DELINEATION OF PUNCTURE FORCES FOR EXOCARP AND MESOCARP TISSUES IN CUCUMBER FRUIT[1]

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ABSTRACT

A puncture test was used to differentiate exocarp (skin) and mesocarp tissues of fresh cucumbers for resistance to penetration. Optimum instrumental test conditions were a punch size of 3.15 mm diameter and crosshead speed of 5 cm/min. The force required to penetrate the exocarp of whole fruit was determined and was deemed to represent a composite of the exocarp and the underlying tissue. By placing 7 mm thick, longitudinal slices skin down on a die plate, failure forces representing the mesocarp and exocarp tissues were determined in fruit ranging from 2.5–5.5 cm diameter. Exocarp force measurements were not influenced by slice thicknesses greater than 1 mm. Mesocarp measurements were lower with thicker slices, and required uniformity of thickness to maximize precision. The exocarp was found to represent about 60% of the composite force required to penetrate whole cucumbers, regardless of fruit size. Toughness of both exocarp and mesocarp increased with fruit size. The relative contributions of exocarp to penetration of seven other fruits varied from 58 to 88%.

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INTRODUCTION

Since the introduction of the Fruit Pressure Tester (FPT) by Magness and Taylor (1925), various efforts have been made to distinguish the contribution of the skin and that of the underlying tissue to the force required to penetrate the walls of fruits. Magness and Taylor (1925) showed that the skin of apples complicated the measurements on the firmness of the underlying parenchyma. Their recommendation was to remove the skin in the area where the test was to be conducted.

Bourne (1965) mounted a FPT tip on the Instron Universal Testing Machine (UTM) and penetrated apples with the skin on and the skin off. The penetration force curves with skin on were always higher than those with the skin off. Bourne's conclusion was that the skin added to penetration force, and he supported the recommendation to remove the skin before testing. He also varied the crosshead speed and noted this had little effect upon the penetration force.

Bourne *et al.* (1966) used the Instron (UTM), fitted with a cherry pitter, to determine puncture forces in cherries. He described three peaks produced by this method. The first peak represented the force necessary to penetrate the skin. The second peak was the force necessary to push the pit through the flesh. The third peak was when the dislocated pit ruptured the skin from within. Of special note was his comment on the similarity of the first and third peak heights. However, the first penetration was with a sharp-edged, star-shaped die and the third by an irregular, rounded cherry pit. Thus, similar forces were obtained for penetration of the skin with very dissimilar dies, regardless of orientation, out to in or in to out.

Breene *et al.* (1974) also mounted the 5/16 in. FPT tip on the Instron. They tested two cucumber cultivars, a pickling cultivar (Explorer) and a slicing cultivar (Green F). The cucumbers were tested with skin on and skin off. Cucumber size and Instron crosshead speed were other variables. The "skin off" force values over the commercial size grades 1–4 did not vary for either cultivar. When tested with the skin on, the force for the large size, size 4 Green F cultivar, was higher than the smaller sizes, while force readings were invariant among sizes for the Explorer cultivar.

Jeon and Breene (1973) applied the technique of Instrumental Texture Profile Analysis (TPA) to seven cultivars of cucumbers. The breeding line MSU 6902 G did not fall in the same ranking scheme for skin off as for skin on. They postulated that skin thickness and ratio of mesocarp to endocarp tissue caused the deviation in the trends. The complexity of the cucumber, which involves three tissue types (mesocarp, endocarp, and exocarp) and the varying ratios of these tissues along the fruit length, complicates interpretation of TPA values from slices.

The preparation of machinable and relatively uniform samples for testing by torsion or uniaxial compression, as routinely done for commodities such as potatoes, melons, and apples (Diehl and Hamann 1979), cannot easily be done for cucumbers. It is also difficult to do tension testing on the cucumber skin. Su and Humphries (1972) prepared skin specimens for tension testing to contrast with their work on penetration tests. They made note of the difficulty in sample preparation. One other possible pitfall of tension testing the skin is that the skin will fail at its weakest point. Microscopic cracks or faults that cannot be detected by the naked eye will determine the failure point of the skin specimen (Clevenger and Hamann 1968).

In light of the aforementioned difficulties, the authors chose to further study possible application of a penetration test to differentially evaluate exocarp and mesocarp tissue toughness. A penetration test has been shown previously to allow differential evaluation of mesocarp and endocarp tissue types in cucumbers (Thompson *et al.* 1982). The objective of this paper is to describe a simple and reproducible method for segregating the skin's resistance to penetration from that of the supporting underlying tissues. Sample preparation is quick; therefore, a sufficient number of tests can be conducted rapidly. Although cucumbers represent the model of choice for the bulk of this work, a brief survey over seven other commodities also was conducted.

MATERIALS AND METHODS

The Instron UTM Model 1122 was set up as described by Thompson *et al.* (1982), with the exception that a 490 N force transducer was used. This cell had sufficient capacity for any of the tests performed. A home-style, manually operated food slicer with a rotary blade was modified so that the thickness of the slices was uniform and could be controlled to 0.1 mm of the desired setting.

All cucumbers were fresh, free from disease and injury, and were uniform in shape. Tests were conducted within 24 h of harvesting. Size 3B (4.44–5.08 cm diameter) fruit were used for most of the work, but size 2 (2.54–3.81 cm diameter) and size 4 (5.08–5.51 cm diameter) fruit were also tested. Unless otherwise noted, 15 cucumbers represented the sample size for penetration tests of all treatment comparisons. Two cultivars were evaluated, 'Chipper' and 'Calypso'.

The cucumbers were cut into thirds, cross-sectionally, representing the stem, middle, and blossom sections (Thompson *et al.* 1982), and then each section was sliced longitudinally along the lobes (raised portions) using the modified food slicer. Slice thickness from 1 to 9 mm was evaluated in preliminary tests. Unless noted otherwise, 7 mm thick, longitudinal slices from the middle section of size 3B cucumbers were used. For one experiment, the cucumbers were punched in the middle of the three sections along one lobe before being sectioned and sliced. Otherwise, punches were made on the longitudinal slices with the skin up or down on the die assembly, as illustrated in Fig. 1. Slices were positioned carefully under

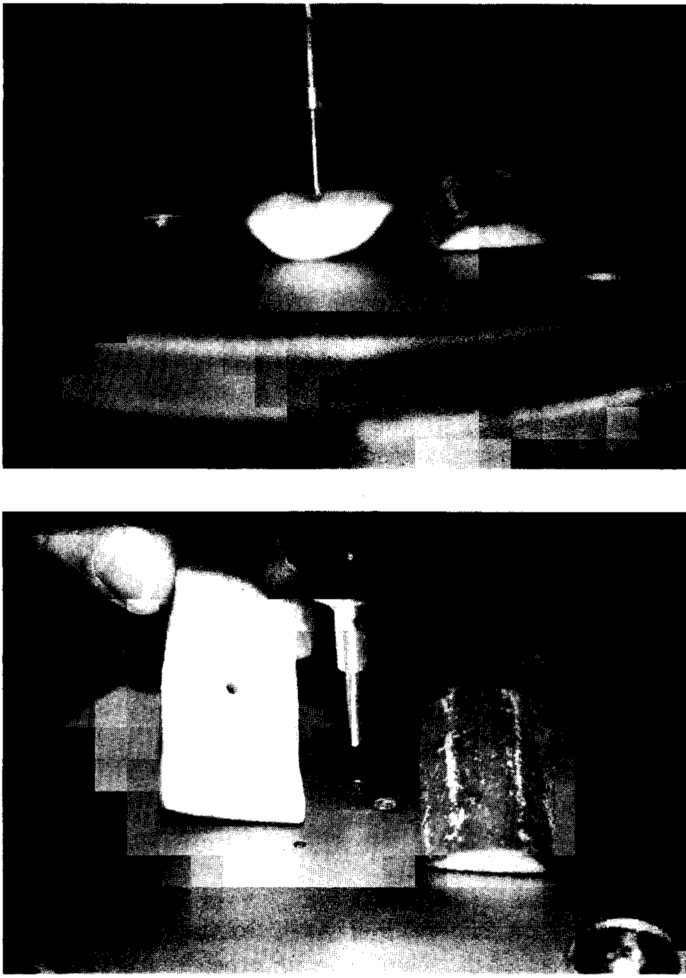

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FIG. 1. CLOSEUP OF PROBE AND DIE PLATE WITH SPECIMEN FOR MEASURING FORCE REQUIRED TO PENETRATE EXOCARP AND MESOCARP TISSUES OF CUCUMBER FRUIT

Cucumber slices were placed on an adjustable milling table mounted on an instron UTM, model 1122. (A) Cucumber slice placed skin down for measurement of first mesocarp, then exocarp tissue firmness. (B) Cucumber slice after being punched. The punch protruded 0.5 mm into the die.

the punch to insure contact at the approximate center. In the "skin down" position, the slice was held lightly between two fingers until the punch made contact perpendicular to the surface, and then the grip was quickly released.

Duplicate specimens of avocado, Bartlett pears, green Bell peppers, slicing cucumbers, McIntosh apples, eggplant, and zucchini squash were purchased at a supermarket. Slices (7 mm thick) were removed from the regions of greatest circumference from all but the peppers. The slices from the green Bell peppers were approximately 2 cm square, middle region, with no attempt at adjusting slice thickness, since the pepper squares were less than 7 mm thick. Testing conditions were identical to those established for cucumbers. Data summarized for these commodities represent means for 16 punches, obtained by punching 2 specimens 8 times each.

The Instron UTM crosshead speed was varied from 2 to 20 cm/min and punch diameter from 2.00–6.35 mm. Die hold diameters were 0.051 mm greater than the corresponding punches. Chart speed was set at either 20 or 50 cm/min. The 3.15 mm diameter punch with 5 and 20 cm/min crosshead and chart speeds, respectively, were the standard settings, unless specified otherwise.

A simple, one-way Analysis of Variance and/or linear regression was used to study effects of punch size, crosshead speed and slice thickness on puncture forces. A replicated, split-plot design was used for studying the effects of cucumber size and section on puncture forces.

RESULTS AND DISCUSSION

Penetration Force Curve Interpretation

An example of the force distance curves produced by punching 7 mm thick, longitudinal slices from 'Calypso' cucumbers is shown in Fig. 2. The first inflection point, skin down position, whether it was a sharp spike or a round shoulder (Fig. 2), represented the force necessary for initial failure of the mesocarp. The maximum peak, in the skin down position, typically occurred when the punch was within 1 mm of the skin and represented the exocarp peak. Subsequent peaks frequently were produced by friction as the punch traveled within the die (see e.g., Fig. 2). Figure 2 also illustrates the force distance curve produced by punching the slice in the skin up position. The maximum "skin up" peak height is referred to as the "composite" peak and represents the force necessary to penetrate the exocarp when supported by the underlying tissue. Composite peaks were determined for longitudinal slices as well as for the whole fruit.

In preliminary tests with fresh fruit of the Calypso cultivar (sizes 2, 3, and 4), probe travel necessary to attain the force peaks illustrated in Fig. 2 was determined. For the mesocarp peak (skin down), the probe travelled 2.0–2.4 mm after initial contact with the sample before maximum peak force was obtained, depending upon fruit size. For the exocarp peak (skin down), the probe travelled

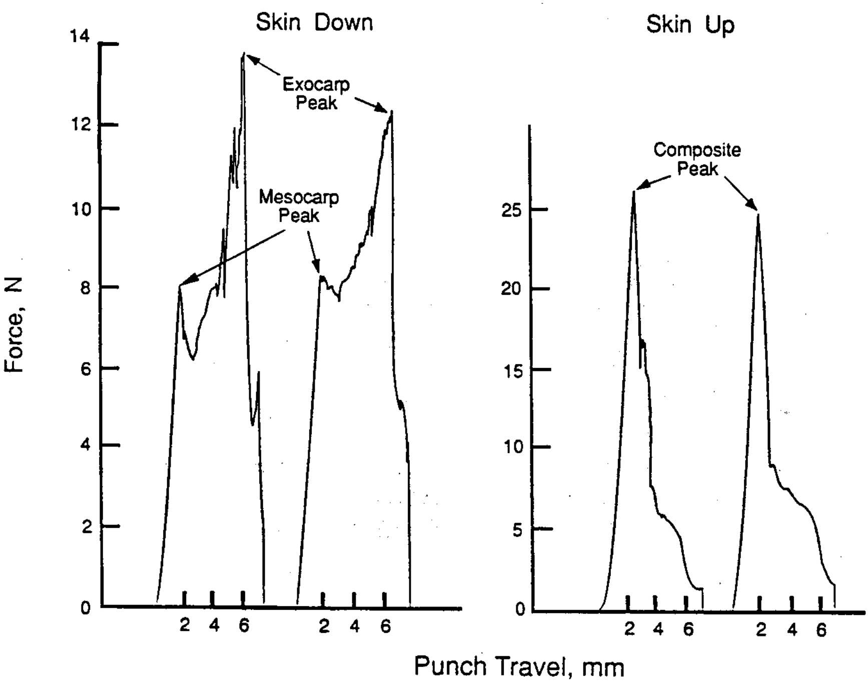

FIG. 2. EXAMPLES OF FORCE DISTANCE CURVES PRODUCED BY PUNCHING 'CALYPSO', SIZE 3B CUCUMBERS
Samples, 7 mm thick, from the midsection were punched.

about 6 mm into the flesh before maximum peak force was obtained, or about 1 mm before reaching the die. The peak representing exocarp failure occurred when the skin tissue gave first evidence of rupture, as observed by visual examination upon penetration of the mesocarp tissue to various depths.

Crosshead Speed

The crosshead speed was tested at four different settings, 2, 5, 10, and 20 cm/min on size 3B 'Calypso' cucumbers, middle section, 7 mm thick slices. Mesocarp peak force readings did not vary statistically ($P \leqslant 0.05$;) by linear regression or analysis of variance. The exocarp peak force readings at the 2 cm/min crosshead speed were significantly less ($P \leqslant 0.05$; ANOVA by Duncan's New Multiple Range Test) than values obtained at the higher speeds, but from 5–20 cm/min the values were statistically invariant. We chose the 5 cm/min crosshead speed for subsequent testing. This speed is slow enough to allow the development of the peaks on the force distance curves with little or insignificant recorder lag. It was also fast enough that a considerable number of tests could be conducted in a reasonable period.

Punch Size

A series of four punch diameters (2.00, 3.15, 4.75, and 6.35 mm) was tested using 7 mm thick, longitudinal slices from the center section of size 3B 'Calypso' cucumbers. The mesocarp, exocarp, and composite forces all responded in a linear manner over the range of punch sizes (Fig. 3). Linear regressions with correlations ranging from 0.96 to 0.98 indicated good fits to a linear model. When the regressions were computed using means rather than individual readings, all correlations were greater than 0.99. The skin, being thin (approximately 50 μm, Fig. 4), does not have an appreciable volume of material underneath the punch to compress, therefore, the linear relationship between penetration and punch diameter is consistent with the assumption that resistance to shear is primarily being measured.

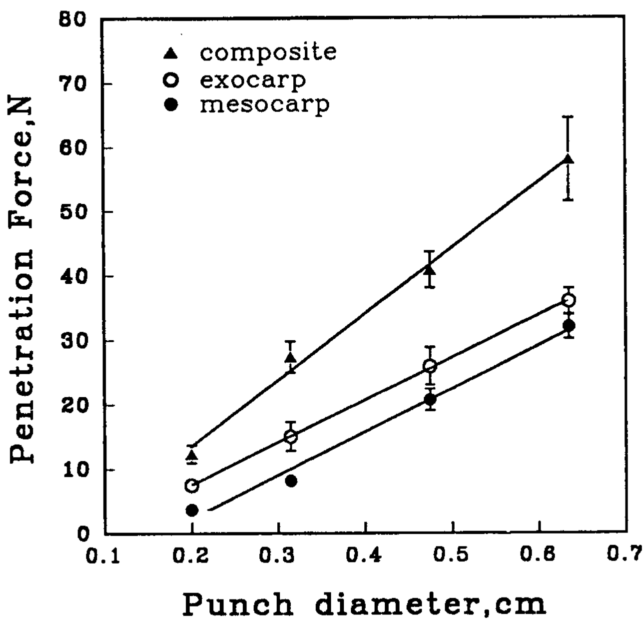

FIG. 3. EFFECT OF PUNCH DIAMETER ON PENETRATION FORCE OF 'CALYPSO', SIZE 3B CUCUMBERS
Slices, 7 mm thick, were placed skin down.

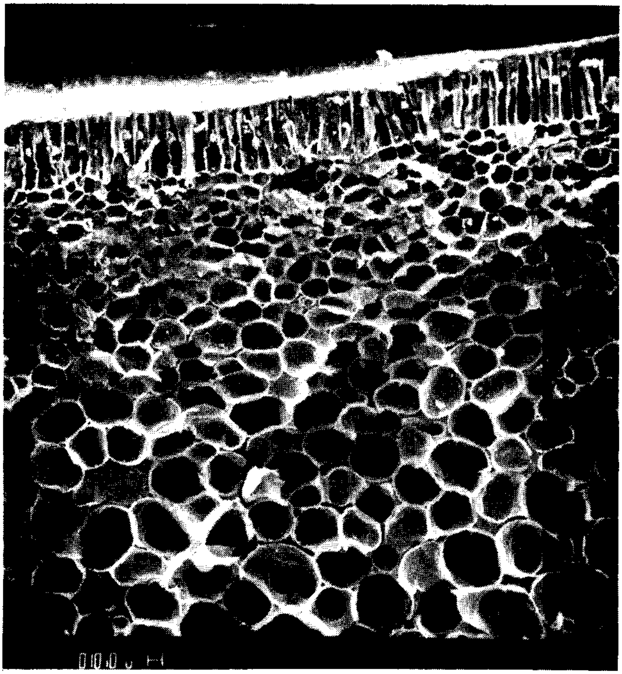

FIG. 4. SCANNING ELECTRON MICROGRAPH OF A CROSS-SECTION OF 'CHIPPER' CUCUMBER FRUIT
Note that the parenchymatous cells increase in size at greater distances from the epidermis (From Smith 1978).

The 3.15 mm diameter probe was selected as the punch size for all further tests. It is small enough to be utilized on the smaller fruit, and large enough to yield easily interpreted force distance curves.

Slice Thickness

The middle sections of size 3B 'Calypso' and 'Chipper' cucumbers were longitudinally sliced in 2 mm thick increments from 1 to 9 mm (± 0.1 mm). The slices were then tested in the "skin down" position; 15 tests were conducted for each thickness. For 1 and 3 mm thicknesses, there was no discernible mesocarp peak force, just one sharp peak on the force distance curve. As the slice thickness increased, the inflection point, previously defined as the mesocarp peak force, was produced along with the exocarp peak force. The exocarp peak force remained invariant over the thickness range; whereas the mesocarp peak force decreased with increasing slice thickness for 'Calypso' fruit (Fig. 5). 'Chipper'

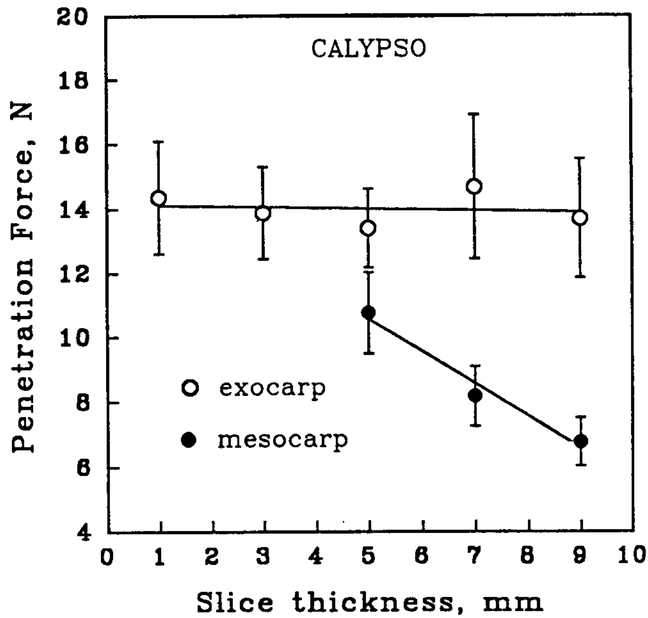

FIG. 5. EFFECT OF SLICE THICKNESS ON PENETRATION FORCE OF EXOCARP AND MESOCARP TISSUES OF 'CALYPSO', SIZE 3B CUCUMBERS

fruit behaved similarly. If this test segregates the skin from the underlying tissues, the data portray what we would predict. The thicker the slice, the closer the sliced plane lies to the endocarp. It has been established that resistance to penetration for mesocarp tissue increases with separation from the endocarp in cross-sectional slices (Thompson *et al.* 1982). The slice thickness would have no effect on the exocarp reading as long as none of the exocarp is removed from the thinner slices. Therefore, the exocarp penetration value should not change over slice thickness.

For the Calypso cultivar, the distance from probe contact at the slice surface to the exocarp peak was measured on the force distance curves. The penetration depths for 1, 3, 5, 7, and 9 mm thick slices were 0.99, 2.19, 4.66, 6.72, and 8.54 mm, respectively, averaged over the 15 tests per thickness setting. We conclude, due to the invariance of the exocarp peak values over the thickness range tested and the closeness of the penetration depth where the exocarp peak was observed to the theoretical thickness setting, that this is a reliable measure of the exocarp resistance to penetration.

Cell size is relatively larger at greater distances from the exocarp (Fig. 4), which probably accounts for lesser mesocarp readings than were observed for progressively thinner slices (Fig. 5). This observation emphasizes the need for the punch to initiate contact near the same relative location between exocarp and endocarp tissues, if the mesocarp value is of interest. In that case, special care must be taken in slicing the cucumber in a manner to assure that the desired location for initial punch contact is achieved.

Distinction of Penetration Forces for Tissue Types

Penetration force curves of cucumber slices, skin down (Fig. 2), suggested that the resistance of mesocarp and exocarp tissues could be determined differentially. The fact that the peak force attributed to the exocarp remained constant with slices 3 mm or greater in thickness (Fig. 5) seems to justify this conclusion. Thus, the relative merits of punching cucumbers from the exterior (penetration from outer to inner flesh) versus from the interior (penetration from inner to outer flesh) was considered. Penetration forces were greater when cucumbers were punched from the exterior (both whole and slices) than from the interior (Table 1). However, it was unclear what tissues the exterior punch represented.

Since exterior punch forces greatly exceed those attributed to the exocarp (Table 1), it was concluded that the exterior punch force is a composite of the exocarp and the underlying tissue. The relative contribution of the exocarp to puncture forces obtained from external punches was calculated from the relationship: exocarp/composite × 100 (Table 1). Thus, the exocarp of cucumbers accounted for 56–64% of the force required to puncture the fruit with an external punch.

The mesocarp peak force consistently was discernible on the force distance curves (Fig. 2) for the size 3 and 4 cucumbers with a full-scale setting of the force transducer of 19.6 N. On the smaller size 2 cucumbers, there was an occasional failure of the method to clearly define the mesocarp peak force. Of 15 tests made for size 2 cucumbers, distinct mesocarp peaks for blossom, middle, and stem sections existed 73, 86, and 86% of the time respectively. The 7 mm thick slice on some of the smaller size 2 cucumbers results in the punch initiating contact at greater relative distance from exocarp tissue. Since mesocarp tissue was shown to be progressively softer at greater distances from the exocarp (Fig. 5), this could account for the occasional failure of the force distance curve to clearly differentiate the inflection point for smaller fruit. Herein, failure to observe a mesocarp peak force was treated as a missing value for statistical analysis. Alternatively, the full-scale force setting of the instrument can be reduced and the sample can be repositioned and repunched.

Reasonable care was taken to assure uniformity of cucumber size and longitudinal slice thickness in the current study. However, generally higher coefficients of variation were observed for mesocarp than for exocarp tissue or for composite readings. In an earlier study (Thompson *et al.* 1982), mesocarp firm-

TABLE 1.
PENETRATION FORCES (N) OF FRESH CUCUMBERS WITH THE DIRECTION OF PENETRATION BEING FROM INNER TO OUTER OR FROM OUTER TO INNER TISSUES[1]

Cucumber		Direction of Penetration				
		Inner to Outer[2] (Skin Down)		Outer to Inner (Composite) (Skin Up)		
Section	Size	Mesocarp	Exocarp	Slice[3]	Whole[3]	(Exocarp/Composite)[4] X 100
Blossom end	2	7.4	12.5	18.7	20.2	62
	3	7.4	14.5	19.9	23.2	63
	4	9.0	17.6	29.4	28.8	62
Middle	2	7.6	12.5	19.1	19.9	64
	3	7.8	14.6	20.2	23.7	62
	4	9.0	17.2	29.1	30.0	58
Stem	2	7.8	12.8	19.5	23.3	56
	3	8.6	14.9	21.0	25.5	59
	4	9.2	17.2	29.9	28.6	60

[1]Size 3B, Chipper cv. cucumbers were used. Penetration forces are means of punches from 15 cucumbers, 2 punches per fruit. Coefficients of variation for the above measurements were: mesocarp, 7.4; exocarp, 10.3; slice, 9.3; and whole, 9.5%.

[2]Penetration forces of 7 mm thick longitudinal slices of cucumbers.

[3]The whole cucumbers were tested only on one lobe; the longitudinal slices were prepared and tested on the other two lobes.

[4]The composite date for whole cucumbers were used for these calculations.

ness was measured by positioning the punch at the approximate mid-point within the mesocarp of cross-sectional slices. While it may be relatively easy to orient a cross-sectional slice for mesocarp firmness, exocarp resistance cannot be established with the same puncture as it can with the longitudinal slice method described herein.

Cucumber Variables: Size and Section

Penetration forces trended higher for larger fruit and for stem end of the fruit for all measurements (Table 1). Analysis of variance revealed highly significant ($P \leqslant 0.01$) effects among sizes of fruit and among fruit of a given size (Table 2).

Mesocarp firmness was greater toward the stem end of the fruit ($P \leqslant 0.01$), but no statistically significant differences existed among sections for exocarp or composite measurements (Tables 1 and 2). Previous work also indicated mesocarp firmness to be greater near the stem end (Thompson *et al.* 1982). The failure to observe significant variations in exocarp resistance among sections was surprising since the thickness of skin has been shown to vary by section for Chipper cultivar, size 3 cucumber (62.1, 50.6, and 42.6 μm for the stem, middle, and blossom end sections, respectively; Smith 1978).

By Instrumental TPA, greater variance among slices within the same cucumber existed than between cucumber fruit of the same cultivar (Breene *et al.* 1972). This punch test (Table 2) and earlier data (Thompson *et al.* 1982) indicated fruit to fruit variability to be much greater than the within fruit variability. One advantage of the punch test lies in its utility for isolating individual tissue types, in contrast to the Instrumental TPA, which does not.

The punch test was extended to a second cucumber cultivar, Calypso, as a comparison to the Chipper cultivar discussed above (Table 3). Penetration forces for the two cultivars were similar. The exocarp of both cultivars became significantly tougher with increasing size. The exocarp was slightly tougher ($P \leqslant 0.05$) at the stem end of the Calypso cutivar, but otherwise no differences in exocarp toughness among sections of either cultivar existed. Mesocarp firmness was greater for size 4 than for size 2 and 3 fruit of both cultivars ($P \leqslant 0.05$), and mesocarp firmness trended higher toward the stem end of both cultivars. It is possible that the punch test for various tissue types would be useful in cucumber breeding studies. Sneed and Bowers (1970) used an external punch of cucumbers to predict brine-stock quality. A test for differential evaluation of tissue types might have proved more informative.

Applicability of the Test to Other Commodities

A brief survey of various items of produce was undertaken to obtain an impression of applicability of the punch test for delineating puncture forces for

TABLE 2.

ANALYSIS OF VARIANCE FOR PENETRATION OF CUCUMBERS, WHOLE AND THEN SECTIONED LONGITUDINALLY SLICED

Source	Mesocarp			Exocarp			Composite			Whole Cucumbers		
	df	MS	F-ratio	df	MS	F-ratio	df	MS	F-ratio	df	MS	F-ratio
Size	2	29.28	9.87**	2	525.58	45.37**	2	2881.72	118.66**	2	736.66	58.39**
Cucumbers (Size; Error A)	41	2.97	7.99**	42	11.58	4.92**	42	24.29	5.30**	42	12.62	2.29*
Section	2	4.61	12.41**	2	0.74	0.313	2	15.50	3.38	2	35.83	6.50**
Size*Section	4	2.41	0.86	4	1.83	0.777	4	1.31	0.28	4	23.52	4.27**
Section*Cucumbers (Size)	82	0.73	0.13	84	2.23	0.95	84	5.19	1.13	84	5.51	
Lobe (Size Section Cucumbers)	122	2.8		135	2.35		135	4.58				

TABLE 3.

COMPARISON OF PENETRATION FORCES IN LONGITUDINAL SLICES FROM CHIPPER AND CALYPSO CV. CUCUMBERS[1]

	Cucumber Size			Cucumber Section		
Cultivar	2	3	4	Stem	Middle	Blossom
<u>Chipper</u>						
Mesocarp	7.6^{b}	7.9^{b}	9.1^{a}	8.5^{a}	8.2^{b}	8.0^{c}
Exocarp	12.5^{c}	14.7^{b}	17.4^{a}	15.0^{a}	14.8^{a}	15.0^{a}
Composite	19.1^{b}	20.4^{b}	29.5^{a}	23.5^{a}	22.8^{b}	22.7^{b}
<u>Calypso</u>						
Mesocarp	7.6^{b}	7.9^{b}	8.9^{a}	8.5^{a}	8.1^{b}	7.8^{b}
Exocarp	12.6^{c}	14.9^{b}	18.4^{a}	15.8^{a}	15.1^{b}	14.9^{b}
Composite	19.0^{c}	20.7^{b}	30.5^{a}	23.9^{a}	23.5^{ab}	22.9^{b}

[1]Numbers with different superscript letters within rows by size or section differ significantly ($P \leq 0.05$) by LSD.

mesocarp and exocarp tissues. Distinct puncture forces for mesocarp and exocarp tissues were obtained with avocado (67), Bartlett pear (77), green Bell pepper (58), slicing-type cucumber (60), McIntosh apple (77), eggplant (64), and zucchini squash (88). Numbers in parentheses represent the percent contribution of the exocarp (as determined with inner to outer punch) to the composite punch force (as determined with outer to inner punch) for each commodity. We have had more difficulty in obtaining consistent, distinct force readings to represent both mesocarp and exocarp tissues of cherry peppers. This was particularly true with peppers that had been brined. We attributed this lack of distinction of tissue type in cherry peppers to the relatively thin flesh of this commodity. Thus, applicability of the test reported herein for delineating exocarp and mesocarp firmness must be validated for each commodity of interest.

CONCLUSIONS

Traditional methods for measuring firmness of cucumbers involve an external punch of the whole fruit. This results in a composite force measurement, with no information on the relative contributions of exocarp and underlying tissues to the measurement. Puncture forces for mesocarp and exocarp tissues of pickling cucumbers can be determined by the punch and die method described herein, where the direction of force is from inner to outer tissues of the fruit.

Exocarp puncture forces were invariant for longitudinal cucumber slices 1 mm or greater in thickness, but mesocarp forces were influenced by slice thickness due apparently to increase in mesocarp cell size at greater distances from the exocarp. Thus, attempts to determine the contribution of the exocarp of cucumbers to external puncture force by making measurements before and after skin removal are subject to errors created by skin removal. The punch method may be applicable to determining puncture forces of exocarp and mesocarp of other items of produce, but applicability for each item must be experimentally determined.

ACKNOWLEDGMENT

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