FINAL PROJECT REPORT
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Project Title: Estimating Apple firmness using Tensile Mechanical Properties

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Other funding Sources: None

Agency Name:
Amount awarded:
Notes:

Total Project Funding: $60,073

Budget History:

Item	**Year 1:** 7/2005 – 6/2006	**Year 2:** 7/2006 – 1/2007
Salaries	6 478	11 622
Benefits	2 656	4 251
Wages	2 720	0
Benefits	272	0
Equipment	800	0
Supplies	573	400
Travel	1 500	800
Sensory Panel	15 000	13 000
Miscellaneous	0	0
Total	30 000	30 073

Introduction and Summary

This report covers the activities performed in Fall 2005 and Spring and Fall of 2006 comparing the tensile and compressive mechanical properties of apples and pears to human sensory intensity ratings of texture, and the Guss Penetrometer. The project was funded by WSTFRC grants awarded in August 2005 and February 2006. Data was collected in Fall 2005, Spring 2006 and Fall 2006.

Following Spring 2005 (year 1), we refined existing protocols for future data collections. These revisions were based on results from the Spring 2005 tests which indicated a low correlations between the mechanical properties and sensory evaluations. Revisions for Year 2 of the study (Fall 2006) included selection of apple and pear varieties, sample size and loading tests to measure the mechanical properties. Specifically, in Fall 2006, we compared the mechanical properties of apples and pears to sensory evaluations of texture, Sinclair (nondestructive) and the Guss (destructive) Penetrometer. Analysis of the Fall 2006 data indicate a relatively strong correlation between one sensory evaluation measurement (crispness) and the tensile material properties of apples and pears.

Objectives:

2005

1. Determine if human perceived apple firmness is related to the tensile material properties (elastic modulus, failure stress) of tissues from cultivars of apples and pears commercially grown in Washington State.
2. Determine if there is a relationship between the tensile material properties of the apple and pear varieties and the firmness pressure test originally developed by Magness and Taylor and refined over the years.

2006

1. Confirm 2005 results.
2. Develop design tools for use in designing and evaluating destructive and nondestructive firmness sensors.

Significant Findings:

Fall 2005

- Developed procedure (sample size, loading rate, photographic settings) to measure tensile forces in apple and pear tissue
- Weak correlations between tensile mechanical properties (elastic modulus, failure stress and failure strain) and compressive material properties (elastic modulus, failure stress and failure strain) in both apples and pears.
- Poor correlations between tensile mechanical properties and Guss Penetrometer measurement of firmness in both apples and pears
- Good correlations between compressive mechanical properties and Guss Penetrometer
- As the apple or pear matures, the tensile elastic modulus decreased more rapidly the compressive elastic modulus

Spring 2006

- Good correlations between compressive material properties and sensory evaluations
- Good correlations between Guss Penetrometer and sensory evaluations
- Good sensory correlations between Guss Penetrometer and compressive material properties
- Poor correlations between tensile material properties (measured in an orientation perpendicular to the core line) in apples and sensory evaluations (crispness, hardness,

juiciness , chewiness and fracturability) lead to a redesign of the experimental techniques used in Fall 2006

Fall 2006

- Good correlations between tensile material properties (measured in an orientation parallel to the core line) in apples and pears and at least one sensory evaluation (crispness)
- Good correlations between compressive material properties and some sensory evaluations (hardness, fracturability).
- Good correlations between compressive material properties and Guss Penetrometer
- Good correlations between Guss Penetrometer and sensory texture attributes (hardness and fracturability)
- Computer models of typical apples and Anjou pears were constructed and verified.

Methods

The three testing sessions (Fall 2005, Spring 2006 and Fall 2006) used similar methods to select fruit, conduct the sensory evaluation, and measure the mechanical properties. This common methodology is described below.

Fruit Selection

Spring 2006

Gala, Granny Smith, Braeburn, Red Delicious, Golden Delicious apples were removed from air storage in late February 2006 and transported to WSU Pullman. the apples selected had a range of firmness values when evaluated by the sensory panel – a difficult prediction task. To increase the likelihood of having apples with a range of firmness values, we identified apples from historically strong and weak lots of apples. Fruit was screened twice, once nondestructively with Sinclair and samples tested destructively in Wenatchee. In February 2006, apples from these lots were pressure tested with the Slinclair nondestructive firmness to ensure a wide range of firmness.

Fall 2006

Apples were selected in Wenatchee as follows:

Golden Delicious - soft overmature fruit provided from an orchard, stored in air storage. Selected as being less than 13.5 lbf and less than 34 on the Sinclair.

Gala - soft fruit provided from an orchard stored in air. Less than 14.0 lbf and less than 37 on the Sinclair.

Red Delicious - medium firmness provided from an orchard stored in air. 15-16 lbf, not correlated with the Sinclair.

Braeburn - firm fruit again from an orchard stored in air. 19-20 lbf and above 49 on the Sinclair

Granny Smith - firm fruit from a commercial packer. Stored in air and commercially sorted. 18-20 lbf and above 38 on Sinclair.

Pears were selected in Wenatchee as follows:

Anjou pears - from an orchard stored in air.

Bosc and Bartlett pears purchased from a commercial packer stored in air.

Classification of apples for sensory evaluation

Apples from regular cold storage (1-3°C) were brought up to room temperature 24 hours before analysis. Prior to evaluation by the sensory panels, the fruit were characterized using instrumental measures of hardness using the Guss Penetrometer and the Sinclair iQ. These measurements were performed by the Kupferman group in Wenatchee and apples arrived in Pullman, characterized by their hardness level. On the day of the sensory evaluation panels, the measurements using the Guss Penetrometer and the Sinclair iQ were verified as some time had elapsed between the original measurements.

Trained sensory evaluation panel

A sensory panel of 10 panelists (2005) and 17 panelists (2006) was recruited using advertising in the WSU/Pullman community. Panelists were screened for any known allergies and anosmias. Panelists will be trained to recognize the apple texture attributes of hardness, juiciness, crispness and fracturability as defined in Table 1. In 2005, the panelists were also trained to recognize chewiness; however, this attribute was excluded from evaluations in 2006 as it was not found to yield significant results. The texture attributes were selected based upon previous literature. For training, published texture scales were used for the different texture attributes and panelists were trained to both recognize the attribute and assign it an intensity rating. Fruit of varying texture intensities and different varietals were used for the training process.

Table 1: Texture attributes of apples that were evaluated during the 2005 and 2006 trained sensory panels.

Texture:	
Hardness	Force required to bite completely through sample placed between molars
Crispiness	Amount of pitch of sound generated when the sample is first bittern with the front teeth
Juiciness	Amount of juice released on mastication in the first three chews
Fracturability	Force with which sample ruptures when placing sample between molars and biting down completely at a fast rate

During apple evaluation, panelists were presented with 6 sections of apple per evaluation session and these sessions were replicated. Following apple classification by hardness level, apples from the low, medium and hardness groupings were split in half. Half of the sample was used for tensile property measurement and half of the apple was used for sensory testing. The apple was labeled such that the sensory data and the tensile data for that apple could be compiled. The half that was used in the sensory testing was split in half. Thus, each panelist was presented with ¼ of a washed apple for evaluation and a knife to peel his/her own fruit.

Evaluations took place in individual sensory booths equipped with lap top computers for recording data. The apple sections were randomly presented to the panelists at room temperature. Apple selections were identified using three-digit codes and presented one at a time to panelists. Each panelist was provided with water to rinse between samples as well as a cuspidor for sample expectoration. The samples were scored for intensity of each texture attribute using a 15-cm unstructured line scale, with the left end of the scale corresponding to the lowest intensity (0 mm=absent) and the right end corresponding to the highest intensity (150 mm=extreme). Results were collected and analyzed using Compusense 6.0 software (Guelph, ON) and sensory data was quantified by measuring the distance of the mark along the line.

Mechanical Properties

Compressive elastic modulus, failure stress and failure strain

Cylindrical tissue samples 15 mm in length and 9.22 mm in diameter were excised from the fruit. In the Fall 2005 and Spring 2006 tests, these the centerline of these samples was perpendicular to the core line of the fruit. Based on the redesign of the experimental techniques following the Spring 2006 test, in the Fall 2006 test the samples' center line was parallel to the core line of the fruit. The cylinders were compressed to failure between the parallel plates of a universal testing machine (Fall 2005, Instron Model 1350, Spring and Fall 2006, Texture Analyzer TAXT2 by SMS). Force and deformation data was collected at intervals of 10 milliseconds. Stress values were computed from the recorded force data and sample diameter; strain values were computed from recorded deformation data and the original length of the sample. From the stress and strain data the compressive elastic modulus (slope of the stress vs. strain data), failure stress and failure strain values were computed.

Tensile elastic modulus

Measuring the tensile material properties of fruit tissue is problematic due to the difficulty of forming and gripping a suitable test specimen. In our tests, the failure mechanical properties were computed using a bending apparatus and image analysis. Central to this analysis is the determination of the location of the neutral axis – the plane about which the sample deforms in response to a bending load. In this project, the neutral axis of the fruit tissue samples were determined using digital image analysis.

A rectangular block of tissue, 8.16 mm wide, 26.76 mm in length, and 8.16 mm in height was removed from the fruit. The sample was excised from the fruit so that the length dimension of the sample was parallel to the core line, and the height dimension of the sample was perpendicular to the core line.

The sample was placed in a 3 point bending jig (Image 1) and slowly deformed to failure. A digital video record was made of the deformation. Two digital images were extracted from the video; one prior to deformation of the sample (Image 1), and a second image at a point where the sample had been deformed to a point near failure (Image 2). Image 2 was then subtracted (on a pixel-by-pixel basis) from Image 1, resulting in a difference image (Image 3). Of particular interest are the dark and light triangular regions on the sides of Image 3. The dark region is where the side of the sample rotated toward the center of the sample due to the bending load. The light region is where the side rotated away from the center of the sample due to the bending load. The point where the two regions meet was the pivot of the side's rotation. This pivot point is on the neutral axis of the sample. The square of the ratio of the distance between the bottom of the sample and the neutral axis to the distance between the neural axis and the top of the sample is equal to the ratio of the compressive elastic modulus to the tensile elastic modulus. Using the compressive elastic modulus computed from the compressive test and the square of the ration of distances to the neutral axis, the tensile elastic modulus was computed.

Image 1

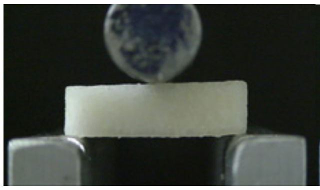
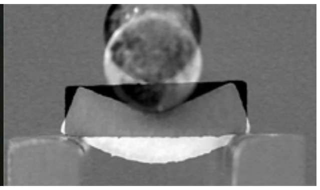


Image 2

Image 3



RESULTS AND DISCUSSION

Sensory attributes ANOVA results for apple firmness level characterization (soft, intermediate and hard as determined by instrumentals measures), panelists and interaction between apples (sample) and panelists are shown in Table 2. Differences between panelists and interaction between apples and panelists were not significant. This reveals consistency between panelists and that the level of error was small. Significant differences between the apple samples were observed at $p \leq 0.05$ (Tukey's HSD test) for all the sensory parameters (crispness, hardness, fracturability, juiciness and chewiness) in the 2006 cultivars. Apple results from 2006 showed that the panelists were able to differentiate apples based on firmness level. However, in 2005 there were not significant differences found between intermediate and hard apples for all texture sensory parameters.

Table 2. Interaction between Apple Sensory Parameters

2005	**Crispness**	**Hardness**	**Fracturability**	**Juiciness**	**Chewiness**
Sample (S)	241.67*	2676.63*	285.91*	837.42*	172.99*
Panelist (P)	2.04	132.90	11.64	48.73	29.19
Interaction (S x P)	0.42	13.52	2.13	12.07	2.25
2006					
Sample (S)	130.00*	416.00	240.47*	271.49*	N/A
Panelist (P)	0.42	10.61	1.27	3.74	N/A
Interaction (S x P)	0.18	1.09	0.63	2.25	N/A

F value and significant levels from a two-way ANOVA

*** Significant at P < 0.05**

A logarithmic relationship between the physical properties of fruit and associated sensory response can be observed in our 2005 data. When fruit is soft, the consumers might be expected to be more sensitive to texture differences than any instrument is capable of measuring. When fruits are hard, the ability of consumers to sense texture differences may become saturated, and thus instrumental measurement is better than the consumer at discriminating between hard and very hard fruit.

Table 3 shows the two-way ANOVA sensory attributes F values for pear parameters (soft, intermediate and hard groupings) panelists and interaction between apples and panelists. Significant differences were found between pear samples at $p < 0.05$ (Tukey's HSD test) for all attributes with the exception of juiciness indicating that the training received was adequate and that panelists were able to differentiate pears with varied firmness levels. There were not significant differences between the panelists demonstrating consistency within the group. Also, not significant interactions were found between pear samples and panelists for all attributes.

Table 3. Interaction between Pear Sensory Parameters

	Crispness	**Hardness**	**Fracturability**	**Juiciness**
Sample (S)	330.29*	258.55*	1771.90*	204.84*
Panelist (P)	11.97	8.05	50.65	63.17
Interaction (S x P)	3.61	2.26	19.87	21.54

F value and significant levels from a two-way ANOVA

*** Significant at P < 0.05**

Table 4 showed the one-way ANOVA results of instrumental determinations (Guss, Sinclair, elastic modulus by compression and tension) and their relationship with apple groups. The one-way ANOVA results of instrumental determinations (Guss, Sinclair, elastic modulus by compression and tension) and pear groups are shown in Table 5. Significant differences at p < 005 (Tukey's HSD test) between apple and pear groups were observed, indicating that all instrumental measurements were able to differentiate between different groups of apples and pears. Instrumental measures were originally used to characterize the apples and pears and these results support these initial groupings.

Table 4. One Way ANOV for Instrumental Analysis of Apples

2005	Guss	Sinclair	AEMC	AEMT
Sample (S)	765.39*	420.93*	255.45*	27.01*
2006				
Sample (S)	1468.33*	1283.47*	195.76*	98.63*

F value and significant levels from a One-way ANOVA
*** Significant at $P < 0.05$**

Table 5, One Way ANOV for Instrumental Analysis of Pears

	Guss	Sinclair	AEMC	AEMT
Sample (S)	891.78*	138.25*	79.87*	110.12*

F value and significant levels from a One-way ANOVA
*** Significant at $P < 0.05$**

Correlation matrices for sensory texture attributes of apples are presented in Table 6. Strong correlations were observed between crispiness, hardness, fracturability and juiciness in 2005. In 2005, chewiness showed weaker correlations with the other sensory attributes, indicating that this term was not a good predictor of apple firmness. Thus chewiness was removed from the apple texture profiling in 2006. In the 2006 harvest year, correlations between sensory attributes were slightly lower, especially juiciness which was not as highly correlated to crispness, hardness, and fracturability as previously demonstrated in the 2005.

Correlation matrices for sensory attributes for pears are presented in Table 7.
In pears, strong correlations were observed between crispness, hardness, and fracturability. However, juiciness was weakly correlated to the other sensory texture attributes. These findings demonstrate that the mechanism for releasing juice in the mouth is not the same between apples and pears, with the release of cell fluids depending upon the biology of the fruit.

Table 6. Correlation Matrix of Sensory Attributes in Apples

Year 1	Crispness	Hardness	Fracturability	Juiciness	Chewiness
Crispiness	1.00	**0.88**	**0.91**	**0.82**	**0.62**
Hardness	**0.88**	1.00	**0.92**	**0.80**	**0.64**
Fracturability	**0.91**	**0.92**	1.00	**0.85**	**0.61**
Juiciness	**0.82**	**0.80**	**0.85**	1.00	**0.58**
Chewiness	**0.62**	**0.64**	**0.61**	**0.58**	1.00
Year 2	**Crispness**	**Hardness**	**Fracturability**	**Juiciness**	**Chewiness**
Crispiness	1.00	**0.82**	**0.79**	**0.73**	**N/A**
Hardness	**0.82**	1.00	**0.85**	**0.65**	**N/A**
Fracturability	**0.79**	**0.85**	1.00	**0.67**	**N/A**
Juiciness	**0.73**	**0.65**	**0.67**	1.00	**N/A**

Table 7. Correlation Matrix of Sensory Attributes for Pears

Year 1	Crispness	Hardness	Fracturability	Juiciness
Crispiness	1.00	0.86	0.87	-0.25
Hardness	0.86	1.00	0.90	-0.32
Fracturability	0.87	0.90	1.00	-0.28
Juiciness	-0.25	-0.32	-0.28	1.00

In firm apples, tissue fracture is associated with breakage of individual cells and results in the release of all fluids. In soft apples, fracture occurs as a result of cell to cell debonding. Individual cells do not always break open and release their contents, and these results in a mealy apple.

Pears appeared to behave differently from apples, in that increased firmness resulted in a low amount of juice released in the fruit as evaluated by the sensory panel. This relationship between firmness and juice release was attributed to cell to cell debonding and little juice release. Soft pears are associated with breakage of individual cells, resulting in the release of juice often associated with a juicy pear. Differences between apples and pears in the way juice contents are released may be attributed to fruit physiology and how the starch hydrolyses during ripening.

In apples, correlation analysis of the degree of association between instrumental and sensory measurements is provided in Table 8. Large positive or negative values indicated a strong association. In 2005, strong to moderate correlations were observed between the Guss, Sinclair and compressive elastic modulus, and the sensory attributes of crispness, hardness, fracturability and juiciness. Weaker correlations were observed between the tensile elastic modulus and all sensory texture attributes. In 2006, strong correlations were found between the Guss, Sinclair, compressive elastic modulus, tensile elastic modulus, and the sensory attributes of crispness, hardness and fracturability. Guss, Sinclair, and compressive elastic modulus provided measurements that did not significantly differ ($p < 0.05$) in their relationship to sensory attributes for both harvest years. However, tensile elastic modulus measurements differed significantly ($p < 0.05$) between apples from 2005 and 2006.

Table 8. Correlation Matrix of Apples Sensory Attributes and Instrumental Measurements

Year 1	Crispness	Hardness	Fracturability	Juiciness	Chewiness
Guss	0.72	0.78	0.74	0.66	0.64
Sinclair	0.81	0.82	0.83	0.76	0.65
Compressive EM*	0.76	0.78	0.78	0.70	0.64
Tensile EM*	0.57	0.62	0.63	0.53	1
Year 2	**Crispness**	**Hardness**	**Fracturability**	**Juiciness**	**Chewiness**
Guss	0.78	0.83	0.76	0.66	N/A
Sinclair	0.75	0.79	0.74	0.63	N/A
Compressive EM*	0.68	0.73	0.67	0.57	N/A
Tensile EM*	0.88	0.78	0.74	0.69	N/A

***EM: Elastic Modulus**

An increased predictability of apples crispness, hardness, and fracturability was observed in 2006. Also, some small variability in correlations between instrumental and sensory measurements was observed in apples between both harvest years. In 2005, correlations between the Sinclair and the

Guss measurements and sensory attributes were higher than the 2006 correlations. This variability may be associated with the structural differences in different varieties of apples and the differences where the fruit was taken when sampling. The possible reasons for the range of correlations obtained over different harvest years include the different range of firmness of fruit presented to different panelists, the difference between the texture of apples at the point of instrumental measurement and region eaten by each panelist, and the range of sensory acuities and cognitive abilities of individual panelists. The mechanical and texture characteristics of apples and pears are influenced by the structural features of the flesh and are affected by storage conditions that cause a high structural variability.

Correlation analysis of the degree of association between instrumental and sensory measurements for pears is provided in Table 9. Strong correlations were observed between the Guss, tensile elastic modulus and the texture sensory attributes of crispness, hardness and fracturability. Measurements made using the Sinclair and the average elastic modulus by compression showed poor correlations at predicting sensory texture attributes in pears. The term juiciness was negatively and poorly correlated to all instrumental measurements.

Table 9. Correlation Matrix of Pear Sensory Attributes and Instrumental Measurements

Year 1	**Crispness**	**Hardness**	**Fracturability**	**Juiciness**
Guss	**0.79**	**0.83**	**0.81**	**-0.41**
Sinclair	**0.68**	**0.71**	**0.71**	**-0.25**
Compressive EM*	**0.59**	**0.61**	**0.59**	**-0.21**
Tensile EM*	**0.85**	**0.79**	**0.81**	**-0.31**

*** EM = Elastic Modulus**

Tensile elastic modulus differed significantly between apples from the first and second harvest years. Differences of tensile measurements between harvest years may be attributed to the difference in how the measurement was made between the two years. In 2005, the tensile elastic modulus and failure modulus were measured in a direction parallel to the core line. However in 2006, the measurements were made perpendicular to the core line due to the redesign of the experimental technique. Sensory evaluation techniques and training did not differ between years.

Tensile material properties have been found to be highly orthotropic in that the properties change with orientation of the tissue sample with respect to the core line of the fruit. Strong correlations of tensile measurements and crispness for apples and pears were observed when samples were taken perpendicular to the core line as opposed parallel to the core line. These observations were associated with the fact that tissue failure from biting with the front teeth was crack-related. Tensile material properties played a dominant role when a crack propagates and the length of the crack propagation. In the current study, fracturability and hardness were measured with the molars where compressive material properties dominated. The finding showed that tensile material properties were correlated to compressive properties, and compressive properties were related to fracturability and hardness.

Fruit firmness or strength is a function of the mechanical properties of the cell wall, cell turgor, and bonding between cells. Another factor that impacts fruit firmness is the contents of the cell. Cell strength is a hydrostatic phenomenon that is diminished in the absence of cell contents. Studies using pressure probes as a measure of compressive forces showed that the cell wall elastic modulus increased with increased turgor pressure in the cell. The results of the tensile material properties studies were attributed to the dependence on the strength of the pectin bonds between cells and the cell wall strength. The compressive material properties were attributed to a high dependence on the turgor pressure in the cell, and to a lesser extent on the pectin bonds and cell wall strength. Under certain storage environments, the fruit could mature without noticeably changing cellular turgor pressure.

An advantage of tensile tests is that they provide the opportunity to determine the mechanism of tissue failure through the examination of the fracture surface in fruit. There are three forms of tissue failure: cell fracture, cell rupture, and cell-to-cell debonding.

There is a difference of mechanical properties of a population of cells versus individual cells. In puncture tests of whole fruits, the compression and shear properties of the cell population is evaluated, while during tensile testing, the strength of thin layers of individual cells is determined. In the tensile measurements, the strength of the weakest cell may define the strength of the entire sample. Generally, failure in uniaxial compression is associated with an increase in turgor pressure which involves a change of volume in the cells and rupturing of cell walls. Failure during tension involves tearing of the cell walls and/or cell to cell debonding. Compressive tests may be relevant to understanding factors affecting the development of bruises while tensile measurements may be closely related to biting and chewing of food.

The analysis on the Fall 2005 fruit indicate that the tensile material properties decline at a faster rate than compressive material properties as the fruit matures. One explanation of this observation could be that the tensile material properties are highly dependent on the strength of the pectin bonds between cells and the cell wall strength, while the compressive material properties are highly dependent on the tugor pressure in the cell, and to a lesser extent on the pectin bonds and cell wall strength. Under certain storage environments, the fruit could mature without noticeably changing cellular tugor pressure.

The tensile material properties are highly orthotropic (the properties change with orientation of the tissue sample with respect to the core line of the fruit. The sensory evaluations and tensile properties measured in the Spring 2006 test were orientated perpendicular to each other, and showed little correlation, while in the Fall 2006 test the tensile material properties and sensory evaluations were both taken parallel to the core line, and there was a high correlation between the sensory and tensile measurements. Although we did not measure tensile material properties and sensory evaluations perpendicular to fruit core lines, we suspect that the correlations between sensory and tensile measurements would also be high in this orientation.

One very clear outcome from this project is that the orientation of the load applied by a firmness sensor must be specified. The correlation between material properties parallel and perpendicular to the core line is low, and comparing firmness measurements taken without specifying the orientation will vary widely.