A Procedure for Testing Padding Materials in Fruit Packing Lines Using Multiple Logistic Regression

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Abstract. *Padding materials are commonly used in fruit packing lines with the objective of diminishing impact damage in post–harvest handling. Two sensors (IS 100 instrumented sphere and UC–LPF impact tester) were compared to analyze the performance of six different padding materials used in Spanish fruit packing lines. Padding materials tested were classified according to their capability to decrease impact intensities inflicted on fruit in packing lines. A statistical procedure to test padding materials was tested for Golden Delicious apples. Its basis is a multiple logistic regression to predict bruise probability in fruit. The model combines two groups of parameters: padding material parameters measured with the IS, and fruit properties.*

Keywords. *Padding material, Packing line, Impact tester, Instrumented sphere, Bruises, Logistic regression, Fruit.*

Fresh fruits and vegetables suffer impacts as they are mechanically handled in commercial packing lines. Impacts commonly occur when the product crosses transfer points along the line. Bruising occurs when product tissue failure stress is exceeded. Bruise onset and size depend on a range of factors: height of the transfer points, fruit velocity at impact, hardness of the impact surfaces, curvature of the surfaces, and fruit characteristics (mass, curvature, temperature, hydration, firmness).

The choice of a padding material must be such that the most bruise sensitive products may be handled without damage. Damage can be reduced or avoided by locating padding materials on the surfaces of the machines (Burkner et al., 1972). A good padding material must satisfy three requirements (Bollen et al., 1995): (1) it must absorb the impact energy without damaging the product; (2) it should not apply a high rebound energy to the produce and it should avoid fruit–fruit impacts; and (3) it must be durable and compatible with packing line specifications (non–toxic, no absorption of dirt, etc.). In addition to the three requirements from Bollen et al. (1995), the combination of padding thickness and elastic modulus must be such that the fruit neither "bottoms out" (i.e., pushes through the padding to be stopped by the hard surface beneath) nor is bruised by padding that is too stiff (rigid).

Some studies have been carried out to establish evaluation procedures of padding materials, but with limited success. Traditional tests (e.g., ASTM static stiffness) used to evaluate properties of foam materials are not appropriate in the case of dynamic impacts. The dynamic force required to obtain a specific deformation lies between 1.5 and 4 times higher than the static force (Armstrong et al., 1995). The ASTM static stiffness value (ASTM, 1995) represents the force required to deflect a flat 645 mm^2 cushion surface to a depth equal to 25% of the original cushion thickness.

Bittner et al. (1967) developed a method for analyzing padding materials based on the absorbed energy, calculating the dropping height and the rebound height of a wooden ball anchored to an impacting pendulum. They used balls of different diameters to evaluate the effect of the contact area (radius of curvature of fruit). Hemmat et al. (1980) developed a mathematical model to estimate the thickness of the padding materials based on cushioning properties obtained with static methods, physical properties of the fruit, and impact energy. Bollen et al. (1995) proposed a method based on the measurement of three parameters of the padding material: (1) cushioning properties measured with an instrumented sphere, (2) restitution coefficient, and (3) durability of the padding material (6 out of the 8 materials tested showed fatigue signs after receiving 4400 impacts with a rubber ball of 170 g).

The instrumented sphere (IS) (Zapp et al., 1990) may be an appropriate tool for establishing dynamic characteristics of any padding material by means of its triaxial accelerometer (Bollen et al., 1995; Miller, 1998; Schulte et al., 1992). A different impact sensor (UC–LPF) composed of a spherical steel mass with a uniaxial accelerometer on top (Chen et al., 1985; Jarén et al., 1992) can be used with the same goal. The spherical mass is attached to a vertical support, adjustable in height, by means of an electromagnet. This sensor was developed initially to measure the impact effect on fruits. In a further application, Jarén et al. (1992) used the sensor to measure firmness of apples and pears in a non–destructive way. Chen et al. (1996) improved the sensor signal, decreasing the impacting mass. This sensor was the basis for developing a new version, based on the same technique, to measure fruit firmness on line (Chen and Ruiz-Altisent, 1996).

The spherical mass drops and impacts the padding material. The electromagnet and the data acquisition system are controlled by a computer. The impactor supplies the time and the maximum acceleration of each impact recorded by the uniaxial accelerometer, from which further relevant parameters are extracted such as velocity, deformation, and time duration of contact.

Bajema and Hyde (1998) also developed an alternative instrument to the IS–100 to establish damage thresholds in fruits and vegetables consisting of a precision–instrumented pendulum. This device allows simultaneous measurement of the impact force, the contact area, the restitution energy, and the resonant frequency of the specimen. In this study, this method is also proposed to evaluate padding materials.

Padding materials can be tested on the packing lines or under laboratory conditions. Whenever a laboratory test will allow a proper evaluation that is comparable to actual working conditions, it will be preferable to on–line testing, with the aim of simplifying the choice of a padding material for selected produce species and varieties.

The objective of this study was to develop an evaluation procedure for padding materials commonly used in fruit and vegetable packing lines, taking into account the EU (European Union) tolerance level for bruising of apples (for first category, up to a 10% of apples with bruises larger than 1 cm^2 is allowable). Several tests were carried out, with three goals:

1. Define an experimental procedure to characterize the performance of padding materials with minimum sample requirements.
2. Develop a statistical model, applied to Golden Delicious apples, to predict probability of damage based on the characteristics of the padding material.
3. Study the performance of two sensors (IS 100 instrumented sphere and UC–LPF impact tester) to classify padding materials according to their padding effectiveness.

Materials and Methods

An IS 100 instrumented sphere (161 g mass and 70 mm diameter; triaxial accelerometer) and a UC–LPF impact tester consisting of a spherical mass with a uniaxial accelerometer attached to it (50 g mass and 19.5 mm diameter) were used to test six different padding materials commonly used in Spanish fruit packing lines. Impact data are reported in gravity units (g), where 1 g is equivalent to 9.8 m/s^2 (ASAE Standard S365.3). Characteristics of the IS 100 were: sample rate = 3906 Hz, impact measurement range = 6 to 300 g, accuracy = 3%, and detection threshold = 8 g. The acquisition software was Peird (IS software), version 3.03.

Characteristics of the padding materials are listed in table 1. The stiffness of the padding materials was estimated with a Texture Analyzer XT2, which measured the force required to obtain a deformation of 2 mm with a cylindrical tip of 0.5 mm diameter at a velocity of 20 mm/min.

Golden Delicious apples used in the experiments were collected in the province of Gerona (Spain) and sent the same day to the LPF, Polytechnic University of Madrid, where they were tested immediately at a temperature of 20° C.

Table 1. Characteristics of the padding materials.

Padding Material	Thickness (mm)	Designation	Force at 2 mm Deformation (N)
Polythene with polyester cover	4	A	42.3
Polythene with PVC cover	5	B	8.2
Polythene	5	C	10.6
Polythene	10	D	9.3
Urethane	5	E	9.6
Polythene	10	F	9.0

Padding Materials Classification

The IS was dropped 10 times from seven heights (4, 8, 12, 16, 20, 24, and 28 cm) onto the six padding materials (A, B, C, D, E, and F). Measurements were taken: (1) to classify the padding materials according to impact intensity, which is the peak acceleration recorded by the IS for each impact; the higher the impact intensity, the lower the impact reduction for the same mass and radius of curvature (i.e., that of the IS), and (2) to develop a statistical model to predict damage in Golden Delicious apples.

Properties of the Apples

The Golden Delicious apples used in the experiments were homogeneous in firmness and turgidity and were grouped into four sizes: size 1 (70 mm diameter, 160 g average weight), size 2 (75 mm diameter, 188 g average weight), size 3 (80 mm diameter, 217 g average weight), and size 4 (85 mm diameter, 254 g average weight). A total of n= 648 apples was tested. Physical properties (firmness and turgidity) of a sample of 12 apples (3 of each size) were measured. Magness–Taylor firmness was measured using a Texture Analyzer XT2. The average Magness–Taylor firmness value for the apples was 23.3 N ±5.4 N. Turgidity was estimated by measuring the deformation of the apple during puncture with a cylindrical tip of 0.5 mm diameter at a velocity of 20 mm/min using the Texture Analyzer XT2. The average value of deformation to skin puncture was 0.76 mm ±0.11 mm at an average force of 3 N. According to García et al. (1995), deformation values lower than 0.5 mm define turgid apples. The tested apples can be considered as not turgid, and therefore with low damage probability.

Assessing Bruise Probability for Golden Delicious Apples

The traditional method of impacting a number of fruit onto a padding material and then testing the percentage of bruised fruit (sampling method) is laborious and difficult. The size of the sample (n) must be large enough to obtain low confidence intervals for the evaluated percentage of bruised fruits. Equation 1 refers to the confidence interval values for binomial distributions; in our case, they are a function of the percentage of bruised fruit and the sample size. Confidence intervals decrease when sample size (n) increases, and they reach a maximum as p and q approach 0.5 (i.e., random probability, $p = q = 0.5$). This means that each fruit sample must be large enough (around 30 apples) to obtain confidence intervals lower than the EU tolerance level (10% of fruits with bruises ≤ 1 cm^2):

$$CI = \pm t_{1-\alpha/2} \cdot SE = \pm t_{1-\alpha/2} \cdot \sqrt{\frac{p \cdot q}{n}} \quad (1)$$

where

CI = confidence interval

SE = standard error

t = Student's t

α = significance level

p = 0/1 rate of bruised fruit on the sampling

q = $1 - p$.

As a consequence, a padding material must fulfill the following premise to be accepted for use on a packing line:

$$\textit{\% bruised fruit in sample} + CI < \textit{EU tolerance}\ (10\%) \quad (2)$$

To test a large number of padding materials, the experimental design needed for the sampling method would be unfeasible, especially for a large number of susceptibility stages of the fruit. A procedure for analyzing a large number of padding materials using a low number of fruits and obtaining accurate results is described below. It consists of generating relevant and reduced data sets with several experiments, and modeling bruise probability with multiple logistic regression.

Experiment 1 with padding materials A to F: A total of 168 Golden Delicious apples (see "Properties of the Apples") of four sizes (size 1 = 70 mm diameter, size 2 = 75 mm diameter, size 3 = 80 mm diameter, and size 4 = 85 mm diameter) were divided into groups of four apples (one for each size). These were impacted onto the six padding materials from seven drop heights (4, 8, 12, 16, 20, 24, and 28 cm) in the same way as with the IS (metal rod held by pincers, see "Evaluation of New Sensors"). For each padding material and height, a group of four apples were impacted, one of each size.

Experiment 2 with padding materials B and C: A total of 480 apples (240 of size 1 and 240 of size 3) were divided in groups of 30 of the same size in order to achieve a confidence interval of 7% for low (10%) percentages of damage. Apples were dropped onto padding materials B and C from four drop heights (4, 12, 20, and 28 cm).

Bruises (discoloration larger than 1 cm^2 showing through the skin and determined by eye) were checked after 24 h at ambient conditions. The bruise area was measured with a digital caliper, which was used to measure both axes of an ellipse that circumscribed the bruise. Depth of bruise was not measured. This parameter is not included in the EU standards.

For development of the bruise prediction model, multiple logistic regression is a statistical tool that can predict probabilities when the dependent variable is bounded by 0 and 1. This type of regression can relate continuous variables (impact intensity, mass) with discrete variables (damaged or not damaged) without establishing initial conditions of the data. A model selection procedure based on a backwards stepwise elimination (Bielza et al., 2000) allows us to select the most meaningful and simple model, starting from a user-defined set of independent variables of any number. The complete model, the starting point for the selection procedure, consists of all linear plus quadratic effects. This procedure has been implemented in a user interface (SIMLIN 2.0). When the impact characteristics (acceleration and velocity change) and the fruit mass are known, the model can predict the percentage of fruit damaged under those impact conditions.

Bollen and Cox (1991) used logistic regression to estimate the probability of bruising in apples based on the impact energy. Their analysis used only one fruit size. Fruit characteristics and confidence intervals were not considered.

In the present study, a multiple logistic regression was computed based on the following variables: occurrence of damage (1 = damage; 0 = no damage), apple mass (m), maximum acceleration obtained with the IS (g), and velocity change obtained with the IS (vc). The set of data used for model calibration consisted of all data from experiment 1 (all padding materials, 168 fruits) plus 40/480 apples from experiment 2 (exhaustive analysis of materials B and C). The concept was to test whether an incomplete factorial design can lead to accurate predictions by using multiple logistic regression. The subset of 40 apples from experiment 2 was randomly chosen from the samples indicated in table 2. Note that the fruits belong to the extreme impact conditions (4 and 28 cm drop) in order to enhance the estimation of model parameters. The model was validated against the remaining 440/480 data.

For the case of a multiple logistic regression that considers the variables m, g, and vc, the boundaries of the confidence interval (BCI) are calculated by equation 3 (results are shown in tables 5 and 6). In terms of comparison with the confidence interval (CI) stated for the sampling procedure, the confidence interval of prediction is calculated as half the distance between its boundaries:

$$BCI = \left(\frac{1}{1+e^{-a}}, \frac{1}{1+e^{-b}} \right) \quad (3)$$

where

$a = \beta_0 + \beta_1 m + \beta_2 g + \beta_3 vc - 1.96\,ASE$

$b = \beta_0 + \beta_1 m + \beta_2 g + \beta_3 vc + 1.96\,ASE$

$$ASE = \sqrt{Var(\beta_0 + \sum_{j=1}^{k} \beta_j x_{ij})} = \sqrt{\begin{pmatrix} 1 & m & g & vc \end{pmatrix} Cov(\hat{\beta}) \begin{pmatrix} 1 \\ m \\ g \\ vc \end{pmatrix}} \quad (4)$$

(ASE = Asymptotic Standard Error, Bielza et al., 2000).

Evaluation of New Sensors

A specific test was developed to study the effectiveness of the IS and the UC–LPF impact tester for classifying the padding materials. The IS and UC–LPF were each dropped 10 times from five different heights (4, 8, 12, 16, and 20 cm)

Table 2. Selection of data set from experiment 2 for multiple logistic regression. Table displays the number of fruits used for model calibration, randomly selected, relative to the total amount available.

Padding Material	Impact Height (cm): 4 — Fruit diameter (mm): 70	4 — 80	28 — Fruit diameter (mm): 70	28 — 80
B	5/30	5/30	5/30	5/30
C	5/30	5/30	5/30	5/30

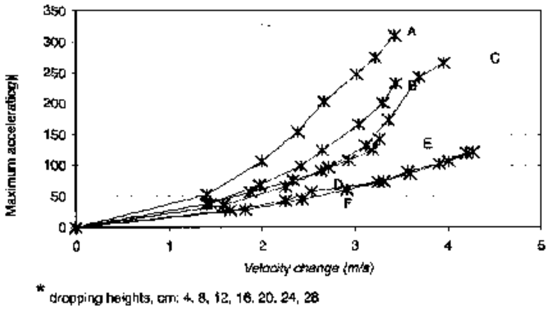

Figure 1. IS impact responses for padding materials A to F. Data points are the average maximum acceleration and average velocity change for each drop height (4, 8, 12, 16, 20, 24, and 28 cm) with 10 replicates per height. Padding material characteristics are listed in table 1.

onto four padding materials (A, B, C, and D). The UC–LPF is dropped by switching off the electromagnet that holds the spherical impacting head. The dropping height is regulated by a mechanical control. The IS height is regulated by a vertical metal rod that is held by a pincer. The pincer opens mechanically, and the IS falls onto the padding material.

Results and Discussion

Padding Materials Classification

The IS parameters (maximum acceleration and velocity change) were used to classify padding materials, as shown in figure 1. It is observed that the flatter the curve, the more effective the padding material (lower peak acceleration) will be for similar conditions. Padding material F (thickest) is the most effective, and padding material A (thinnest) is the least effective. Materials of the same thickness (for instance: E, B, and C) developed different impact intensities for similar dropping heights, as shown in figure 1. Polythene (material C) shows a lower efficiency than urethane (material E) for the same thickness (5 mm), according to material C's higher stiffness. Although curves have the same shape, the position of the impacting points according to the drop height is different for each material (C and E).

As a consequence, padding materials with flatter curves must be chosen. When two materials have curves with the same slope, the material with a curve with smaller ordinate distances between drop heights must be selected. For instance, in comparing C and E (similar slope), E must be selected. To know which material will perform better is a first step, necessary but not sufficient. The padding material may be chosen at this step, but additional information is needed. The best padding material must be identified by damage occurrence, not just by the impact responses of the sensors.

Statistical Model

Comparison of Averages

Table 3 shows bruise occurrence for the extreme condition (4 and 28 cm) samples used in experiment 1. Each sample of fruits is composed of one apple per size (4 apples total). This experiment was performed to establish the range of behavior of the padding materials with these fruits (Golden Delicious apples), which is the reason for the reduced number of repetitions.

Table 3. A selection of data from experiment 1. Number of bruised fruits per sample (4 fruits) is shown. Results for intermediate drop heights (8, 12, 16, 20, and 24 cm) not shown.

Impact Height (cm)	Padding Material					
	A	B	C	D	E	F
4	0/4	1/4	0/4	0/4	0/4	0/4
28	3/4	2/4	2/4	2/4	2/4	1/4

Table 4. Percentage of bruised fruit corresponding to experiment 2.

Padding Material (5 mm thick)	Fruit Size	Drop Height (cm)	Sample Size (n)	No. of Bruised Fruit	% of Bruised Fruit in Sample	CI (%)
B (PVC with polythene)	1	4	30	0	0	0
		12	30	1	3.3	±6.42
		20	30	3	10	±10.74
		28	30	8	26.7	±15.82
B (PVC with polythene)	3	4	30	4	13.3	±12.16
		12	30	9	30	±14.31
		20	30	8	26.7	±15.82
		28	30	14	46.7	±17.85
C (Polythene)	1	4	30	0	0	0
		12	30	1	3.3	±6.42
		20	30	3	10	±10.74
		28	30	4	13.3	±12.16
C (Polythene)	3	4	30	0	0	0
		12	30	6	20	±14.31
		20	30	9	30	±16.40
		28	30	15	50	±17.89

Table 4 shows the percentage of bruised fruit obtained in experiment 2. There are no significant differences between padding materials B and C (similar material, same thickness) when considering the bruise percentage assessed by sampling. Increasing the drop height and mass led to increasing damage, as expected. PVC coating had no effect.

Logistic Model

A logistic regression to estimate bruise probability for Golden Delicious apples was computed based on the following variables: apple mass (m), IS maximum acceleration (g), and IS velocity change (vc). The developed model predicted bruise probability according to equation 5:

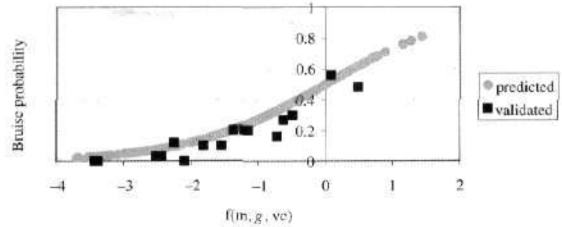

Figure 2. Logistic regression to predict bruise probability in Golden Delicious apples.

Table 5. Predicted bruise probability and associated confidence intervals (CI) calculated with the multiple logistic regression for the 440/480 apples from experiment 2 used to validate the model: n = number of fruits in each sub-sample.

Padding Material (5 mm thick)	Fruit Size	Drop Height (cm)	No. in Validation Set (n)	Predicted Bruise Probability (%)	CI (%)
B (PVC with polythene)	1	4	25	3.2	±2.9
		12	30	7.5	±4.4
		20	30	14.1	±6.5
		28	25	24.3	±9.6
B (PVC with polythene)	3	4	25	9.7	±6.2
		12	30	20.5	±6.4
		20	30	35.1	±6.2
		28	25	51.8	±8.6
C (Polythene)	1	4	25	3.3	±2.9
		12	30	8.1	±4.7
		20	30	17.7	±7.5
		28	25	32.9	±12.8
C (Polythene)	3	4	25	11.1	±6.5
		12	30	23.3	±6.2
		20	30	38.2	±6.5
		28	25	61.7	±10.2
Total			440		

$$\text{Bruise probability } (\%) = \frac{e^f}{1+e^f} \cdot 100 \qquad (5)$$

where

$f = \beta_0 + \beta_1 \cdot m + \beta_2 \cdot g + \beta_3 \cdot vc$ and

$f = -7.6367 + 0.02019\, m + 0.00581\, g + 0.55565\, vc$

in the adjusted model (fig. 2).

The model, computed with 208 apples, predicts bruise probability correctly (as demonstrated by the validation with 440 apples) with unexplained variance of 0.104 (coefficient of determination $R^2 = 0.896$). With the alternative statistical sampling procedure, a total of 5040 fruits would have been necessary (6 padding materials × 7 impact heights × 4 fruit sizes × 30 fruits per sample) to be able to predict fruit damage for the same ranges of all independent variables.

This result shows that, knowing the characteristics of padding material A, B, C, D, E, or F (acceleration and velocity change for an established drop height) and the mass of the fruits, we can use equation 5 to estimate the probability of damage (tables 5 and 6) for similar fruits and drop heights. We can then establish the working conditions under which a padding material can be used, associating the impact intensity registered on the packing line with the drop height

Table 6. Predicted bruise probability (P) and associated confidence intervals (CI) simulated under the multiple logistic regression model for fruit size 2 and 4 and for the six padding materials.

	Fruit Size 2			Fruit Size 4		
Padding Material	Drop Height (cm)	P (%)	CI (%)	Drop Height (cm)	P (%)	CI (%)
A	4	5.9	±4.5	4	20.1	±11.7
	16	23.2	±8.5	16	54.7	±12.6
	28	46.2	±14.3	28	77.4	±11.6
B	4	5.6	±4.2	4	19.0	±11.1
	16	15.9	±5.6	16	43.0	±9.9
	28	35.5	±9.1	28	68.8	±9.8
C	4	5.9	±4.2	4	20.0	±10.9
	16	20.4	±6.2	16	50.5	±9.3
	28	47.1	±11.6	28	78.1	±9.2
D	4	5.9	±4.1	4	19.9	±10.5
	16	16.4	±7.3	16	43.9	±11.8
	28	30.3	±13.7	28	63.4	±14.6
E	4	5.4	±4.2	4	18.7	±11.1
	16	13.4	±5.3	16	38.1	±9.9
	28	22.8	±6.6	28	54.1	±9.3
F	4	6.4	±4.2	4	21.4	±10.4
	16	16.9	±7.6	16	44.9	±12.1
	28	31.4	±14.4	28	64.7	±14.9

threshold for the fruits. For a complete assessment of specific applications, the fruit species, cultivar, turgidity, and eventually temperature and ripeness stage should be considered as additional independent variables in the model.

Table 5 shows the predicted damage probability and its confidence interval calculated with the multiple logistic regression for the 440/480 apples from experiment 2 used to validate the model. This procedure points out a slight but consistently better performance for material B in comparison with material C, which could not be concluded from the sampling method (table 4) nor from the IS response alone (see fig. 1). In addition, the confidence intervals (CI) are lower for multiple logistic regression than for the sampling method. For large fruit sizes, even a 4 cm impact would lead to percentages of bruised fruit above the EU tolerance.

Table 6 shows a simulation of expected percentages of bruised fruits for all padding materials under the same conditions (fruits size and drop height). They may be ranked from worse to best as: C, A, B, F, D, and E. The confidence interval allows us to establish three different categories for padding materials: best performing (E, urethane), medium (B, polythene with PVC cover; and F and D, polythene 10 mm), and worst performing (A, polythene with polyester

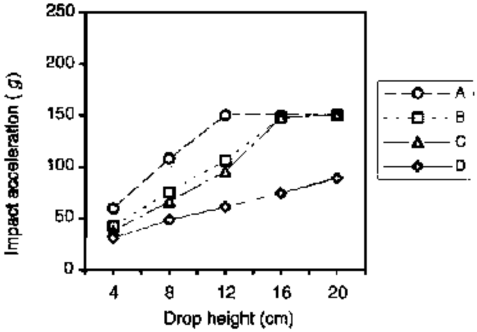

Figure 3. Peak acceleration values obtained with the UC–LPF impact tester.

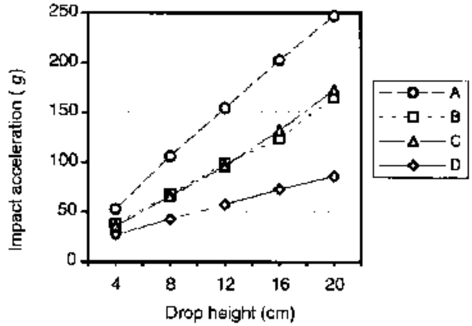

Figure 4. Peak acceleration values obtained with the instrumented sphere (IS).

cover; and C, polythene 5 mm). These conclusions confirm the power of the proposed method. For large fruits sizes (85 mm diameter), even a 4 cm impact onto any padding material leads to percentages of bruised fruit above the EU tolerance, as stated with the sampling procedure (eq. 2).

Evaluation of Sensors

Both sensors (IS 100 instrumented sphere and UC–LPF impact tester) were capable of classifying the different padding materials according to their impact intensity. The results of peak acceleration obtained are shown in figure 3 (for the UC–LPF impact tester) and figure 4 (for the IS) for each padding material and drop height. Each impact datum is the average peak acceleration (average of 10 repetitions) expressed in acceleration of gravity units (g). Note that the maximum acceleration value registered by the UC–LPF impact tester accelerometer is 150 g, due to the saturation of the dynamic range of the A/D card.

Table 7 presents the average values and standard deviation of each test. Standard deviations were consistently and significantly higher with the IS than with the UC–LPF impact tester. The average peak acceleration with the UC–LPF impact tester is slightly higher than with the instrumented sphere, mainly due to the different shape of the sensors (radius of curvature) and sensor mass.

The use of the UC–LPF impact tester is appropriate for precise measurements in the laboratory because of its higher repeatability and easier handling when compared to the IS. As is known, the IS is designed as a testing and evaluation tool for pack–house equipment and not as a high–resolution measuring instrument, but it is useful as well for testing the response of padding materials regarding bruising of fruit, as shown.

Conclusions

- A procedure for testing padding materials was developed and tested successfully for Golden Delicious apples and seven different padding materials. It is based on a multiple logistic regression model computed with two groups of parameters: padding materials characteristics measured with the IS (acceleration of gravity and velocity change), and fruit properties.
- The test procedure consisted of dropping the IS and a group of fruits onto different padding materials. The IS impact data and fruit mass were selected by the modeling process as most relevant for predicting the percentages of bruised fruits. With this equation, the probability of bruise when a fruit impacts against a padding material (for a specific impact intensity) can be calculated. The model

Table 7. Average peak acceleration values and standard deviations (SD) for each test.

Padding Material	Thickness (mm)	Designation	Drop Height (cm)	Average Value (g)		Standard Deviation (g)	
				UC–LPF	IS	UC–LPF	IS
Polyester–Polythene	4	A	4	60	53	0.65	3.97
PVC–Polythene	5	B	4	42	39	1.19	0.83
Polythene	5	C	4	38	36	0.86	1.25
Polythene	10	D	4	31	27	0.85	1.23
Polyester–Polythene	4	A	8	108	106	0.76	1.23
PVC–Polythene	5	B	8	76	67	0.97	2.30
Polythene	5	C	8	67	65	2.06	1.80
Polythene	10	D	8	49	43	1.15	1.65
PVC–Polythene	5	B	12	107	99	1.51	1.70
Polythene	5	C	12	96	96	2.33	2.42
Polythene	10	D	12	61	57	3.15	5.29
Polythene	10	D	16	74	72	1.33	2.03
Polythene	10	D	20	89	86	2.45	2.51

was successfully validated with further data obtained by testing fruits with similar properties.

- The main advantage of the proposed procedure is that it reduces the number of fruits needed for the bruising tests when compared to statistical sampling methods. It can also be easily extended to create models that include defining parameters of different susceptibility stages (like firmness and turgidity). The use of this statistical procedure is more effective than existing sampling methods, for example in establishing the conditions for the acceptance of a padding material, as shown in this work.
- The proposed method enables us to rank the behavior of seven padding different materials: best performing (E, urethane), medium (B, polythene with PVC cover; and F and D, polythene 10 mm), and worst performing (A, polythene with polyester cover; and C, polythene 5 mm). In all padding materials, the largest fruits (85 mm diameter) bruise just about enough to reach the EU tolerance, even at the lowest drop height (4 cm).
- The IS instrumented sphere and the UC–LPF impact tester can be used effectively to test the performance of padding materials. The UC–LPF impact tester is more precise than the IS, but the upper limit of the UC–LPF's peak acceleration values was lower, thus preventing the testing of highly damaging drop heights in apples.

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