Measurement of Tomato Fruit Firmness

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Abstract. Flat-plate compression, constant area compression, and puncture tests were examined for their sensitivity in differentiating the firmness of previously chilled (6C, 85% RH, 15 days) and nonchilled mature-green tomato (*Lycopersicon esculentum* Mill cv. Caruso) fruit during 10 days of ripening at 22C. Firmness, as measured by each of the three methods, progressively decreased ($P < 0.001$) with ripening. Previously chilled tomatoes were initially softer ($P < 0.01$) than nonchilled tomatoes, as measured by puncture of whole fruit and constant area compression of pericarp tissue sections, but not by flat-plate compression of whole fruit. Flat-plate compression was therefore found to be a relatively insensitive method by which to measure differences in tomato firmness that are characteristic of slightly chilling-injured fruit.

Chilling injury (CI) is a term used to describe the physiological damage that occurs in many plants and plant products as a result of their exposure to low, but nonfreezing, temperatures (Parkin et al., 1989; Raison and Lyons, 1986). The tomato represents a classic example of a chilling-sensitive fruit. Hobson (1987) classified the chilling response of tomatoes according to extent of damage: slight CI was characterized by loss of fruit firmness and nonuniform coloration; moderate CI by translucent water-soaked patches and/or mottled yellow areas on otherwise red fruit and an uneven surface; severe CI by large, firm, extensive green patches on otherwise red fruit, uneven surface contours due to cell collapse, desiccation, and wrinkling. Symptoms of CI are often apparent only after removal of fruit from chilling temperatures. The loss of firmness and uneven ripening induced by chilling can affect overall tomato quality, whereby major post-harvest losses are incurred (Jackman et al., 1988; Morris, 1982).

Reports of changes in firmness of tomatoes stored at chilling temperatures have been inconsistent (Buescher, 1974; Efiuvwevwe and Thorne, 1988) due, among other things; to differences in the definition of firmness, in methods used to measure firmness, and in the degree to which fruits had been chilled. Firmness of tomatoes has commonly been measured by flat-plate compression (Giovannoni et al., 1989; Tong and Gross, 1989) or by puncture (Adegoroye et al., 1989; Holt, 1970; Olorunda and Tung, 1985) of whole fruit and defined as either the force to rupture or the ratio of force to rupture/deformation.

Firmness values derived from puncture tests reflect the integrity of pericarp tissue (Holt, 1970), where fruit-softening enzymes are primarily localized (Huber, 1983; Tieman and Hand a, 1989). However, firmness values derived from flat-plate compression tests may not be sensitive enough to reveal differences in tomato fruit firmness characteristic of slight CI.

The present experiments were carried out to determine whether flat-plate compression of whole fruit could differentiate between previously chilled and nonchilled tomatoes differing slightly in firmness, compared with puncture of whole fruit and constant area compression of pericarp tissue sections. Two mature-green 'Caruso' tomato fruit at stages 3 and 4 (Kader and Morris, 1976) were harvested at random from each of 50 plants in a local commercial greenhouse. The fruit were surface-sterilized by immersion in 20% (v/v) commercial bleach for 3 min, followed by rinsing in deionized water for 3 min. Fifty nonchilled (control) fruit were allowed to ripen at 22C for 10 days, while 50 fruit were stored at 6C (85% RH) for 15 days, then transferred to 22C for a subsequent 10 days of ripening. Although the effects of aging during chilling cannot be discounted, the chilling treatment was previously shown to induce symptoms of slight CI in 'Caruso' tomatoes, as defined by Hobson (1987), i.e., previously chilled

tomatoes required less force to rupture and developed nonuniform coloration, relative to nonchilled fruit (A.G.M. and D. W. S., unpublished data). Five tomatoes from each of the previously chilled and nonchilled groups were evaluated for firmness at day 0, 2, 5, and 10 of the ripening period using an "M" series materials testing machine (J.J. Lloyd Instruments, Omnitrone, Mississauga, Ont., Canada).

For flat-plate compression tests, whole tomato fruit were placed on a stationary steel plate and aligned from stem end to stylar end, with the stylar end down. A 5-kN load cell was used in conjunction with a 17.8×11.7 -cm upper steel plate to compress tomatoes at a deformation speed of 10 mm·min⁻¹. For constant area compression tests, three 1.5×1.5 -cm pericarp samples were excised from the equatorial region of each tomato fruit, carefully avoiding regions where the columellar tissue joined the pericarp. Thickness of tissue sections generally ranged from 6.5 to 7.5 mm. The excised pericarp sections, with epidermal tissue intact, were placed exocarp down on a steel plate and compressed with a 500-N load cell in conjunction with an 11-mm flat-ended cylindrical probe at a deformation speed of 5 mm·min⁻¹. During puncture tests, whole tomato fruit were placed in a plastic holder to prevent slipping. A 10-N load cell was used with a 1.6-mm flat-ended cylindrical probe at a deformation speed of 5 mm·min⁻¹. Three separate force-deformation profiles were obtained from puncture tests along the equatorial region of each tomato fruit.

The peak or bioyield force (F_m (i.e., force to rupture) and deformation up to the bioyield point (L_m) were obtained from force-deformation profiles for each of the flat-plate compression, puncture, and constant area compression tests (Fig. 1). Firmness values were calculated as the average initial slope of force-deformation curves from zero to the bioyield point (i.e., firmness = F_m/L_m). From force-deformation curves, as those shown in Fig. 1, values for peak or bioyield force, fruit deformation, fracturability, toughness, compliance, and firmness can be derived for whole fruits and/or specific tissues, e.g., epidermis, exocarp, mesocarp (Adegoroye et al., 1989; Holt, 1970). However, fruit firmness, or its reciprocal, compliance, has been described by Olorunda and Tung (1985) as the most "useful" parameter for detecting

Table 1. Analysis of variance of the effects of chilling treatment and ripening time on peak force and firmness of tomatoes as measured by flat-plate compression, constant area compression, and puncture tests.

	Flat-plate compression		Constant area compression		Puncture	
	Peak force	Firmness	Peak force	Firmness	Peak force	Firmness
Chilling treatment (C)	NS	NS	**	**	***	***
Ripening time (T)	***	***	***	***	***	***
C × T	NS	NS	*	NS	NS	***
RMSE ²	91.70	4.91	6.89	2.72	0.56	0.37

²RMSE = root mean square error.

NS,*,**,* Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively. df = 39.

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Fig. 1. Typical force-deformation curves for flat-plate compression (top), constant area compression (center), and puncture (bottom) of individual tomatoes. Curves shown are for previously chilled (A) and nonchilled (B) tomato fruit at day 0 of ripening. F_m = peak or bioyield force; L_m = deformation up to the bioyield point.

changes or differences in softening of tomato fruit. Since peak force itself maybe as powerful as firmness in distinguishing between treatments and is easier to measure, it was also used in analysis of variance (ANOVA) to test for significant effects of chilling and ripening time.

Peak force and firmness of tomatoes were influenced similarly by chilling treatment, ripening period, and their interaction (Table

1). However, firmness values were more sensitive in detecting treatment differences than peak force values, as reflected in their respective root mean square error (RMSE) terms for each of flat-plate compression, constant area compression, and puncture tests (Table 1). Sensitivity, i.e., the ability to detect true differences, increases proportionally as the RMSE decreases (Bender et al., 1982). The greater variability associated with

peak force measurements was reduced or attenuated by taking account of deformation in the calculation of firmness.

The firmness of whole tomatoes and of pericarp tissue progressively decreased ($P < 0.01$) with ripening (Fig. 2). The significant ($P < 0.001$) influence of ripening time on firmness of tomatoes was demonstrated by results of ANOVA (Table 1) for each of the tests investigated. The rate of softening was

Fig. 2. Changes in firmness of previously chilled (●) and nonchilled (○) tomatoes during 10-days of ripening at 22C, as measured by flat-plate compression of whole fruit, constant area compression of 1.5×1.5 -cm pericarp tissue sections with an 11-mm flat-ended cylindrical probe, and puncture of whole fruit with a 1.6-mm flat-ended cylindrical probe. Each point represents the mean of five determinations; bars are half standard errors.

generally greater for the nonchilled than previously chilled tomato fruit (Fig. 2). Results of flat-plate compression tests revealed no significant ($P > 0.05$) differences in firmness of previously chilled and nonchilled tomatoes during the 22C ripening period (note the overlapping standard errors in Fig. 2). This is reflected in a nonsignificant effect of chilling treatment in ANOVA (Table 1). In contrast, puncture and constant area compression tests revealed that the pericarp tissue of mature-green tomatoes softened during or as a consequence of chilling, i.e., previously chilled tomatoes were initially softer ($P < 0.01$) than nonchilled tomatoes (Fig. 2). The greater sensitivity of puncture and constant area compression tests to detect differences in firmness between previously chilled and nonchilled tomato fruit, compared to flat-plate compression tests, is indicated by the significant ($P < 0.01$) influence of chilling treatment on puncture and constant area compression firmness and by the

reduced RMSE values associated with these tests (Table 1).

Results from this investigation demonstrated that, in contrast to puncture and constant area compression tests, slight differences in tomato firmness induced by chilling could not be detected when flat-plate compression tests were carried out. Given the many factors that influence firmness, as measured by flat-plate compression, results obtained therefrom should be viewed with caution to avoid false conclusions. Based on results of this investigation, flat-plate compression tests are not recommended for routine use in measurement of tomato firmness.

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