Strawberry Bruising Sensitivity Depends on the Type of Force Applied, Cooling Method, and Pulp Temperature

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Abstract. Strawberry (*Fragaria × ananassa* Duch.) fruit are very susceptible to mechanical injury and for this reason are normally field-packed. Fruit of three cultivars (Chandler, Oso Grande, Sweet Charlie) were subjected to forced-air or hydrocooling to reach pulp temperatures between 1 and 30 °C and then individually subjected to compression and impact forces representative of commercial handling operations. Strawberries with a pulp temperature of 24 °C exhibited sensitivity to compression but greater resistance to impacts. As pulp temperature decreased, fruit were less susceptible to compression as shown by up to 60% reduction in bruise volume. In contrast, strawberries at 1 °C pulp temperature had more severe impact bruising with up to 93% larger bruise volume than at 24 °C depending on the cultivar. Strawberries also showed different impact bruise susceptibility depending on the cooling method. Impacted fruit that were forced-air cooled had larger bruise volumes than those that were hydrocooled. The impact bruise volume for strawberries forced-air cooled to 1 °C was 29% larger than for fruit hydrocooled to 20 °C, 84% higher than those forced-air cooled to 20 °C, and 164% higher than those hydrocooled to 1 °C. Because incidence and severity of impact and compression bruises are temperature-dependent, strawberry growers should consider pulp temperature for harvest scheduling and for potential grading on a packing line. Hydrocooling shows promise to rapidly cool strawberry fruit while reducing weight loss and bruising sensitivity.

Strawberry fruit show a high metabolic rate based on measured rates of respiration, and it is classified as a nonclimacteric fruit because there is no dramatic rise in respiratory activity or in ethylene biosynthesis during ripening (Kader, 2002; Knee et al., 1977). Therefore, strawberries must be harvested in an essentially ripe condition. Mitcham (1996) stated that the two most important factors for strawberry keeping quality are temperature management and rapid marketing. Strawberries are very fragile and thus highly susceptible to mechanical injury. The major causes of postharvest strawberry losses are decay and accelerated senescence associated with bruising. Proper handling and tempera-

ture management significantly reduces these losses. Because fresh produce is typically handled several times from harvest to retail level, proper worker training and supervision is critical to keep mechanical injuries to a minimum (Sargent et al., 2007).

For some crops, the majority of bruising occurs during harvest, whereas for others, packing and transportation require the most attention (Prussia and Shewfelt, 1993). Bruising can be caused by any one or a combination of impact, compression, and vibration forces (Brusewitz et al., 1991; Vergano et al., 1991). Impact bruising results from a sudden sharp force, for example when a fruit falls onto another fruit or onto a hard surface on a packing line (Garcia et al., 1988) or when an object strikes the fruit (Crisosto et al., 1993). Compression bruising occurs when tissue is subjected to a constant force such as during hand harvest (finger pressure) or when the fruit is on the bottom layer of a container

(Banks et al., 1991; Schoorl and Holt, 1982). Vibration bruising results from repeated high-frequency impacts at low energy levels (Maness et al., 1992; Zeebroeck et al., 2006) and can result from a combination of impact and compression forces resulting from the weight of upper layers of fruit in a container (Vergano et al., 1991). It can also be caused when fruit rub against each other or some other surface (Crisosto et al., 1993). Vibration bruising usually occurs during transportation and can cause a high percentage of losses (Jones et al., 1991).

Compression was reported to cause more severe bruising on strawberries than impact (Guillou, 1964). For the same amount of energy (0.2 to 1.5 Joule), bruise volumes in strawberries were 40% higher under compression compared with impact (Holt and Schoorl, 1982). It was proposed that this is the result of the conformation of the cell wall: strawberry tissue was likened to an arrangement of liquid-filled, spherical cells bounded by viscoelastic membranes with air-filled interstitial spaces. Compression affects the cell wall, causing cell bursting, especially under high stress. Holt and Schoorl (1976) reported that apple tissue is also more easily bruised by compression than by impact. Bruise volumes were ≈40% higher under compression than impact.

As pulp temperature drops, different commodities have different responses to applied forces. Hyde et al. (2001) reported that cultivars of the same species can also respond differently to applied forces as temperature changes. For some commodities, the tissue resistance to applied force increases as the temperature decreases. Among these commodities are strawberry (Ourecky and Bourne, 1968; Rose et al., 1934), blueberry (Ballinger et al., 1973), peach (Brusewitz et al., 1992), banana (Banks and Joseph, 1991), and apricot (DeMartino et al., 2002). However, it was reported that tissue resistance to applied force for other crops decreased as the temperature decreased, including cherry (Crisosto et al., 1993; Lidster and Tung, 1980), potato (Baritelle and Hyde, 2001; Bartz and Kelman, 1984; Johnston and Wilson, 1969), and pear (Baritelle and Hyde, 2001; Chen et al., 1987). Hyde et al. (2001) noted that turgid pears should be warmed to at least 15 °C before handling, whereas flaccid pears should be handled at storage temperature (0 °C). There also have been conflicting reports for the response of fruit bruising to temperature changes. Some researchers have reported that a decrease in apple temperature caused an increase in bruise susceptibility for the cultivars Gravenstein, Red Delicious, and Golden Delicious (Sekse and Opedal, 1993; Zhang and Hyde, 1992). Saltveit (1984), however, observed a decrease in bruise volume when the temperature decreased for ‘Starkrimson Delicious’ and ‘Golden Delicious’ apples. Others reported that temperature had no effect on bruise volume of ‘Jonathan’, ‘Delicious’, and ‘Granny Smith’ apples (Schoorl and Holt, 1977). Hyde et al. (1997) also reported that temperature change

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had no effect on bruise sensitivity for 'Red Delicious', but they identified fruit tissue hydration level as the major factor affecting the apple bruise threshold, which probably accounts for the disagreement among the previous reports.

Rose et al. (1934) reported that firmness of strawberry fruit (measured with a puncture device) increased as temperature decreased. They concluded that this response was the result of increased resistance of the epidermis rather than increased firmness of the underlying tissue. Ourecky and Bourne (1968) reported that strawberries subjected to compression after hydrocooling exhibited an increase in firmness and skin toughness as the temperature was decreased. They also reported a similar response for strawberries that came from the field on cold days compared with strawberries harvested on hot, sunny days. Ballinger et al. (1973) reported similar results for blueberry, in which firmness increased 8% to 9% in fruit subjected to compression after being cooled from 21.1 to 4.4 °C. On the other hand, Asian pears were softer at cold temperatures, although there was some variability between cultivars (Chen et al., 1987). Banana has also been reported to exhibit reduced firmness at lower temperatures (Banks and Joseph, 1991). This was considered to be related to the turgor pressure of the fruit cells.

Forced-air cooling rapidly removes field heat by creating a difference in air pressure on opposite faces of palletized produce. The resulting high-volume air is humidified to greater than 90% relative humidity (RH) to minimize water loss during cooling. Forced-air cooling is the standard method for cooling many crops, including strawberry. However, our previous report demonstrated that sound strawberries maintained better overall fruit quality during storage when hydrocooled than when forced-air cooled. Incidence and severity of decay were lower in hydrocooled than in forced-air cooled fruit (Ferreira et al., 2006).

The objective of this research was to determine the sensitivity of strawberry fruit cooled by forced-air cooling or hydrocooling to pulp temperatures ranging from 30 to 1 °C and then subjected to compression or impact forces designed to simulate commercial handling.

Materials and Methods

Compression tests

'Chandler', 'Oso Grande', and 'Sweet Charlie' strawberries of uniform size and average weight (± 20 g) were picked at the full-red stage of fruit development (no green or white area on the fruit) from a commercial farm in Floral City, FL. These commercial varieties were selected because they are widely grown in many production areas around the world. Fruit from each cultivar were field-packed into eight plastic mesh, open-top containers (10.5 cm $\times$ 10.5 cm) per corrugated carton with an open-top configuration. The fruit were immediately transported (≈ 1 -h travel time) to the University of Florida

Postharvest Horticulture Laboratory in Gainesville at 21 °C, where they were placed in a 35 °C controlled temperature room for 1 h until the pulp temperature reached 30 °C. After temperature equilibration, 40 fruit per cultivar and treatment were either forced-air cooled to 1 °C; hydrocooled to 20, 10, 5, or 1 °C; or held constantly at 30 °C. Commercial cooling conditions were simulated by using forced-air cooling (1 °C, 90% to 95% RH) through circulating air through the strawberries at 0.156 m³·min⁻¹·kg⁻¹ fruit with a pressure drop of 71 Pa across the flats, representative of commercial procedures. Hydrocooling was accomplished by immersing fruit in baskets in a constant-temperature circulating water bath at 1 °C (Model 900; Poly-Science, Niles, IL). On reaching the desired pulp temperatures, the fruit were held at the same respective temperatures and RH until testing.

Fruit were subjected to a constant compression force using the IFAS Firmness Tester (Gull, 1987). This device applied a static load of 9.8 N for 5 s to the widest point on one side of each whole strawberry fruit using a convex-tipped probe 15 mm in diameter. For hydrocooled fruit, the baskets were briefly placed on paper towels after bruising to remove excess water. These tests were conducted twice for each cultivar.

Impact tests

Impact tests were performed by two methods, either dropping the fruits or using a pendulum impactor, as described subsequently.

Drop tests. 'Oso Grande' and 'Sweet Charlie' strawberries at full-red stage and average mass of 20 g $\pm$ 2 g were obtained from a commercial farm in Floral City, FL. The fruit were immediately transported (≈ 1 -h travel time) to the University of Florida Postharvest Horticulture Laboratory in Gainesville at 21 °C. The objective of this test was to evaluate the response of strawberry fruit at different temperatures to vertical drops. On the day of harvest, individual fruit at room temperature (24 or 20 °C) or cooled (1 °C) were dropped from three different heights (38, 20, or 12 cm) such that the equator impacted a heavy steel plate. Considering an average strawberry mass of 20 g, the equivalent impact energies were 0.075, 0.040, and 0.025 J, respectively, for the three heights, almost identical to the pendulum impact forces described subsequently. 'Oso Grande' fruit ($n = 30$) were only forced-air cooled. On arrival in Gainesville, pulp temperature was 24 °C and fruit were dropped at that temperature or were forced-air cooled to 1 °C and then dropped in a 1 °C room. 'Sweet Charlie' fruit ($n = 40$) were either forced-air cooled or hydrocooled. Fruit were warmed to 30 °C as previously described and then cooled either by forced air or hydrocooling to 20 or 1 °C before the drop tests were conducted at those temperatures as previously described. 'Oso Grande' and 'Sweet Charlie' fruits were evaluated for bruising after 24 h at 24 °C to simulate handling at retail level and in a separate

test 'Sweet Charlie' after 7 d at 1 °C to simulate commercial shipping conditions.

Pendulum impactor. For pendulum impactor, 'Sweet Charlie' and 'Oso Grande' strawberry fruit were obtained from farms in Dover, FL, at two commercial stages of development, full-red and three-fourths red (light green or white shoulders). The fruit were handled as previously described and were also immediately transported (≈ 2 -h travel time) to the University of Florida Postharvest Horticulture Laboratory in Gainesville at 21 °C. The fruit were then placed in a 1 °C controlled temperature room for 24 h after harvest and then were either impacted at 1 °C or were transferred to 24 °C for 5 h and then impacted. There were 30 fruit per treatment. In a subsequent test, 'Chandler' strawberries at full-red and three-fourths red stages were obtained from a farm near Gainesville, FL, and were handled as previously described. The fruit were forced-air cooled to 1 °C immediately after harvest or after 5 h at 24 °C and 90% to 95% RH. The strawberries were then subjected to impact bruising at 1 or 24 °C. There were 20 fruit per treatment.

An apparatus was constructed to permit a controlled impact on each fruit. A pendulum (chrome steel ball bearing, 32.6 g, diameter = 20 mm) was attached by a swivel to monofilament line (88-N test strength) and suspended from a horizontal bar (height = 360 mm). A single berry was suspended in a cheesecloth pouch such that the fruit contacted a solid backstop. 'Sweet Charlie', 'Oso Grande', and 'Chandler' strawberries were impacted on the opposite side using pendulum angles of 45° or 90° to simulate low- and high-energy impacts corresponding to 0.024 J and 0.083 J, respectively. Energy at impact was calculated using the formula $E = mgh$ [m = pendulum mass; g = acceleration constant; h (vertical height) = $r - r \cdot \cos \theta$; r = radius].

Bruise evaluation

After impact or compression treatments, fruit were held for 24 h at 24 °C and evaluated for bruising. In a separate test, 'Sweet Charlie' fruit at 20 °C were dropped, cooled to 1 °C, and held at 1 °C for 7 d before bruising evaluation. High RH was maintained by placing the cartons containing the baskets in a plastic bag with the open end loosely folded over. Bruise severity was determined by estimating bruise volume. Each fruit was sliced through the center of the impact area and was considered to have been bruised if damaged tissue was visible below the impacted area. Bruise width (W) was measured by caliper at the fruit surface from edge to edge of the bruise on two perpendicular axes and averaged. Bruise depth (D) was measured from the fruit surface to the deepest point of the damaged tissue. Total bruise volume (V) was estimated by the formula for volume of a cone, $1/3(\pi[w/2]^2D)$, where w = width and D = depth (Mohsenin, 1970).

Statistical analyses

A completely randomized design was used for experiments. Analysis of variance

was performed using the Statistical Analysis Systems computer package (SAS Institute, Cary, NC). Unless cultivars revealed significant differences, overall treatment means were compared by least significant differences ($P = 0.05$). Otherwise, means from each cultivar were analyzed separately.

Results and Discussion

Compression tests

'Chandler', 'Oso Grande', and 'Sweet Charlie' strawberries were harvested at the full-red stage and compression tests were performed at the desired pulp temperatures. There were significant differences in bruise volume among the cultivars after compression; therefore, the statistical analysis was conducted separately for each cultivar. Cultivars Chandler and Oso Grande showed no differences between the two harvests. However, results for 'Sweet Charlie' were significantly different from the other cultivars.

Pulp temperature was positively correlated with bruise volume, in which bruise volume decreased as temperature decreased (Table 1). The largest bruise volume for all cultivars occurred at 30 °C (no cooling), which was significantly larger than at lower temperatures. Bruise volume was generally smallest when the pulp temperature was 1 °C. Bruise volume was smaller in 'Chandler' fruit when compressed at 1 or 5 °C than at 10 °C and in 'Sweet Charlie' when hydrocooled to 1 °C versus 5 or 10 °C and when forced-air cooled to 1 °C. These results agree with those of Rose et al. (1934) and Ourecky and Bourne (1968), who reported an increase in strawberry fruit firmness as temperature decreased. Strawberries exposed to low field temperatures before harvest were firmer than those harvested during higher temperature periods (Ourecky and Bourne, 1968; 'Sweet Charlie' in this study). There was no significant difference in bruise volume between forced-air cooled and hydrocooled 'Chandler' and 'Oso Grande' at 1 °C pulp temperature. 'Sweet Charlie' had larger bruise volume when forced-air cooled than when hydrocooled to 1 °C.

Impact tests

Drop tests. In contrast to the compression tests, in which bruise volume was significantly larger at higher temperatures, 'Oso Grande' strawberries had larger bruise volume when dropped at 1° than at 24°. Bruise volume increased as impact height increased, notably from 20 to 38 cm (Table 2). However, there was no significant interaction between temperature and drop height (Table 2). For the highest impact height (38 cm), bruise volume was 93% larger for fruit at 1 °C than at room temperature. It has been reported that for some commodities such as bananas, stone fruits, and pears, there is a different injury response when the fruit are subjected to different types of force at low temperatures (Banks and Joseph, 1991; Sommer et al., 1960). For example, bananas subjected to im-

Table 1. Bruise volumes for 'Chandler', 'Oso Grande', and 'Sweet Charlie' strawberries after compression testing at several cooling method/pulp temperature combinations.

Cooling method	Pulp temp (°C)	Bruise volume (cm ³)		
		Cultivar		
		Chandler	Oso Grande	Sweet Charlie
Forced-air	1	0.246	0.343	0.342
Hydrocooling	1	0.267	0.271	0.226
	5	0.287	0.334	0.389
	10	0.345	0.355	0.393
	20	0.427	0.520	0.333
No cooling	30	0.649	0.631	0.579
Least significant difference $P = 0.05$		0.065	0.090	0.107

pect forces showed increased injury as temperature increased, whereas when subjected to compression injury, injury decreased as temperature increased (Banks and Joseph, 1991).

There were also different responses to impacts resulting from cooling method. 'Sweet Charlie' strawberries dropped from 38 cm had larger bruise volume when forced-air cooled to 1 °C compared with 20 °C, whereas hydrocooled fruit had larger bruise volume at 20 °C compared with 1 °C (Table 3). When fruit were forced-air cooled to 1 °C, the bruise volume was 29% larger than for fruit hydrocooled to 20 °C, 84% larger than fruit forced-air cooled to 20 °C, and 164% larger than fruit hydrocooled to 1 °C. For Evaluation 1, bruise volumes for 'Sweet Charlie' fruit hydrocooled to 20 °C were not significantly different from those of fruit forced-air cooled to 1 °C. However, for Evaluation 2, fruit forced-air cooled to 1 °C had significantly larger bruise volume (Table 3).

In another test, 'Sweet Charlie' fruit were dropped after cooling to 1 or 20 °C and then stored for 7 d at 1 °C before evaluation for bruising to simulate commercial handling (Table 3). The smallest bruise volume occurred when fruit were hydrocooled to 1 °C and the highest bruise volume was observed with fruit that were forced-air cooled to 1 °C, which were similar results to the previous test. After the hydrocooling treatment, wounds were previously observed to be temporarily water-soaked and fruit increased in mass; however, residual moisture left on the berries by the hydrocooling treatment did not predispose the fruit to postharvest decay during storage (Ferreira et al., 1996).

Pendulum impactor. Bruise volume of 'Chandler', 'Oso Grande', and 'Sweet Charlie' strawberries subjected to the pendulum impactor did not differ significantly at 1 or 24 °C (Table 4). Bruise volume at 90° impact angle was significantly larger than at 45° for 'Sweet Charlie' strawberries at 1 °C. 'Oso Grande' did not show significant differences in bruise volume between the two energy levels, whereas full-ripe 'Chandler' fruit impacted at 24 °C had significantly larger bruise volume at 90 than at 45 °C. 'Chandler' fruit impacted at the full-red stage had significantly more severe injury than at the three-fourths red stage at either temperature. For 'Oso Grande' and 'Sweet Charlie' fruit, there were no differences in bruise volume

Table 2. Bruise volume for 'Oso Grande' strawberries dropped from 13, 20, or 38 cm onto a solid surface at room temperature (24 °C) or at 1 °C (forced-air cooled).

Pulp temp (°C)	Drop ht (cm)	Bruise volume (cm ³)
1	13	0.213
	20	0.150
	38	0.310
24	13	0.103
	20	0.094
	38	0.161
Least significant difference at $P = 0.05$		0.090
Temperature		****z
Height		*
Temperature × height		NS

^zNS, *, ****Nonsignificant or significant at $P = 0.05$ and 0.0001, respectively, by the F-test.

Table 3. Bruise volume for 'Sweet Charlie' strawberries dropped from 38 cm after hydrocooling or forced-air cooling to 1 or 20 °C.

Cooling method	Pulp temp (°C)	Bruise volume ^z (cm ³)	
		Evaluation 1	Evaluation 2
Forced-air	1	0.307	0.427
Forced-air	20	0.167	0.088
Hydrocooling	1	0.116	0.059
Hydrocooling	20	0.238	0.176
Least significant difference at $P = 0.05\%$		0.103	0.118
Cooling method		NS ^y	***y
Temperature		NS	**
Cooling method × temperature		**	****

^zBruise volume evaluated after 24 h at 24 °C (Evaluation 1) or after 7 d at 1 °C (Evaluation 2).

^yNS, **Nonsignificant or significant at $P = 0.01$, respectively, by the F-test.

between the two ripeness stages, probably because of the use of the backstop. This method caused bruising on the opposite side of the fruit as well as at the impact site but was not uniform for measurement.

Conclusions

Strawberries had different responses to compression and impact forces based on pulp temperature. Fruit at low temperature (1 °C) were more resistant to compression, whereas fruit at higher temperature (20 or 24 °C) were more resistant to impacts. Therefore, strawberry bruising caused by compression may be

Table 4. Bruise volume for 'Chandler', 'Sweet Charlie', and 'Oso Grande' strawberries harvested at full-red or three-fourths red stage and cooled to 1 or 24 °C and then subjected to pendulum impact at angles of 45° or 90°.

			Bruise volume (cm ³)		
Pulp temp (°C)	Harvest maturity	Pendulum angle (°)	Cultivar		
			Chandler	Oso Grande	Sweet Charlie
1	Full red	45	0.142	0.069	0.046
		90	0.213	0.048	0.145
	Three-fourth red	45	0.022	0.115	0.008
		90	0.070	0.131	0.133
24	Full red	45	0.054	0.165	0.081
		90	0.163	0.09	0.105
	Three-fourths red	45	0.023	0.077	0.031
		90	0.031	0.134	0.102
Least significant difference at <i>P</i> = 0.05			0.101	0.070	0.091
Harvest maturity			<i>z</i>	NS	NS
Pulp temperature			NS	NS	NS
Pendulum angle			*	NS	
Maturity × temperature			NS	*	NS
Maturity × angle			NS	NS	NS
Temperature × angle			NS	*	*

zNS, *, ****Nonsignificant or significant at $P = 0.05$ and 0.0001, respectively, by the F-test.

minimized by harvesting and transporting early in the day when pulp temperatures are lowest.

These results show there is potential for strawberries to be graded and packed on a packing line; however, impact bruising at transfer points must be minimized. In this scenario, the strawberries could be harvested into field lugs (only two or three layers deep of fruit) and transported to the packing house. It would be more advantageous to use hydro-cooling than forced-air cooling because hydrocooling cools fruit at a much faster rate, and fruit at 1 °C are more resistant to impacts. If the strawberries were immersed in a hydro-cooling flume before grading and packing, a refrigerated packing area would be required to minimize rewarming. However, if forced-air cooling were used, there would be less impact bruising if the strawberries were graded and packed before cooling.

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