m s$^{-2}$ for the control and Pulp-1 in order from the bottom of $V_C$ were 227.7, 345.5, and 434.4, and 233.1, 394.1, and 564.2, respectively. Thus, it was manifested that the cushioning performance of Pulp-1 was worse than that of the control when the value of $V_C$ was less than 4.0.

Further, for Pulp-2, the values of $B_A$ for 490.3 m s$^{-2}$ of $P_{acc}$ were decreased significantly from the control with different $V_C$; the values of $B_A$ for 735.5 m s$^{-2}$ for Pulp-2 in order from the bottom of $V_C$ were 0.0, 0.0, and 9.8, respectively. The values of $B_A$ for 735.5 and 980.7 m s$^{-2}$ of $P_{acc}$ were decreased significantly when the values of $V_C$ were 3.0 and 4.0. The values of $B_A$ for 735.5 m s$^{-2}$ for Pulp-2 in order from the bottom of $V_C$ were 0.0, 48.2, and 115.2, respectively, and the values of $B_A$ for 980.7 m s$^{-2}$ for the Pulp-2 in order from the bottom of $V_C$ were 7.9, 37.6, and 208.4, respectively. Thus, it was manifested that the cushioning performance of Pulp-2 was superior to that of the control when the value of $V_C$ was less than 4.0. In any case, the results of measurement of $V_C$ in Experiment 1 suggest that the situation with $V_C$ exceeding 4.0 is difficult to occur if the box is dropped from 0.2 m and 0.4 m.

For Experiment 1, the $P_{acc}$ between the control and Pulp-2 were not different. If the cushioning performance of Pulp-2 for drop shock is superior to that of the control, the values of $P_{acc}$ for Pulp-2 should be less than those of the control. For Experiment 1, the accelerometer for Pulp-2 was attached on the bottom surface of the inside of the hollow of the mold tray; it did not measure the acceleration delivered to the dummy fruit. Therefore, no difference was observed in the value of $P_{acc}$ between the control and Pulp-2. If we could measure $P_{acc}$ for the dummy fruit, the values of $P_{acc}$ for Pulp-2 would be smaller than that of the control. Thus, it was concluded that the space between each molded tray was compressed due to shock. In addition, our results suggested that the space between the fruit and the inside surface of the hollow of the top layer only contributed to reducing bruises on the fruit.

For the shock test using a half-sine pulse for a stacked product, it was suggested that the transmissibility of shock acceleration might be changed depending on the properties of the product (Nakajima et al., 1999). To determine the shock condition for Experiment 2 based on the measurement results from Experiment 1, we did not consider the change in acceleration due to the corrugated fiberboard of the box and the foam net laid on the bottom surface inside the box. However, these materials usually play the role of cushioning material (Jarimopas et al., 2007). Therefore, our results exhibit certain safety margin to estimate the

### Table 1: Relationship between drop height and cushioning system, and peak acceleration (m s$^{-2}$).

<table>
<thead>
<tr>
<th>Drop height (m)</th>
<th>FN (control)</th>
<th>Pulp-1</th>
<th>Pulp-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>451.8 ± 30.3</td>
<td>664.9 ± 23.4*</td>
<td>441.6 ± 32.9</td>
</tr>
<tr>
<td>0.4</td>
<td>988.7 ± 30.9</td>
<td>1295.1 ± 49.0*</td>
<td>1028.1 ± 97.4</td>
</tr>
</tbody>
</table>

*Average ± standard deviation (n = 3)

Asterisk indicates that significant difference from control within the same drop height according to the Student’s t-test with Bonferroni correction (Family-wise error rate: $\alpha = 0.05$).

### Table 2: Relationship between drop height and cushioning system, and velocity change (m s$^{-1}$).

<table>
<thead>
<tr>
<th>Drop height (m)</th>
<th>FN (control)</th>
<th>Pulp-1</th>
<th>Pulp-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>2.56 ± 0.01*</td>
<td>2.56 ± 0.02</td>
<td>2.76 ± 0.07*</td>
</tr>
<tr>
<td>0.4</td>
<td>3.22 ± 0.03</td>
<td>3.66 ± 0.04</td>
<td>3.49 ± 0.08</td>
</tr>
</tbody>
</table>

*Average ± standard deviation (n = 3)

Asterisk indicates that significant difference from control within the same drop height according to the Student’s t-test with Bonferroni correction (Family-wise error rate: $\alpha = 0.05$).
damage occurrence due to drop shock.

Based on all the results, we concluded that the proposed cushioning system for apples exhibits superior cushioning performance compared with the conventional packaging system using the foam net within the range of our investigation.

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