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Identification of Deformation Parameters and Fruit Response to Mechanical Damage in Sweet Cherry[1]

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Abstract. **The incidence of surface pitting and bruises in sweet charries (*Prunus avium* L. cv. Van) increased with distance of free fall. Mature fruit developed less surface pitting but developed more flattened bruises than less mature fruit in response to impact forces. Increased impact force applied to fruit resulted in a decrease in titratable acidity after storage. Fruit firmness and bioyield determined after storage increased to a maximum with the height of free fall of 45 cm for the intermediate fruit maturity only. Fruit contact with rough surfaces resulted in a significantly higher incidence of surface pitting than in fruit damaged by smooth surfaces.**

The incidence of surface disorders resulting from mechanical damage poses a serious threat to efficient, mechanized packing and transport of sweet cherries. There is a great impact damage potential inherent in automated cherry packing lines. Many commercial installations have a combined vertical drop of 1 m or more. Individual vertical drops may be as great as 30 cm which may occur when graded fruit are dropped into a bulk corrugated paperboard container for shipment to market.

Cherry surface damage resulting from a single impact may appear as surface pitting (11) or as fruit bruises (2). Pitting appears as a sunken area usually, 0.5-1 cm in diameter, on the surface of the fruit. Microscopical examinations revealed that impact damage had caused cell fracture and collapse of internal cells 8-10 layers deep while the epidermal cells and intermediate cell layers were apparently unaffected (11). Bruises appear as flattened areas on the surface of the fruit and result from permanent cell wall distortion of the epidermal cells and cells 3-4 layers beneath the epidermis (personal observation). O'Brien et al. (10) determined that subthreshold impact forces resulting from vibration during transit could also damage fruit. However, sweet cherries are also subject to compressive forces when transported in 136-kg half-bins or 9.3-kg commercial bulk fruit cartons. No prior evidence was found to relate compression forces to the incidence of surface damage in sweet cherries.

Whittenberger (12) reported that aging of damaged 'Montmorency' cherries resulted in fruit firmer than the non-damaged controls. The firming effect following fruit ddamage was ascribed to strengthening of intercellular "cement" and cell wall structures. LaBelle et al. (6) inferred that the intercellular cement, comprised mainly of pectic materials (4) may indeed be strengthened following tissue damage. Callose formation on cell wall structures may also contribute to the firming effect of cherries following impact damage (3).

The purpose of this study was to define the relationship between the distance of free fall and the incidence of surface disorders in sweet cherries and to investigate the effects of impact damage on fruit firmness in storage at 3 maturities. This study also determined the effect of different belt textures and the relative effects of impact and compressive forces on the incidence of surface disorders on sweet cherries.

Materials and Methods

Drop height study 1977. Sweet cherries were harvested at 3 maturities corresponding to No. 3 (red), 6 (red-mahogany) and 33 (mahogany) fruit color indices (1). The fruits were picked to avoid impact collisions and were uniformly divided among 4 treatments with 4 replications of 150 fruits each. The fruits were cooled immediately after harvest to 0°C and impact damaged by dropping distances of 0, 22.5, 45.0 and 90.0 cm onto a woven fiber belt. The fruits were placed in 38 μm perforated polyethylene liners and replaced in 0° storage for 21 days. One hundred fruits were examined for the incidence of surface disorders using the classifications of Lidster et al. (8). Soluble solids and titratable acidity were determined on the juice of 35 fruits by refractometry and titration with 0.1 N NaOH to endpoint of pH 8.1, respectively. A further sample of 15 fruits was warmed to 21° and texture determined by the method of Lidster et al. (7). The data were analyzed as a 3 maturity × 4 drop height × 4 replication factorial experiment by analysis of variance and by forward stepwise multiple regession using each and all combinations of the potential independent variables: maturity, drop height, and drop height^2.

Drop height study 1978. 'Van' cherries were carefully harvested at No. 6 color maturity and uniformly divided among 2

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series of 4 treatments with 5 replications of 150 fruits each. All fruits were cooled to 0°C and dropped distances of 13, 25, 51 and 102 cm onto either a woven fiber or a smooth neoprene belting material. Care was taken to avoid fruit-to-fruit collisions at the belting surface. All fruits were stored at 0° in polyethylene liners and examined for surface disorders after 16 days. The data were analyzed by analysis of variance and by forward stepwise multiple regression using each and all combinations of the potential independent variables: surface texture, drop height, and drop height^2.

Deformation, loading rate and bruising surface texture study 1978. Van cherries of No. 6 color maturity were carefully harvested and randomly placed to form a composite sample. Subsamples of 35 fruits were removed and divided into an experimental design of 2 bruising surface textures × 2 loading rates × 3 depths of deformation. Individual fruit were deformed using an Instron Model 1122 universal testing machine fitted with two flat plates. The bottom plate was covered with either a piece of woven fiber or smooth, neoprene belting material. The fruit was placed with its suture line parallel to the belting surface. The upper flat plate descended at 10 or 1000 mm/min and forced the cherry against the appropriate belting material at deformations of 2, 4, 8 mm. Fruits were then placed into polyethylene liners in 0°C storage for 10 days and examined for surface disorders. The data were analyzed by analysis of variance and by multiple regression using each and all combinations of the potential independent variables: bruising surface texture, deformation, deformation^2 and loading rate.

Results and Discussion

The height of free fall (impact forces) did not significantly affect the soluble solids levels after 21 days storage (Table 1). However, height of free fall significantly decreased the titratable acidity of the juice after storage with the exception of fruit of No. 6 maturity dropped 22.5 cm. Greater height of drop resulted in more tissue damage as evidenced by increased incidence of surface pitting. Tissue damage was previously found to be positively correlated with respiration rate (9). Accelerated tissue respiration would utilize a greater portion of acid substrate and account for the decreased titratable acidity observed with increased cellular damage (9).

The impact forces and fruit maturity showed a significant interaction effect on fruit firmness and bioyield after storage. Fruit firmness or bioyield at No. 3 or 33 color maturities was not significantly affected by impact forces. Fruit bioyield values were positively correlated with impact forces applied to fruit of No. 6 color maturity. Fruit firmness of No. 6 color maturity fruit reached a maximum when fruit were dropped from 45 cm; however, the values decreased when fruit were dropped 90 cm. The firming effect following fruit damage may be similar to that observed by Whittenberger (12) and LaBelle et al. (6) in 'Montmorency' cherries. Whittenberger (12) ascribed the firming of damage tissues to the strengthening of the cell walls and intercellular cement between cells. LaBelle et al. (6) determined that repeated bruising decreased water soluble pectin and the degree of esterification of pectic substances in the middle lamella which may result in increased fruit firmness. Dekazos and Worley (3) determined that cell walls were fortified with callose deposits following fruit bruising which also may contribute to the firming of fruit tissues. Fruit damage induced by dropping fruit 90 cm, however, may result in excessive disruption of cell walls and intercellular structures which reduced the extent of fruit firming following bruising.

The height of free fall was positively correlated with the incidence of fruit bruises (Tables 2 & 3). Mature fruit developed a greater incidence of bruises than did less mature fruit. Cells of mature fruit are more resistant to rupture, as evidenced by a lower incidence of surface pitting, but the cells

Table 1. Effect of distance of free fall of fruit on soluble solids, titratable acids, firmness and bioyield in 'Van' sweet cherries at 3 maturities, 1977 crop.

Maturity	Height of drop (cm)	Soluble solids (%)		Titratable acidity (mg malic/100 ml)		Bioyield (kg)		Firmness (kg/cm)	
		Calculated	Observed	Calculated	Observed	Calculated	Observed	Calculated	Observed
3[z]	0.0	13.1[y]	13.0	840[x]	868	2.19[w]	2.17	3.55[v]	3.61
3	22.5	13.1	13.2	834	827	2.19	2.20	3.55	3.43
3	45.0	13.1	13.0	817	811	2.19	2.31	3.55	3.64
3	90.0	13.1	13.2	747	725	2.19	2.06	3.55	3.52
6	0.0	15.8	15.3	840	820	1.75	1.73	2.44	2.42
6	22.5	15.8	15.9	834	860	1.81	1.81	3.07	3.14
6	45.0	15.8	15.7	817	807	1.87	1.91	3.43	3.39
6	90.0	15.8	16.0	747	789	2.00	1.98	3.32	3.32
33	0.0	18.1	18.1	840	844	2.05	2.02	3.87	3.87
33	22.5	18.1	18.4	834	809	2.05	2.02	3.87	3.82
33	45.0	18.1	18.0	817	826	2.05	2.12	3.87	3.96
33	90.0	18.1	17.9	747	729	2.05	2.04	3.87	3.84
Analysis of variance	Df								
Maturity (M)	2		***[u]		NS		***		***
Drop height (Dh)	3		NS		***		NS		*
M × Dh	6		NS		NS		**		**

[z]Color comparator qualitative indices of maturity. Color maturity of fruit coded as: Three = 1 (red); Six = 1 (red-mahogany); Thirty-three = 0 (mahogany).

[y]Values fitted from equation: Soluble solids = 18.1 − 4.98 Three − 2.35 Six (R^2 = 0.85, p = 1%).

[x]Values fitted from equation: Titratable acidity = 840 − 0.0115 Height^2 (r^2 = 0.38, p = 1%).

[w]Values fitted from equation: Bioyield = 2.05 + 0.137 Three − 0.298 Six + 0.00270 Six × height (R^2 = 0.50, p = 1%).

[v]Values fitted from equation: Firmness = 3.87 − 0.324 Three − 1.43 Six + 0.0343 Six × height − 0.000273 Six × height^2 (R^2 = 0.70, p = 1%).

[u]Significance levels denoted as: 5% (*), 1% (**), 0.1% (***) or nonsignificant at 5% (NS).

Table 2. Effects of distance of free fall on the incidence of surface disorders of 'Van' sweet cherries at 3 maturities, 1977 crop.

Maturity	Height of drop (cm)	Bruised fruit (%) Calculated	Bruised fruit (%) Observed	Pitted fruit (%) Calculated	Pitted fruit (%) Observed
3[z]	0.0	5.3[y]	0.0	8.4[x]	6.8
3	22.5	12.2	17.9	50.8	51.9
3	45.0	17.5	12.9	76.7	76.0
3	90.0	23.3	23.1	78.5	76.7
6	0.0	5.3	1.5	8.4	10.4
6	22.5	28.7	42.9	35.3	47.5
6	45.0	44.9	34.0	48.1	63.6
6	90.0	55.8	55.8	31.7	42.8
33	0.0	5.3	0.0	8.4	8.1
33	22.5	50.8	60.6	20.5	20.2
33	45.0	77.8	70.5	26.8	27.6
33	90.0	76.6	77.1	21.1	22.3
Analysis of variance	Df				
Maturity (M)	2		***[w]		***
Drop height (Dh)	3		***		***
M x Dh	6		***		***

[z]Color comparator qualitative indices of maturity. Color maturity of fruit coded as: No. 3 (red), Three = 1, Six = 0; No. 6 (red-mahogany) Three = 0, Six = 1; No. 33 (mahogany), Three = 0, Six = 0.

[y]Values fitted from equation: Bruised fruit = 5.28 + 2.43 Height – 2.09 Three x height + 0.0167 Three x height^2 – 1.23 Six x height + 0.0111 Six x height^2 – 0.0182 Height^2 (R^2 = 0.89, p = 1%).

[x]Values fitted from equation: Fruit with pitting = 8.38 + 0.667 Height + 1.59 Three x height – 0.0107 Three x height^2 + 0.839 Six x height – 0.00814 Six x height^2 – 0.005724 Height^2 (R^2 = 0.95, p = 1%).

[w]Significance levels denoted as: 5% (*), 1% (**), 0.1% (***) or nonsignificant at 5% (NS).

Table 3. Effects of height of drop of fruit and bruising surface on disorder incidence in 'Van' sweet cherries, 1978 crop.

Height of drop (cm)	Bruising surface	Bruised fruit (%) Calculated	Bruised fruit (%) Observed	Pitted fruit (%) Calculated	Pitted fruit (%) Observed
13	smooth[z]	10.9[y]	12.0	15.6[x]	17.5
25	smooth	10.9	10.5	24.1	21.5
51	smooth	10.9	11.8	42.7	42.3
102	smooth	10.9	10.3	79.0	79.5
13	rough	23.2	24.0	38.5	37.8
25	rough	22.0	20.8	46.3	48.3
51	rough	19.3	19.5	61.7	60.3
102	rough	14.0	14.0	85.4	85.3
Analysis of variance	Df				
Drop height (Dh)	3		NS[w]		***
Bruising surface (Bs)	1		***		***
Dh x Bs	3		**		**

[z]Bruising surface coded as: Smooth = 0; Rough = 1.

[y]Values fitted from regression equation: Bruised fruit = 0.8 + 0.114 Height (r^2 = 0.68, p = 1%).

[x]Values fitted from regression equation: Pitted fruit = 6.3 + 23.2 Surface + 0.713 Height – 0.00161 Surface x height^2 (R^2 = 0.96, p = 1%).

[w]Significance levels denoted as: 5% (*), 1% (**), 0.1% (***) or nonsignificant at 5% (NS).

permanently distort in response to impact forces to form bruises. The incidence of bruised fruit was not significantly affected by the loading rate or texture of the bruising surface, but were positively correlated to the amount of deformation (Table 4). Fruit bruises apparently result from a permanent cellular distortion without cell rupture (data not shown). The degree of cellular compression therefore is critical in determining whether the cells are to remain permanently distorted.

Greater height of fall which increased impact forces to the fruit generally increased the incidence of surface pitting (Tables 2 & 3). However, in the 1977 study (Table 2) a maximum incidence of surface pitting occurred when fruit were dropped 45 cm. When fruit were dropped 90 cm, the incidence of surfact pitting remained the same in red fruit and decreased in red-mahogany and mahogany colored fruit.

Rough impact surfaces increased the incidence of surface

Table 4. Effects of deformation, loading rate and bruising surface on the incidence of surface disorders in 'Van' sweet cherries, 1978 crop.

Bruising surface	Deformation (mm)	Loading rate (mm/min)	Bruised fruit (%)		Pitted fruit (%)	
			Calculated	Observed	Calculated	Observed
Smooth[z]	2	10	2.4[y]	0.0	0.0[x]	2.2
Smooth	4	10	12.0	7.2	5.6	3.7
Smooth	8	10	50.6	54.3	18.2	20.1
Rough	2	10	2.4	1.5	1.2	2.9
Rough	4	10	12.0	13.6	13.1	4.3
Rough	8	10	50.6	52.9	48.2	43.5
Smooth	2	1000	2.4	2.9	7.4	5.0
Smooth	4	1000	12.0	22.7	16.4	18.6
Smooth	8	1000	50.6	48.6	50.8	50.9
Rough	2	1000	2.4	3.6	9.3	9.7
Rough	4	1000	12.0	11.5	29.4	32.9
Rough	8	1000	50.6	46.6	80.7	72.9
Analysis of variance	Df					
Rate (R)	1			NS[w]		***
Deformation (D)	2			***		***
R x D	2			NS		***
Bruising surface (Bs)	1			NS		***
R x Bs	1			NS		NS
D x Bs	2			NS		***
R x D x Bs	2			NS		NS

[z]Bruising surface coded as: Smooth = 0; Rough = 1.

[y]Values fitted from regression equation: Bruised fruit = 0.800 + 0.803 Deformation^2 (r^2 = 0.92, p = 1%).

[x]Values fitted from regression equation: Pitted fruit = −7.0 + 3.11 Deformation + 0.00411 Deformation x loading rate + 0.468 Deformation^2 x bruising surface (R^2 = 0.93, p = 1%).

[w]Significance levels denoted as: 5% (*), 1% (**), 0.1% (***) or nonsignificant at 5% (NS).

pitting (Tables 3 & 4). Rough surfaces would provide many individual pressure points of impact with a cherry. This condition would be conducive to cell rupture at several points as greatly increased impact pressures would be focused on specific tissues. Fruit contacting a smooth surface would have the energy of impact dissipated more evenly across the fruit surface and would cause less total cell fracture.

Surface pitting was positively correlated to the amount of fruit deformation and the loading rate of the fruit by the flat plate (Table 4). Cherry fruit will exhibit visco-elastic properties when deformed (5). Slow loading rates applied to cherry fruits will allow the cherry matrix to distort and flow without cell rupture when small deformation are applied. However, large deformations of 4 to 8 mm severely compress the parenchyma cells and result in cell wall fracture and subsequent surface pitting to form. Similarly, fruit tissue subjected to very fast loading rates (1000 mm/min) would not be able to flow and distort fast enough in response to the pressure applied. Consequently, very fast loading rates may readily cause cell wall fracture and surface pitting at all deformations studied.

The present data indicated that significant levels of surface pitting may occur when fruit are dropped as little as 13 cm. The magnitude of this drop may be exceeded as many as 4-10 times along a commercial packing line. This suggests that, in crop years of high surface pitting susceptibility, commercial packing lines far exceed the minimum drop required to produce surface pitting. Severe compression of fruit may also result in significant levels of surface pitting and fruit bruises. Compressive forces capable of causing surface disorders may occur in commercial operations during transport of fruit in bulk containers.

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