Physical Properties of Oranges in Response to Applied Gripping Forces for Robotic Harvesting

S. J. Flood, T. F. Burks, A. A. Teixeira

Abstract. *In order to understand more fully how an orange would respond to a robotic harvester, studies were conducted that bridged the gap between previously conducted puncture studies and previously conducted burst studies. Field run (unwashed, unwaxed) Valencia oranges (*Citrus sinesis *cv. Valencia) were tested on March 30, May 15, and June 16, 2004, using an Instron universal testing machine. The punch sizes used for the puncture tests were 0.323, 0.632, 0.964, 1.27, 1.90, and 2.540 cm. Burst tests were also performed with the whole fruit under flat plate compression. As expected, the force required to puncture or burst a fruit is directly related to the contact area. This is a function of two variables: the punch diameter used, and the radius of curvature of the fruit. Based on the results of these tests, a model was developed that relates punch diameter to puncture force. It was also noted that as the punch diameter size increased, the punch diameter term in the model approached zero. This left the puncture force term as a function of the radius of curvature only. This correlated well with physical observations in that punch diameters beyond 2.540 cm approached the behavior of a flat plate, where puncture force was no longer a function of the punch diameter but solely of the fruit properties. Recommendations were then made as to the design of a grasping robotic citrus harvester end effector.*

Keywords. *Citrus, End effector, Fruit, Puncture, Mechanical properties, Robots.*

As a result of rising costs and a shrinking labor force, it is increasingly desirable to harvest citrus fruit robotically. Currently, researchers at the University of Florida are working to develop such a harvester. It is important to determine the safe handling limits for citrus fruit during harvest. Specifically, this article examines the result of compressive force testing on oranges using both punch tests and burst tests.

Several studies have been published that examine the resistance of the rind to puncture. Ahmed et al. (1973) examined the forces required to rupture peel oil glands and to puncture the fruit rind. This was done for field run (unwashed, unwaxed), commercially processed, and irradiated fruit. It was observed that both commercial processing and irradiation had a detrimental effect on the structural strength, although the differences between commercially processed and field run fruit were not statistically significant. Twenty fruit were used per replicate, with three replicates performed. The punch diameters used were: 0.258, 0.264, and 0.051 cm.

Churchill et al. (1980) examined the forces that fruit might experience during mechanical harvesting. Both puncture and burst tests were performed. The influence of variety, harvest date, harvest time, and abscission chemical application were examined. The sample size was 20, with two to four replications per year. It was observed that there were varietal differences, with the Pineapple (*Citrus sinesis* cv. Pineapple) variety having a greater structural strength than the Hamlin (*Citrus sinesis* cv. Hamlin) variety. The harvest date and time did not have statistically significant differences, although the Pineapple variety required increasing puncture and burst forces in later harvest dates. The punch diameter used was 0.64 cm.

Coggins and Lewis (1965) examined the change of puncture forces over time as well as the effect of gibberellic acid treatments. A comparison of compressive forces versus shearing forces was also done. They observed that for two different penetration sizes with area ratios of 2 and circumferential ratios of 1.41, a puncture force ratio (larger size puncture force over smaller size puncture force) of 1.56 was required, indicating that both compressive and shearing forces were present. However, shearing forces were more dominant. The gibberellic acid treatment, if applied early enough in the growth process, had the effect of slowing the rate of decrease in puncture resistance. McDonald et al. (1987) found supporting results. They observed that the puncture resistance decreased over time. Twenty fruit were used, with ten punctures per fruit. The punch diameters used were 0.10 and 0.1438 cm.

Juste et al. (1988) examined citrus fruit properties as they pertained to fresh fruit robotic harvesting. In each puncture test, 50 fruit were used with a punch diameter of 0.047 cm. These tests were performed at four different times during the growth season. They found that puncture resistance had a decreasing trend, except for the beginning and end of the growth seasons, where puncture resistance might increase depending on the variety.

Miller (1986) examined dimensional properties and puncture resistance, along with modulus of elasticity and

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average stress. In each test, 40 fruit were measured for their dimensional properties, and 20 fruit were measured for puncture resistance. Results from that work suggested that maximum compressive strength was related to the peel strength, whereas the deformation was related to internal structural integrity. The punch diameter used was 0.64 cm.

Other punch diameters previously used were: 0.5 and 1 cm (Chuma et al., 1978), 0.10 cm (Coggins, 1969), 0.05 cm (Fidelibus et al., 2002a), 0.1 cm (McDonald et al., 1987), and 0.320 cm (Turrell et al., 1964). The aforementioned studies have an equivalent punch diameter range of 0.05 to 1 cm. Separate burst tests were also performed by Ahmed et al. (1973), Chuma et al. (1978), Churchill et al. (1980), Fidelibus et al. (2002b), Miller (1986), and Sarig and Orlovsky (1974). These tests were conducted in the same manner as the punch tests, except the punch was replaced with a flat plate.

The studies cited above were conducted on a wide range of citrus varieties, which included: Valencia (*Citrus sinesis* cv. Valencia), Hamlin, Pineapple, Satsuma (*Citrus reticulata* cv. Satsuma), Washington Navel (*Citrus sinesis* cv. Washington Navel), Shamouti (*Citrus sinesis* cv. Shamouti), Salustiana (*Citrus sinesis* cv. Salustiana), and Temple (*Citrus sinesis* cv. Temple) oranges; Duncan (*Citrus paradisi* cv. Duncan) and Marsh (*Citrus paradisi* cv. Marsh) grapefruit; Bearss (*Citrus limon* cv. Bearss) and Eureka (*Citrus limon* cv. Eureka) lemons; Persian limes (*Citrus latifolia* cv. Persian); and Dancy tangerines (*Citrus reticulata* cv. Dancy). The variety studied most often was the Valencia orange.

These studies used punch sizes that were well below the size that might be experienced by a fruit under robotic harvesting. The largest punch size studied was 1 cm. It was necessary to understand more fully how a fruit would respond to a robotic harvester by conducting studies that bridge the gap between the previously conducted puncture studies and the previously conducted burst studies. Therefore the purpose of this study was to develop a relationship between punch size and puncture force that would be applicable to the development of a robotic harvester.

Objectives

Specific objectives of the work reported in this article were to:

- Bridge the gap in testing of the punch sizes previously used to the burst tests.
- Quantify the relationship between punch size and puncture force.
- Make recommendations on the impact of the design of a grasping robotic citrus harvester end effector.

Materials and Methods

All fruit were of the Valencia variety and were obtained from the University of Florida's Citrus Research and Education Center in Lake Alfred, Florida. The fruit were freshly harvested, and thus they had not been washed, waxed, or sized. After harvest, the fruit were placed in an environmental chamber that was held at 4°C and 78% relative humidity through the use of an automatic controller. These conditions were as close to the USDA-recommended storage conditions as the chamber permitted. Ritenour (2004) lists the USDA-recommended storage conditions as 0°C to 1°C and 85% to 90% relative humidity. The fruit remained in the chamber until they were tested, the total duration of which was one week or less, except in one instance where fruit remained in the chamber for three weeks. This occurred on the first test date with the parallel plate burst test. Ritenour (2004) states that fruit may be stored up to 12 weeks at the specified optimum storage conditions.

Samples from the three different dates for the puncture tests were determined not to be statistically different at the 95% significance level from analysis of variance (PROC GLM; SAS, 2004). However, the burst test samples were statistically different at the 95% significance level, with the burst values from the second date statistically lower than those from the other two dates. Further explanation of this can be found in the Results and Discussion section.

Three sets of tests were run: the first began on 30 March, the second on 15 May, and the third on 16 June 2004. This was done not only to provide several replications of the experiments, but also to examine the change in puncture force over the growing season. The major, minor, and intermediate diameters were taken, as illustrated in figure 1, where *a* is the largest diameter, *c* is the smallest diameter perpendicular to *a*, and *b* is the intermediate diameter perpendicular to both *a* and *c*. The radius of curvature was measured according to the procedure set forth in ASAE Standard S368.4 (*ASAE Standards*, 2000). The mass was recorded using a balance with 0.01 g resolution. The sample size for each punch size was approximately 30 fruit. The sample size chosen was based on the sample size range of 20 to 50 fruit used in the previously cited studies. In one case of the puncture test and one case of the burst test, the sample size was 29 fruit due to data corruption. In another burst test, only 25 fruit were used due to a lack of fruit.

Puncture and burst tests were carried out using an Instron universal testing machine (model 5566) with a 10 kN load cell on the crosshead, following the procedure set forth in ASAE Standard S368.4 (*ASAE Standards*, 2000). The setups for burst and punch testing are shown in figures 2 and 3, respectively. The machine was set at 1.9 cm/min crosshead speed and 0.04 N or 0.03 cm capture interval. Punch diameters were 0.323, 0.632, 0.964, 1.27, 1.90, and 2.540 cm. These punch diameters were selected to expand the range of punches previously used, to more closely represent the surface area that might be encountered in robotic fingers. Burst tests were conducted using a 10.16 cm diameter plate. The fruit were supported with an aluminum die, which had a radius of curvature of 4.45 cm for the punch tests and one set of burst tests. For the other set of burst tests, the fruit were deformed using two parallel plates. The burst test with the die

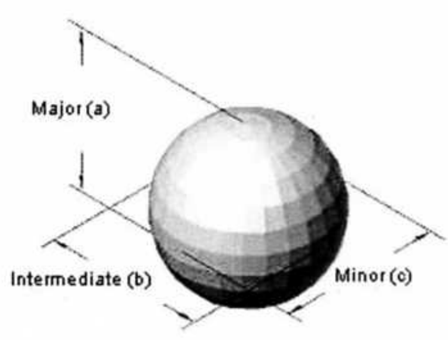

Figure 1. Illustration of characteristic diameters taken of fruit.

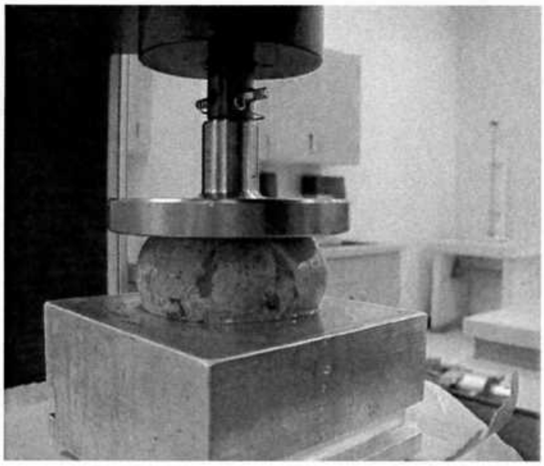

Figure 2. Burst test conducted with fruit-holding die.

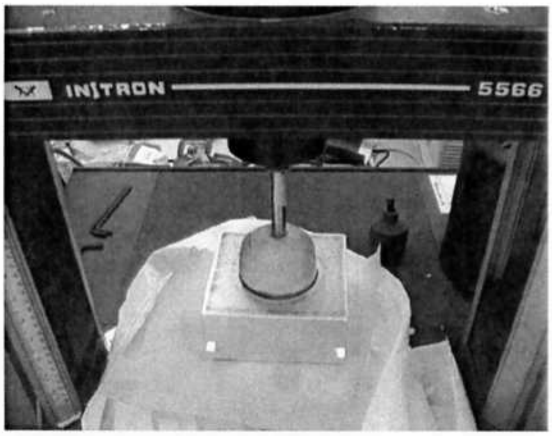

Figure 3. Punch test conducted with the 1.27 cm diameter punch.

was conducted in order to compare the results of the test directly with the results of the punch tests. The burst test with the parallel plates was conducted according to ASAE Standard S368.4 (*ASAE Standards*, 2000).

The fruit were oriented with the fruit stem parallel to the plate in order to mimic the actions of the proposed harvester. They were loaded until failure, which was defined as the point at which the peel was compromised, either through puncture or bursting. This was visually determined. Once the peel had been compromised, the test data were saved for later determination of the exact point at which the peel was punctured through the use of the force deformation curve.

Once the data were acquired, Matlab (2004) was used to reduce the data collected from a single test to just the puncture force from all of the data points taken by the Instron, as well as to graphically analyze the testing results. Microsoft Excel (2003) was then used to graphically analyze how all of the different tested fruit compared to each other and to

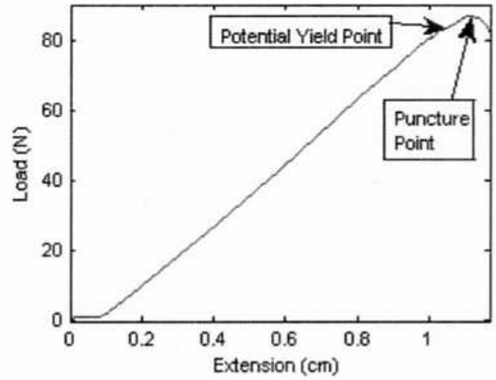

Figure 4. Sample force vs. deformation curve from the 16 June set of tests, using the 1.27 cm diameter punch.

determine potential trends and correlations. The results were then analyzed statistically at the 95% significance level using SAS (2004) to determine correlations and develop statistical models.

Results and Discussion

A summary of the dimensional data for the fruit used in the puncture tests is given in table 1. The results of the dimensional measurements are similar to that reported by Miller (1986). Thus, it is hypothesized that the fruits used were characteristic of the variety tested.

An example force vs. deformation plot is shown in figure 4. A yield stress point is not readily apparent, as the deformation curve is linear up until the point of failure. Some of the deformation curves had slight variances in the linear curve prior to the failure point, which might indicate a potential yield point. An example of this is shown in figure 4. This may indicate when the peel of the fruit was initially penetrated but not completely punctured. As shown in this figure, load was not initially present. The punch was initially placed just above the fruit, and so a slight delay was present between when the punch initially began extending and the fruit began experiencing loading. The results from all test dates are given in table 2, where the force, pressure, and deformation values are at the puncture point. The amount of deformation at the puncture point was taken as the difference between the recorded deformation at the puncture point and the recorded deformation at 2.22 N of loading. This was done in order to account for deformation under the initial settling period when the punch was first engaging the fruit.

The results of the puncture tests were analyzed using SAS (2004) with analysis of variance (PROC GLM). Results showed that the samples from the three different dates were not statistically different at the 95% significance level, as the p-value for this test was 0.148. This meant that the decreasing puncture force trend that was observed by Coggins and Lewis (1965), Juste et al. (1988), and McDonald et al. (1987) was

Table 1. Dimensional data summary of fruit used in puncture tests.

Test Date (2004)	Number of Fruit Tested	Mass (g)		Average Diameter (cm)		Radius of Curvature (cm)	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
30 March	180	203.03	33.79	7.206	0.463	3.736	0.269
15 May	180	176.04	28.05	6.890	0.400	3.478	0.223
16 June	179	205.56	35.09	7.329	0.461	3.710	0.300

Table 2. Summary of puncture test results.

Punch Diameter (cm)	Test Date (2004)	Puncture Force (N)[a]		Strength (N/cm^2)[b]		Deformation (cm)[c]	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
0.323	30 March	21.68	3.15	264.58	38.42	0.504	0.068
0.323	15 May	22.31	4.43	272.23	54.07	0.558	0.119
0.323	16 June	25.09	3.37	306.16	41.12	0.586	0.077
0.632	30 March	51.47	9.68	164.07	30.85	0.902	0.114
0.632	15 May	43.90	9.61	139.93	30.62	0.876	0.133
0.632	16 June	49.57	8.18	158.02	26.07	0.978	0.145
0.964	30 March	71.66	11.73	98.19	16.07	1.060	0.148
0.964	15 May	65.81	13.16	90.17	18.03	1.158	0.227
0.964[d]	16 June	69.30	11.23	94.94	15.39	1.114	0.187
1.27	30 March	93.61	16.24	73.90	12.82	1.223	0.178
1.27	15 May	78.45	17.10	61.93	13.50	1.156	0.180
1.27	16 June	84.64	14.33	66.82	11.31	1.277	0.224
1.9	30 March	138.69	18.07	48.92	6.37	1.469	0.174
1.9	15 May	125.98	24.97	44.43	8.81	1.520	0.177
1.9	16 June	142.65	18.41	50.31	6.49	1.714	0.188
2.54	30 March	209.77	29.47	41.40	5.82	1.818	0.166
2.54	15 May	166.09	46.67	32.78	9.21	1.711	0.294
2.54	16 June	202.78	40.91	40.02	8.07	1.936	0.272

[a] Force is the load recorded at puncture.
[b] Strength is calculated from the puncture force and punch diameter.
[c] Deformation is the difference in recorded extension of the punch between 2.2 N load and the puncture point.
[d] Sample size was 29.

not observed in this study. In order to account for the effects of increasing variability with increasing punch size, a model was developed with the response being the natural log of the puncture force (lnpf). The natural log was also taken of the punch diameter (lnpd), thus generating a log-log relationship between the two.

Regression analysis (PROC REG) was used to determine the best combination of variables in order to predict the response. The variables considered were average diameter, radius of curvature, mass, and lnpd. Since the average diameter, mass, and radius of curvature are all highly correlated, it was necessary to include only one in the model. It was determined that radius of curvature in combination with lnpd yielded the highest r^2 value, and thus the best model. The lnpd term was the predominant contributor to the model, as the r^2 value using that term alone was 0.923. The addition of the radius of curvature term increased the r^2 value to 0.924. The correlation coefficient between lnpf and the radius of curvature was very low (Pearson coefficient = 0.084, Spearman coefficient = 0.103), but it explained enough of the variability in the response to be able to better fit the model when it was combined with the lnpf term. The model was verified to have constant variance and normality through analysis of the residuals. The resultant model has the form:

$$\text{lnpf} = K_1 * \text{lnpd} + K_2 * \text{rc} + C \qquad (1)$$

where

rc = radius of curvature
C = 3.977
K_1 = 0.999
K_2 = 0.078.

Using the same procedure as was reported earlier by Coggins and Lewis (1965), the increase in puncture force was observed to be correlated more closely with punch diameter than area, as puncture force was a linear function of punch diameter. An illustration of the similarity in the relationships is shown in figure 5. Ratios of the value at each punch diameter over the value at the smallest punch diameter were taken in order to obtain similar units. This indicates that the contact perimeter associated with the shearing forces influenced the puncture force more than the contact area.

A summary of the dimensional data for the fruit used in the burst tests is given in table 3. The results of the dimensional measurements were similar to those reported by Miller (1986). This supported the hypothesis that the fruits used were characteristic of the variety tested.

Burst tests produced force vs. deformation curves similar to that shown in figure 4. The results of the burst tests performed with and without the holding die are shown in table 4. The bursting test results without the holding die were observed to be significantly lower at the 95% significance level. This most likely reflected the contribution of the holding die to preventing the fruit from deforming as quickly as when the die was not present. Failure during burst tests was

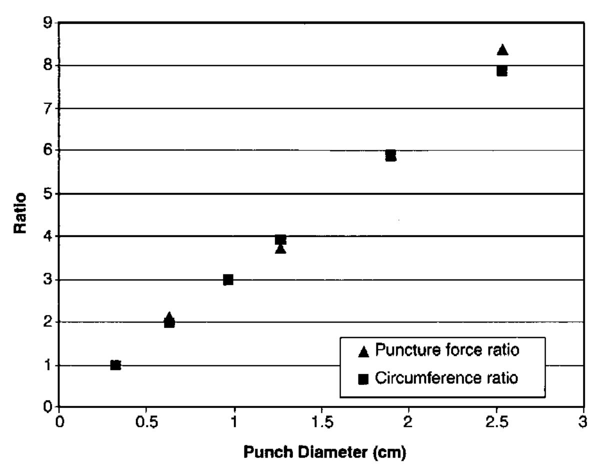

Figure 5. Ratio of increase in value from value at smallest punch.

Table 3. Dimensional data summary of fruit used in burst tests.

Test Date (2004)	Number of Fruit Tested	Mass (g)		Average Diameter (cm)		Radius of Curvature (cm)	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
30 March	60	197.36	40.87	7.097	0.530	3.721	0.315
15 May	55	179.81	32.71	6.964	0.448	3.466	0.231
16 June	59	199.50	28.54	7.285	0.374	3.628	0.217

Table 4. Summary of burst test results.

Test Date (2004)	Force w/ Die (N)[a]		Force w/o Die (N)[a]		Deformation w/ Die (cm)[b]		Deformation w/o Die (cm)[b]	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
30 March	403.70	94.69	317.52	64.61	1.823	0.240	2.412	0.330
15 May	289.04	59.64	221.06[c]	43.02[c]	1.697	0.199	2.141[c]	0.326[c]
16 June	459.00[d]	92.13[d]	336.40	53.81	1.928[d]	0.193[d]	2.576	0.305

[a] Force is the load recorded at the burst point.
[b] Deformation is the difference in recorded extension of the plate between 2.2 N load and the burst point.
[c] Sample size was 25.
[d] Sample size was 29.

a result of the fruit diameter parallel to the loading plate expanding beyond the limits of the fruit strength. This caused the outer skin to split, as shown in figure 2. It was determined that the results from the three different dates were shown to be statistically different using analysis of variance (PROC GLM), with the burst values from the second date statistically lower than those from the other two dates.

The fruit tested during the second date were also observed to be smaller than the other two dates for both the puncture and burst tests, as shown in tables 1 and 3. However, there was not as large a difference in the size of fruit used in the puncture tests between the three test dates as there was in the burst tests, even though the fruit were randomly selected from the same group. The smaller size difference in the puncture tests, coupled with the dominance of the punch diameter term in the model, made date an insignificant parameter for the puncture tests. Conversely, the absence of the punch diameter term, coupled with the larger size difference between dates, made date a significant parameter in the burst tests. Since the smaller fruit used in the second test date were still within the expected range for the Valencia variety, the values obtained from this test were included in the results presented in table 4.

Conclusions

As expected, the force required to puncture or burst a fruit is directly related to the contact area. This is a function of two variables: the punch diameter used, and the radius of curvature of the fruit. The larger the radius of curvature, and thus the flatter the fruit at the point of contact, the more fruit will be in immediate contact with the punch. This results in a larger puncture force, which implies that the fruit can withstand higher contact forces when using larger punch sizes, as would be expected. Most of the model is described by the punch diameter term, as the size of the punch is the variable with the greatest influence on the puncture force. As the punch diameter size increases, the punch diameter approaches one, and lnpd goes to zero. This left lnpf as a function of the radius of curvature only. This correlated well with physical observations, in that punch diameters beyond 2.540 cm approached the behavior of a flat plate, where puncture force is no longer a function of punch diameter but solely of the fruit properties. Principle among the determining fruit properties was the radius of curvature. The model, however, did not account for this plateau. Therefore, it was only valid for punches where failure was at the perimeter of the punch. The limits on overall loading force were determined in the burst tests and were dependent on how much the fruit was allowed to deform as it was loaded.

Based on the results of these tests, recommendations can be made for the design of a grasping robotic citrus harvester end effector. The end effector should be made so that the grasping of the fruit does not exceed the bursting limits or the puncture limits, where the portion of the end effector in contact with the fruit may be expressed in equivalent punch diameter. This may be obtained by using the perimeter that is in contact with the fruit. As discussed previously, the contact perimeter influences the puncture force more than the contact area. The area is associated with preventing the fruit from deforming under applied loading, which would correlate more with determining the bursting limits. Further studies need to be conducted using various shaped punches in order to further define to what extent each of these geometrical properties plays a role in the puncturing of the fruit, and the impact of these roles on the design of a grasping robotic citrus harvester end effector.

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