Research Article

Received: 27 August 2013 Revised: 17 February 2014 Accepted article published: 11 March 2014 Published online in Wiley Online Library: 25 March 2014

(wileyonlinelibrary.com) DOI 10.1002/jsfa.6626

Correlation between sensory and instrumental measurements of standard and crisp-texture southern highbush blueberries (*Vaccinium corymbosum* L. interspecific hybrids)

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Abstract

BACKGROUND: Fruit texture is a primary selection trait in southern highbush blueberry (SHB) breeding to increase fresh fruit postharvest quality and consumer acceptance. A novel crisp fruit texture has recently been identified among SHB germplasm. In this study, we developed a common set of descriptors that align sensory evaluation of blueberry fruit texture with instrumental measures that could be used for quantitative measurements during pre- and postharvest evaluation.

RESULTS: Sensory and instrumental characteristics were measured in 36 and 49 genotypes in 2010 and 2011, respectively. A trained sensory panel evaluated fresh fruit based on five common textural attributes in 2010 and 2011: bursting energy, flesh firmness, skin toughness, juiciness and mealiness. Instrumental measures of compression and bioyield forces were significantly different among cultivars and correlated with sensory scores for bursting energy, flesh firmness and skin toughness ($R > 0.7$, except skin toughness in 2011), but correlations with sensory scores for juiciness and mealiness were low ($R < 0.4$).

CONCLUSION: The results of sensory and instrumental measures supported the use of both compression and bioyield force measures in distinguishing crisp from standard-texture genotypes, and suggest that crisp texture in SHB is related to the sensory perception of bursting energy, flesh firmness and skin toughness.

Supporting information may be found in the online version of this article.

Keywords: southern highbush blueberry; *Vaccinium corymbosum*; firmness; texture; compression force; bioyield

INTRODUCTION

Worldwide blueberry (*Vaccinium* spp.) production increased nearly 50% from 2008 to 2012.[1] Increased consumption leading to record production levels has likely been driven by consumer interest in the potential health benefits of blueberries.[2] However, availability of new blueberry cultivars with a wider adaptive range has also contributed to the rapid expansion in production. Southern highbush blueberry (SHB; *Vaccinium corymbosum* L. interspecific hybrids) cultivars resulting from interspecific hybrids between northern highbush (*V. corymbosum* L.) germplasm and sources of low-chill traits (usually *V. darrowii* Camp and *V. virgatum* Aiton) have increased production in subtropical locations worldwide.[3,4]

The University of Florida (UF) blueberry breeding program has been developing SHB cultivars for over 60 years. As with many horticultural breeding programs, flesh firmness has been a primary fruit quality selection trait. In addition to increasing fruit firmness, two cultivars considered to have a unique crisp texture were selected from this SHB germplasm and released from UF in 1997 ('Bluecrisp')[5] and 2005 ('Sweetcrisp') (Lyrene PM, personal communication). Many current selections in the UF blueberry breeding program are also considered to have a similar crisp texture phenotype. Additional cultivars from other breeding programs that have been described as having crisp texture are 'Dolores' and 'Hortblue Poppins'.[6,7] Berries with this crisp texture are of particular interest owing to their enhanced eating quality, prolonged postharvest life and potential value for mechanical harvesting for fresh marketed.[8–10]

Fruit texture is a major factor influencing overall fruit quality. Fruit texture affects both the postharvest life of the fruit as well

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as consumer eating experience.[11,12] Additionally, owing to rising labor costs and decreasing labor availability for hand harvesting of blueberries, the industry has been looking for ways to mechanically harvest fresh market berries.[1,13] New machine harvesters have been designed and tested for use in blueberry,[14,15] and research has been initiated to determine cultural practices and cultivars best suited for mechanical harvesting.[8,10,16] Several bush and berry traits are thought to be desirable for mechanical harvesting methods, and berry firmness is top among them.[17,18]

Fruit texture is determined by several factors governing cellular structure, including fruit anatomy and cellular construction, the mechanical and physiological properties of cells, biochemical changes in the cell wall, turgor pressure and membrane integrity.[11] These factors contribute to textural traits such as crispness, hardness, juiciness, and mealiness.[11] Fruit texture has been measured in a variety of ways, including bioyield tests, deformation tests, tactile assessment, shearing tests, beam tests, measures of juice content and sensory evaluations.[11] Sensory evaluations are performed by consumers for hedonic characterizations and trained panels are used for profiling and descriptive analysis.[19] Correlating instrumental measures with sensory evaluations is useful for predicting consumer responses, while using instrumentation is often desirable for quantitative assessments in breeding.

Previous studies have surveyed firmness and correlated sensory perceptions of texture with instrumental measurements in blueberry, but none using cultivars described as having a crisp texture.[12,20] In a survey of 87 highbush and species-introgressed blueberry cultivars, SHB cultivars having some *V. virgatum* or *V. darrowii* ancestry were among the highest in firmness, based on compression force measurements, suggesting that low-chill species introgression could be a potential source of increased blueberry firmness.[21] Likewise, shear, compression and bioyield forces were higher in three low-chill rabbiteye cultivars compared with two northern highbush cultivars.[20] Most recently, bioyield force and strain for 49 blueberry cultivars were measured at harvest and during postharvest storage to develop an index describing the different storage potential of the cultivars.[22] However, a weak correlation between compression force measurements and sensory evaluation was found when comparing 12 blueberry cultivars.[12] Although sensory and instrumental correlation studies have been conducted in other crisp-textured fruits such as grape (*Vitis* spp.) and apple (*Malus domestica* Borkh.), crisp texture has not been previously studied in blueberry.[23–26] The ability to objectively phenotype crisp texture in blueberry is important for breeding purposes to identify parents with crisp texture that can be used in developing advanced selections of higher fresh and postharvest fruit quality and adaptation to mechanical harvest.

The objective of this study was to utilize a broad range of SHB germplasm, including crisp-textured cultivars and selections, to develop descriptors for textural traits using a trained panel, survey the germplasm for texture differences based on readily available instrumental measurements, and determine the extent of correlation between trained panel ratings and instrumental measurements of the germplasm.

MATERIALS AND METHODS

Plant material

The genotypes selected for use in these experiments represented a wide range of germplasm utilized by the UF SHB breeding program and included recent cultivar releases, standard cultivars and advanced selections still under trial (supplementary Table 1, supporting information). Because a primary goal was to develop descriptors for the crisp texture phenotype, approximately equal numbers of crisp and standard-texture genotypes were selected for analyses each year (18 crisp texture and 18 standard texture, and 26 crisp texture and 23 standard texture in 2010 and 2011, respectively). For this initial grouping, the determination between crisp and standard texture was a subjective decision made by the blueberry breeders after several years of observation.

Cultivars and selections of southern highbush blueberry were hand harvested from field trials near Archer, Waldo and Windsor, FL. Berries were collected on six dates (5, 10, 13, 17, 19 and 24 May) in 2010 from 36 genotypes and on seven dates (18, 25, 27 April, and 2, 5, 9, 11 May) in 2011 from 49 genotypes as fruits ripened during the harvest season (Supplementary Table 1). Because of the short harvest window in Florida blueberry production (April–May, with an approximately 4- to 6-week harvest period for a given genotype), and the limited number of plants available for many of the advanced selections within the breeding program, the number of replicated genotypes within a growing season that could be provided to a trained panel was limited. Therefore, we adopted a strategy that allowed multiple genotypes to be evaluated by the trained panel while including standard cultivars and selections that could be evaluated multiple times by the panel. To evaluate panelists' reproducibility in sensory evaluations and the potential changes in instrumental evaluations, six genotypes (FL 98–325, 'Emerald', 'Farthing', 'Sweetcrisp', 'Springhigh' and 'Star') replicated on two different harvest dates within the 2010 and 2011 season were compared. Only mature, fully blue, unblemished berries were harvested. Berries were packed in 170 g plastic vented clamshells (Pactiv, Lake Forest, IL, USA) , stored in coolers filled with ice and transported on the same day to the USDA-ARS research lab in Winter Haven, FL, for sensory evaluation and to the blueberry breeding lab at UF in Gainesville, FL, for instrumental analyses. At both locations, berries were stored overnight in a cold chamber at 4 °C and brought to room temperature on the next morning before sensory and instrumental analyses were performed.

Sensory analyses

Thirteen panelists trained to evaluate fruit and fruit products met in four (2010) and six (2011) 1 h sessions to discuss texture descriptors. Using previous definitions for texture adopted for consumer evaluations of blueberry fruit as a starting point,[12] we developed blueberry texture descriptors for our unique crisp texture plant material by a trained panel. A consensus was reached to define descriptors: 'bursting energy' = impression from the first bite, from mushy to crisp/crunchy; 'firmness during chewing' = firmness between the molars, from soft to firm; 'skin toughness' = amount of residual skin that needs chewing after the flesh is gone, from tender/thin skin to tough skin; 'graininess' = texture from stone cells or seeds, from smooth to gritty/grainy; 'juiciness' = amount of juice from the flesh, from not juicy to juicy; 'mealiness' = pasty, dry feeling in the mouth, from not mealy to mealy; 'overall flavor intensity' = blueberry, fruity flavor, from low to high.

Each descriptor was rated on an 11-point scale (0–10). To compensate for fruit-to-fruit variability, panelists were instructed to taste two berries at a time, and repeat at least twice. Six to eight berries were presented in 120 mL soufflé cups with lids (SOLO® Cup Company, Urbana, IL, USA), labeled with three-digit number codes and served at room temperature. Six and five samples were presented per session in 2010 and 2011, respectively, with two sessions per day. Sample presentation was monadic following a Williams design (completely balanced pairwise). Tasting took place in booths under red lighting; spring water and unsalted crackers were provided to panelists to rinse their mouth between samples. To assess panelist reproducibility and cultivar stability within a harvest season and between years, five cultivars and one numbered selection were evaluated on 2 days with three and two replications on each day in 2010 and 2011, respectively. Data were collected using Compusense® 5.0 data acquisition and analysis software (Compusense Inc., Guelph, Ontario, Canada).

Instrumental analyses

Compression and bioyield force were measured on 25 berries from each cultivar in 2010 and 2011. For compression measurements, berries were oriented equatorially upright, on a FirmTech 2 (Bioworks, Wamego, KS, USA) fitted with a 3 cm diameter flat-bottom plate load cell.[21] The point of compression was marked with a permanent marker, and the same berries were rotated 90° along the equatorial plane and punctured with a 4 mm probe in 2010 and a 3 mm probe in 2011 using an Instron texture analyzer (Instron Corporation, Canton, MA, USA). Compression firmness ($N\,mm^{-1}$) measured the average force required to compress the berry 2 mm. Bioyield force (N) was measured as the maximum force required to puncture a berry at a speed of $50\,mm\,min^{-1}$.

Data analyses

Panelist discrimination, reproducibility and consensus with panel were assessed using Senpaq v.5.01 sensory software (QiStatistics, Ruscombe, Reading, UK) for the data from the six replicated genotypes included each year (supporting information). One panelist was removed from the analyses both years for lack of discrimination for some attributes, lack of reproducibility and inconsistency with the rest of the panel. The means across replications (for replicated samples) and panelists were used to perform a principal component analysis (PCA) using XLStat (Addinsoft, Paris, France). PCA was performed using the covariance ($n-1$) option.

Sensory and instrumental measurements of genotypes were analyzed using the mixed procedure using SAS 9.2 (SAS Institute, Cary, NC, USA) to detect differences in the measurements of a single genotype that was evaluated on two different harvest dates within a season and differences in the measurements of a single genotype that was evaluated in two different years. Dates were included as a fixed effect of sensory and instrumental measures and panelists as a random factor of sensory measures.

Analysis of variance (ANOVA) was performed for all genotypes in 2010 and 2011 using the GLM procedure (SAS 9.2) with genotype as a fixed effect of instrumental force measurements. To fit a generalized linear mixed model with random effects and unbalanced replication, the GLIMMIX procedure and Kenward–Roger method (SAS 9.2) with genotype as a fixed effect and panelists as a random factor of sensory measurements were used. Tukey's honestly significant difference (HSD) test was used to determine significant differences ($P \leq 0.05$) between genotype means. Correlation analyses were performed on the mean sensory and instrumental values using Pearson's correlation procedure (SAS 9.2).

RESULTS

Sensory analyses

In general, SHB genotypes will ripen over a 4- to 6-week period. To evaluate the potential changes in sensory evaluations on multiple harvest dates, six genotypes replicated on two different harvest dates within the 2010 and 2011 season were compared (Table 1). There were significant differences in the sensory evaluation of juiciness in 'Emerald', 'Farthing' and 'Springhigh' and in the bursting energy of 'Springhigh' when evaluated on different harvest dates in 2010 ($P < 0.05$, Table 1). In 2011, there were significant

Table 1. *P*-values from analysis of variance for sensory attributes and instrumental measurements of replicated southern highbush blueberry genotypes evaluated on two harvest dates in 2010 and 2011

		Genotype[a]					
Year	Sensory/instrumental measure	FL 98-325[b]	Emerald	Farthing	Sweetcrisp	Springhigh	Star
2010	Bursting energy	0.613	1.000	1.000	0.604	0.011*	0.477
	Firmness during chewing	0.794	0.289	0.479	0.771	0.108	0.368
	Skin toughness	0.572	0.771	0.554	0.534	0.340	0.287
	Juiciness	0.179	0.032*	0.027*	0.760	0.016*	0.492
	Mealiness	0.358	0.554	0.744	0.522	0.785	0.800
	Compression force	0.005**	0.001***	0.029*	0.935	0.053	0.732
	Bioyield force	–	0.943	0.002**	0.955	–	>0.0001***
2011	Bursting energy	0.723	0.736	0.308	0.295	0.223	0.199
	Firmness during chewing	0.036*	0.743	0.169	0.652	0.022*	0.251
	Skin toughness	0.845	1.000	0.571	0.946	0.224	0.585
	Juiciness	0.913	0.360	0.541	0.125	0.949	0.690
	Mealiness	0.850	0.488	0.296	0.046*	0.181	0.516
	Overall flavor intensity	0.676	0.353	0.245	0.160	0.781	0.009
	Graininess	0.916	1.000	0.217	0.765	0.585	0.536
	Compression force	0.008**	0.011*	–	–	0.098	0.210
	Bioyield force	0.491	>0.0001***	0.793	0.071	0.061	0.161

[a] Each genotype was harvested twice during the optimum maturity period for the genotype. A dash (—) indicates missing data.
[b] Significant statistical differences are indicated by asterisks:
*$P < 0.05$,
**$P < 0.01$ and
***$P < 0.001$.

Journal of the Science of Food and Agriculture published by John Wiley & Sons Ltd on behalf of Society of Chemical Industry.

Table 2. Mean scores for sensory attributes (0- to 10-point scale) and instrumental measurements of southern highbush blueberry genotypes evaluated in 2010

	Sensory					Instrumental	
Genotype[a]	Bursting energy[b]	Firmness during chewing	Skin toughness	Mealiness	Juiciness	Compression force ($N \cdot mm^{-1}$)	Bioyield force (N)[c]
FL 01–25	3.3d–k	2.7d–j	3.2b–e	1.0c	4.2a–f	2.12 m–s	1.88q–r
FL 05–252	6.2ab	4.8ab	4.1a–e	0.9c	3.8a–f	2.50 g–l	2.97f–j
FL 05–256	5.4a–d	5.0ab	5.0ab	1.9bc	3.1a–f	2.46 g–l	2.95f–k
FL 06–244	5.1a–e	4.2a–g	4.3a–e	1.7bc	3.1b–f	2.53f–l	–
FL 06–300	2.8f–k	2.6e–j	3.2b–e	1.5bc	3.4a–f	1.81 t–v	–
FL 06–552	5.0a–f	4.0a–g	3.6a–e	1.7bc	3.4a–f	2.63c–h	3.99bc
FL 06–553	5.0a–f	4.9ab	4.2a–e	1.9bc	3.5a–f	2.55d–j	–
FL 06–556	4.6a–h	4.2a–g	4.5a–e	2.5a–c	2.9c–f	2.85a–d	2.95f–k
FL 06–558	6.0a–c	4.9ab	4.9a–c	1.2bc	3.8a–f	2.84a–e	–
FL 06–561	6.2ab	4.7a–c	4.3a–e	1.1c	5.3ab	2.55e–j	–
FL 06–562$_1$	4.5a–i	3.2b–j	3.3b–e	1.5bc	4.3a–f	2.30i–o	2.95f–k
FL 06–562$_2$	4.6a–h	3.5a–j	3.8a–e	0.9c	4.5a–e	2.29i–p	2.50 k–o
FL 06–571$_1$	4.1b–j	3.9a–h	4.4a–e	1.7bc	3.9a–f	2.51 g–l	3.76c
FL 06–571$_2$	4.3b–j	3.7a–i	3.7a–e	1.8bc	4.0a–f	2.55e–k	3.30d–f
FL 06–572	5.0a–f	4.9ab	4.1a–e	1.5bc	3.9a–f	2.82a–f	–
FL 06–80	6.3ab	5.3a	4.2a–e	1.4bc	4.0a–f	3.03a	3.56c–e
FL 06–88	6.6a	5.2a	4.4a–e	1.8bc	2.7d–f	2.93ab	3.85bc
FL 07–100	6.1ab	4.7a–d	4.4a–e	1.0c	4.9a–c	2.97a	4.26b
FL 07–30	6.0a–c	4.7a–d	4.4a–e	1.5bc	4.6a–e	2.64b–h	3.68 cd
FL 07–449	6.8a	4.8a–c	5.4a	1.2bc	4.6a–e	2.62d–h	5.04a
FL 98–325$_1$	4.7a–g	4.5a–e	4.2a–e	1.4bc	3.0c–f	2.27j–p	2.74 h–m
FL 98–325$_2$	4.8a–g	4.3a–f	4.3a–e	1.7bc	3.5a–f	2.49 g–l	–
Bobolink	1.7 k	1.7j	3.4b–e	4.2a	2.1f	1.58v	1.74r
Emerald$_1$	3.5d–k	3.0b–j	3.8a–e	2.5a–c	3.6a–f	2.11 m–s	2.37 l–p
Emerald$_2$	3.5d–k	3.4a–j	3.9a–e	2.8a–c	2.8c–f	2.35 h–n	2.38 l–p
Farthing$_1$	4.2b–j	3.4a–j	4.3a–e	1.6bc	3.4a–f	2.58d–i	3.17e–i
Farthing$_2$	4.2b–j	3.6a–j	4.0a–e	1.5bc	4.2a–f	2.36 h–m	2.72i–n
Flicker	3.2d–k	3.1b–j	3.9a–e	1.9bc	3.5a–f	2.10 m–t	1.99p–q
Jewel	2.4 h–k	2.0 h–j	2.8de	1.4bc	4.6a–d	1.94r–u	1.97p–q
Kestrel	5.3a–d	3.5a–j	4.0a–e	1.2c	4.5a–e	1.95q–u	3.24d–g
Meadowlark	3.7c–k	2.8c–j	3.7a–e	1.7bc	4.0a–f	2.28j–p	2.79 g–l
Millennia	2.3i–k	2.5f–j	3.1b–e	3.4ab	2.1f	2.05n–t	2.12o–r
Primadonna	2.6 g–k	2.4f–j	2.5e	2.2a–c	3.8a–f	2.03o–t	1.91q–r
Raven	4.7a–g	4.1a–g	4.9a–c	1.9bc	4.1a–f	2.92a–c	3.20e–h
Rebel	3.1e–k	2.5f–j	3.0c–e	2.2a–c	2.4ef	2.25 k–q	1.98p–q
Scintilla	2.8f–k	2.7c–j	3.8a–e	1.3bc	4.5a–e	2.40 h–m	2.66j–n
Snowchaser	2.1jk	1.9ij	2.7e	1.7bc	3.0c–f	1.72uv	1.91q–r
Springhigh$_1$	3.4d–k	2.8c–j	3.3b–e	1.1c	4.1a–f	1.99p–u	2.29 m–q
Springhigh$_2$	2.4 h–k	2.3 g–j	2.7e	1.0c	5.3a	2.12 m–s	–
Star$_1$	2.7f–k	2.9b–j	3.4a–e	1.4bc	3.6a–f	2.26j–p	2.67j–n
Star$_2$	2.8e–k	2.5f–j	2.9c–e	1.4bc	4.2a–f	2.24 l–r	2.19o–r
Sweetcrisp$_1$	6.0a–c	4.9ab	4.8a–d	1.3bc	4.1a–f	2.75a–g	3.93bc
Sweetcrisp$_2$	6.2ab	5.0ab	4.8a–c	1.2c	4.0a–f	2.76a–g	3.93bc
Windsor	2.3i–k	2.7c–j	2.9c–e	1.5bc	3.6a–f	1.93 s–u	2.28n–q

[a] Genotypes that appear twice were harvested at two dates in the season.
[b] Different letters within a column indicate significant differences between genotypes using Tukey's test ($P \leq 0.05$).
[c] Dash (—) indicates missing data.

differences in the sensory evaluation of firmness during chewing in FL 98–325 and 'Springhigh', and in mealiness of 'Sweetcrisp' ($P < 0.05$, Table 1). There was no significant year interaction in the sensory evaluation of bursting energy, firmness, skin toughness, juiciness and mealiness of the six replicated genotypes that were evaluated in 2010 and 2011 ($P > 0.24$, data not shown).

Significant differences between genotypes were observed for all sensory traits evaluated by the trained panels in 2010 and 2011 ($P < 0.05$, Tables 2 and 3). Bursting energy demonstrated the

Table 3. Mean scores for texture-related sensory attributes (0- to 10-point scale) and instrumental measurements of southern highbush blueberry genotypes evaluated in 2011.

	Sensory					Instrumental	
Genotype[a]	Bursting energy[b]	Firmness during chewing	Skin toughness	Mealiness	Juiciness	Compression force (N mm^{-1})[c]	Bioyield force (N)
FL 01–15	4.4e–n	3.0f–m	3.3b–d	2.0b–e	4.8a–c	2.50c–j	1.26 s–A
FL 01–25	3.1 l–o	2.2 k–m	3.4b–d	2.2b–e	4.9ab	2.08 m–s	1.20y–B
FL 02–22	3.6i–o	2.6i–m	3.3b–d	2.8b–e	4.3a–d	2.25 h–p	1.25 t–A
FL 03–161	4.4e–n	2.9 g–m	3.1 cd	2.4b–e	4.0a–d	2.19i–q	1.36r–z
FL 05–252	6.8a–d	4.6a–i	4.3a–d	2.5b–e	5.0ab	2.38e–m	1.50 m–s
FL 05–256	6.3a–g	5.1a–f	5.2a–c	3.8a–c	4.0a–d	2.27 g–p	1.48n–u
FL 06–244	5.7a–i	4.7a–h	4.9a–c	2.5b–e	4.2a–d	2.53c–h	1.78 g–l
FL 06–245	3.4j–o	2.9 g–m	3.7a–d	3.2b–e	3.6a–d	1.81st	1.03AB
FL 06–552	7.3ab	5.8a–c	4.0a–d	2.3b–e	4.4a–d	2.89ab	1.95d–i
FL 06–553	6.5a–f	6.1a	4.1a–d	1.6c–e	4.5a–d	2.54c–h	1.54 l–r
FL 06–556	6.9a–c	6.0ab	4.4a–d	2.8b–e	3.1b–d	2.88ab	1.87e–j
FL 06–558	7.1a–c	5.6a–d	5.3a–c	2.9b–e	3.3b–d	2.40d–m	1.71j–n
FL 06–561	6.9a–c	5.9ab	4.9a–c	1.5c–e	4.8a–c	2.51c–i	1.70j–o
FL 06–562	6.2a–g	4.2a–k	3.8a–d	1.8b–e	5.7a	2.24 h–p	1.42p–w
FL 06–571	6.0a–h	4.4a–j	4.1a–d	1.6c–e	5.1ab	2.34f–n	1.71i–n
FL 06–572	6.4a–f	6.0ab	5.3a–c	3.0b–e	4.0a–d	2.67a–e	2.01d–g
FL 06–80	6.5a–e	5.4a–e	4.6a–d	2.0b–e	4.6a–d	2.62a–f	1.80f–k
FL 06–88	6.9a–c	5.1a–f	5.3a–c	3.3b–e	4.2a–d	2.90a	1.78 g–l
FL 07–100	7.3a–c	5.4a–e	5.6ab	1.5c–e	4.7a–d	–	2.18b–d
FL 07–160	5.5b–j	3.9b–l	4.0a–d	1.7c–e	4.1a–d	2.27 g–p	1.85f–k
FL 07–164	6.2a–g	4.8a–h	5.3a–c	2.5b–e	4.6a–d	2.06n–s	1.99d–h
FL 07–176	5.2b–l	4.6a–j	4.9a–c	2.5b–e	3.4a–d	2.49d–j	1.76 h–l
FL 07–23	5.4b–k	4.9a–g	4.1a–d	2.4b–e	4.1a–d	2.42d–l	1.49 m–t
FL 07–30	6.3a–g	4.5a–j	5.1a–c	1.2d–e	4.8a–c	2.81a–c	2.10b–e
FL 07–31	4.4e–n	3.6d–m	4.3a–d	2.1b–e	4.5a–d	2.03n–s	1.41q–y
FL 07–32	3.1 l–o	2.7 h–m	5.1a–c	3.6a–d	2.4c–d	2.30 g–o	1.73i–m
FL 07–38	6.2a–g	4.6a–j	4.6a–d	1.1e	4.7a–d	2.12 l–s	1.61 k–q
FL 07–43	6.5a–f	4.5a–j	5.4a–c	1.7b–e	5.4ab	–	1.99d–h
FL 07–449	7.9a	5.9a–c	5.6ab	1.6c–e	5.1ab	2.49d–k	2.48a
FL 07–452	7.3a–c	6.1a	5.2a–c	3.8a–c	3.4a–d	2.71a–d	2.32ab
FL 07–453	6.4a–f	5.8a–c	5.5ab	2.9b–e	4.4a–d	2.58b–g	1.99d–h
FL 07–87	4.5d–n	3.2e–m	5.1a–c	0.9e	5.2ab	–	2.04c–f
FL 98–325$_1$	5.7a–i	4.9a–g	4.5a–d	2.6b–e	4.2a–d	2.19j–r	1.65j–p
FL 98–325$_2$	5.6b–j	4.9a–g	4.8a–c	2.7b–e	4.2a–d	2.32f–n	1.62 k–q
Bobolink	3.5i–o	3.1f–m	3.8a–d	3.0b–e	3.8a–d	–	1.22v–B
Emerald$_1$	4.1f–o	3.9b–l	4.0a–d	2.8b–e	3.5a–d	1.96p–t	1.44p–w
Emerald$_2$	4.2e–o	3.8c–l	4.0a–d	3.2b–e	3.1b–d	2.10 m–s	1.22v–B
Farthing$_1$	4.5e–n	4.3a–k	4.3a–d	1.9b–e	5.4ab	2.17 k–r	1.47n–u
Farthing$_2$	5.0b–l	3.9b–l	4.6a–d	1.4c–e	5.6ab	–	1.46o–v
Jewel	2.6 m–o	2.2 k–m	3.2b–d	1.9b–e	5.0ab	2.17 l–r	1.17y–B
Meadowlark	4.9c–m	3.6c–m	4.4a–d	1.6c–e	4.8a–c	–	1.81f–k
Millennia	4.1 g–o	3.6d–m	3.8a–d	4.2ab	3.9a–d	2.16 l–r	1.23u–B
Primadonna	4.2e–o	2.7 h–m	4.2a–d	2.3b–e	4.3a–d	1.87r–t	1.17y–B
Raven	5.7b–i	4.8a–h	5.9a	3.2b–e	4.2a–d	2.93a	1.65j–p
Rebel	3.6i–o	2.9 g–m	3.7a–d	5.7a	2.3d	2.30 g–o	1.21w–B
Southern Belle	5.5b–j	4.6a–j	4.7a–d	3.8a–c	3.6a–d	–	–
Scintilla	3.1 l–o	2.9 g–m	3.7a–d	2.3b–e	5.6ab	2.21i–q	1.47n–u
Snowchaser	2.2no	2.1 lm	2.4d	2.7b–e	5.0ab	1.71 t	1.00B
Springhigh$_1$	2.1o	1.6 m	3.4b–d	2.5b–e	4.9ab	1.90q–t	1.06AB
Springhigh$_2$	2.5 m–o	2.5j–m	3.7a–d	2.4b–e	4.6a–d	2.04n–s	1.15z–B
Star$_1$	3.2 k–o	2.9 g–m	3.4b–d	2.8b–e	3.9a–d	2.10 m–s	1.07AB
Star$_2$	3.9 h–o	3.3e–m	3.3b–d	2.4b–e	4.1a–d	2.18 k–r	1.13z–B
Sweetcrisp$_1$	6.6a–e	6.0ab	4.7a–d	1.5c–e	5.2ab	–	2.10b–e
Sweetcrisp$_2$	7.1a–c	5.9ab	4.6a–d	2.1b–e	4.3a–d	2.57c–g	2.26a–c
Windsor	3.7i–o	3.4e–m	4.2a–d	2.5b–e	4.3a–d	2.01o–t	1.27 s–A

[a] Genotypes that appear twice were harvested at two dates in the season.
[b] Different letters within a column indicate significant differences between genotypes using Tukey's test ($P \leq 0.05$).
[c] Dash (—) indicates missing data.

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Journal of the Science of Food and Agriculture published by John Wiley & Sons Ltd on behalf of Society of Chemical Industry.

broadest range of trait variability among cultivars in both 2010 (1.7–6.8) and 2011 (2.1–7.9). Eleven (2010) and 15 (2011) Tukey groupings were identified. Selection FL 07–449 had the highest score for bursting energy in both 2010 and 2011. Panelists were able to differentiate genotypes by firmness during chewing, skin toughness, juiciness, mealiness, grittiness, and overall flavor, but observed less variability in range for these traits and fewer Tukey groupings were identified. PCA was used as an exploratory technique to identify correlations among variables, to identify groups among samples and to identify potential outliers among the samples. The first two principal components explained 94.59% and 81.78% of the total variation in 2010 and 2011, respectively. The plot of the first two components showed that juiciness was negatively correlated with mealiness, and that these two descriptors were uncorrelated with the descriptor indicators of firmness (firmness during chewing, bursting energy and skin toughness) (Figs 1 and 2). In 2011, adding the variables 'graininess' and 'blueberry flavor' did not change how juiciness, mealiness, bursting energy, firmness during chewing and skin toughness related to each other (compare Figs 1 and 2); however 'blueberry flavor' correlated positively with 'juiciness' and negatively with 'mealiness'. Likewise, the distribution of genotypes in the PCA plots was similar in both years. Most named commercial cultivars, except 'Raven', 'Kestrel' (2010) and 'Southern Belle' (2011), were on the negative side of PC1, indicating low firmness during chewing and bursting energy, while most numbered hybrids and 'Sweetcrisp' were on the positive side of PC1 (Figs 1 and 2). 'Rebel', 'Millennia' and 'Emerald' tended to have higher mealiness (or lesser juiciness) both years, as indicated by their position on the F2 axis. Genotypes receiving the highest scores for perceived bursting energy, firmness during chewing and skin toughness were also the same cultivars subjectively identified by breeders at UF to have a unique crisp texture prior to this study (Figs 1 and 2).

Instrumental analyses

FirmTech 2 (compression force) and Instron (bioyield force) measures of six genotypes were repeated on two different dates during 2010 and 2011. There was a significant year × genotype interaction ($P < 0.05$, data not shown), so results within each year were analyzed separately (Table 1). Among the cultivars replicated within the season in 2010, compression force measurements were significantly different between the two dates of evaluation for FL 98–325, 'Emerald' and 'Farthing' ($P < 0.05$), but not significantly different for 'Sweetcrisp', 'Springhigh' and 'Star' ($P > 0.05$, Table 1). Likewise, compression force measurements were significantly different between evaluation dates for FL 98–325 and 'Emerald' in 2011 ($P < 0.05$), but were not significantly different for 'Springhigh' and 'Star' ($P > 0.09$). Bioyield force measurements in 2010 were significantly different between evaluation dates for two cultivars ('Farthing' and 'Star', $P < 0.01$), but not significantly different for 'Emerald' and 'Sweetcrisp' ($P > 0.9$). In 2011, 'Emerald' was the only cultivar for which bioyield force measurements were significantly different between evaluation dates ($P < 0.001$).

There were significant differences between genotypes for compression and bioyield force measurements in 2010 and 2011 ($P < 0.05$, Tables 2 and 3). Compression force ranged from 1.58 to 3.03 N in 2010 and from 1.71 to 2.93 N in 2011, with 22 and 20 Tukey groupings identified by mean separation in 2010 and 2011, respectively. Bioyield force ranged from 1.74 to 5.04 N in 2010 and from 1.00 to 2.48 N in 2011, with 18 and 28 Tukey groupings identified by mean separation in 2010 and 2011, respectively. The scale and range of bioyield force measurements was different in 2010

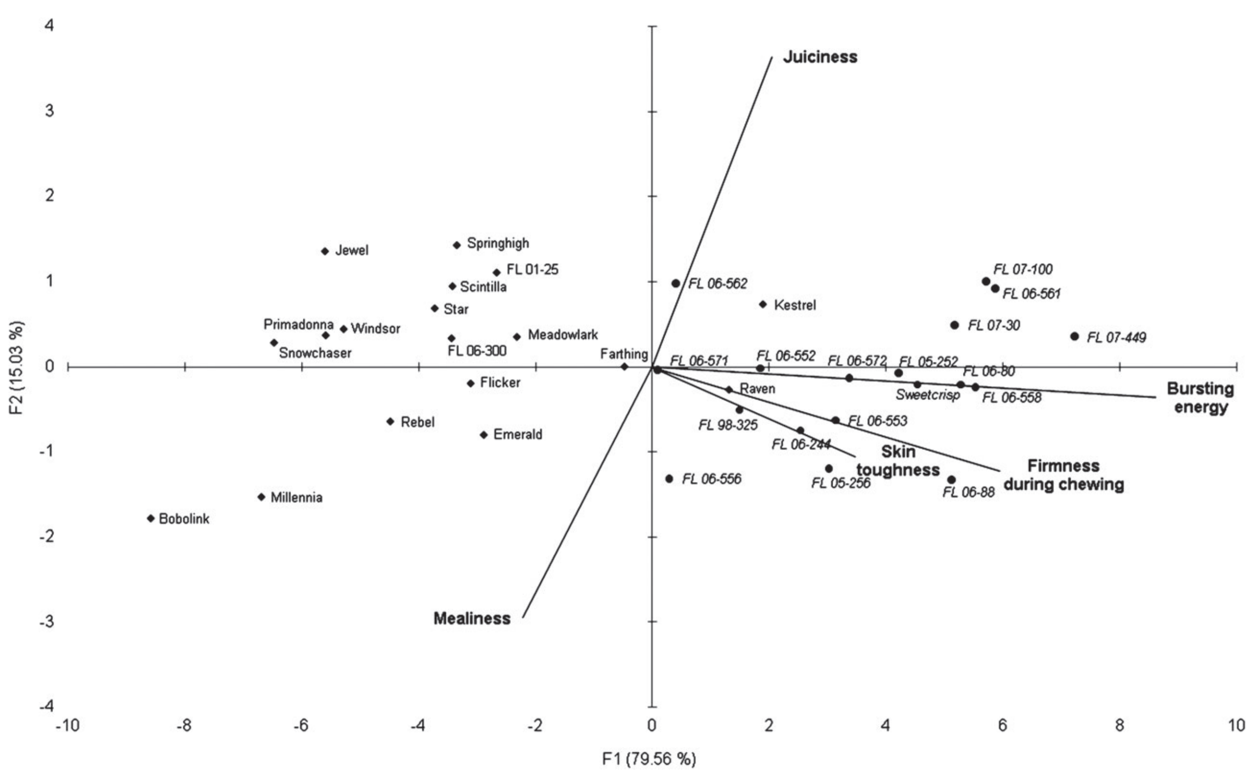

Figure 1. PCA biplot of sensory evaluation of 36 southern highbush blueberry cultivars and hybrids harvested from 5 to 24 May 2010. Genotypes subjectively evaluated as having crisp texture are in italics with circle symbols, while those with standard texture are not italicized and with diamond symbols. For each sensory variable, the arrows (vectors) are pointing to the high value of the attribute.

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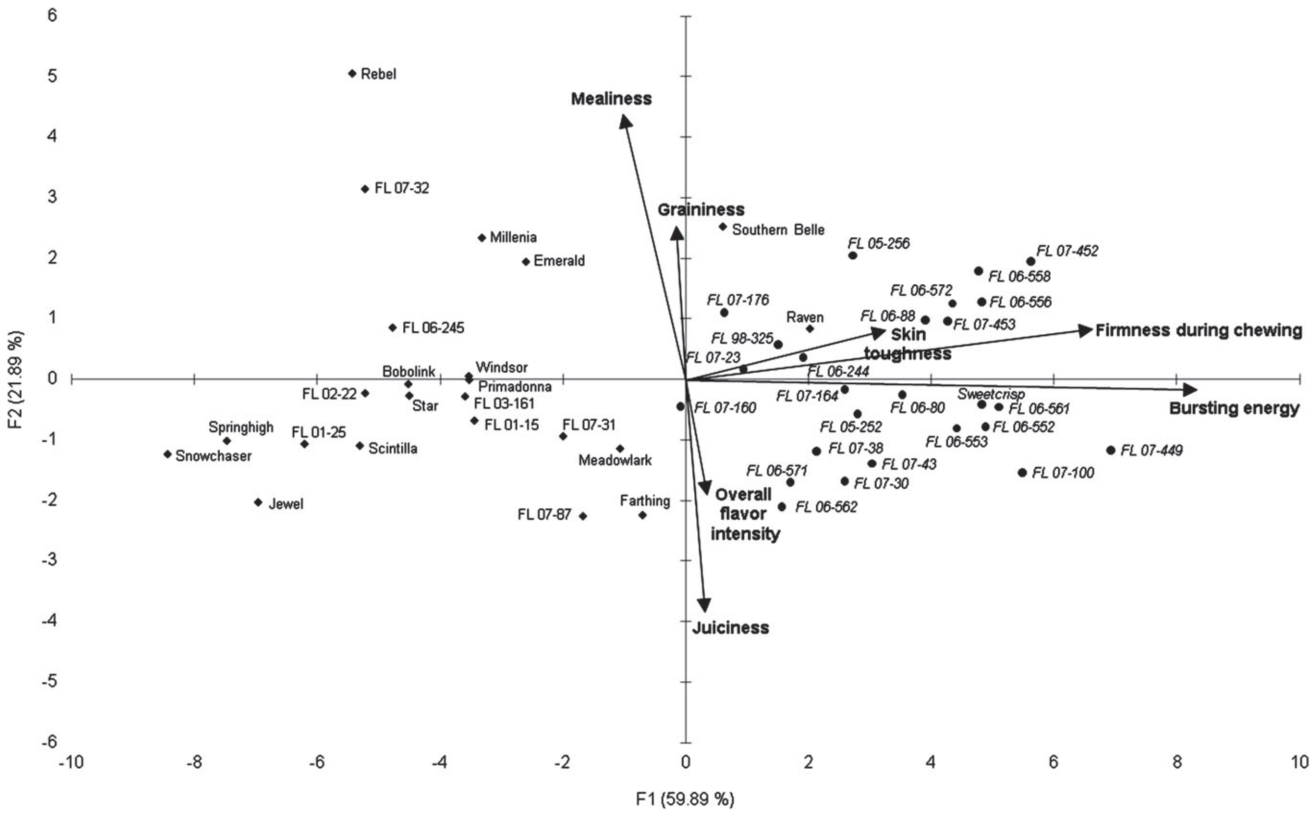

Figure 2. PCA biplot of sensory evaluation of 49 southern highbush blueberry cultivars and hybrids harvested from 18 April to 9 May 2011. Genotypes subjectively evaluated as having crisp texture are in italics with circle symbols, while those with standard texture are not italicized and with diamond symbols. For each sensory variable, the arrows (vectors) are pointing to the high value of the attribute.

and 2011 owing to the unintended use of different-sized probes, but the relationship of bioyield forces between genotypes within a year was unaffected and therefore correlations of bioyield force with compression force and sensory scores in 2010 and 2011 were comparable. Selection FL 07–449 required the greatest bioyield force in both 2010 and 2011. 'Bobolink' had the lowest bioyield and compression force in 2010, and 'Snowchaser' had the lowest bioyield and compression force in 2011. Cultivars having the greatest bioyield and compression force measurements were also the same cultivars subjectively identified by breeders at UF to have crisp texture prior to this study.

Correlation between sensory and instrumental measurements

Correlations between mean sensory measurements of bursting energy, firmness during chewing and skin toughness were significant at $P < 0.001$ in 2010 and 2011 (Tables 4 and 5). Mealiness and juiciness were negatively correlated ($P < 0.001$) in 2010 and 2011. In 2011, the additional sensory categories of graininess and flavor were added to panel evaluations. Juiciness was found to be negatively correlated with graininess ($P < 0.05$) and to be positively correlated with flavor ($P < 0.001$) (Table 5). Compression and bioyield force measurements of all cultivars and selections were correlated with an R value of 0.78 ($P < 0.001$) and 0.71 ($P < 0.001$) in 2010 and 2011, respectively (Tables 4 and 5). Individually, compression and bioyield force were highly correlated to sensory perceived bursting energy, firmness and skin toughness, but poorly correlated to perceived juiciness, mealiness, graininess and flavor (Tables 4 and 5).

DISCUSSION

The use of replicated genotypes within a season and across years revealed reproducibility of panelist ratings. Further, it showed how a genotype could differ between two harvests using one or the other instrumental measurement, and that change may or may not be perceived by the panelists. For example, FL 98–325 had a significant increase in compression force from the first to the second harvest in both years, without significant sensory attribute changes (Tables 1–3). Variable horticultural management practices between farms and blocks within a farm may have influenced sensory evaluation and instrumental firmness. For example, irrigation differences resulting in different fruit turgor could have been a factor affecting perceived bursting energy and juiciness between replication dates. 'Emerald' and 'Springhigh' were irrigated by overhead sprinklers on a three day rotation, while FL 98–325, 'Farthing' and 'Sweetcrisp' received drip irrigation daily. It is unlikely that precipitation was a factor affecting these attributes as rainfall was minimal between evaluation dates, and juiciness increased in 'Emerald' but decreased in 'Farthing' after these light rains occurred.

The relatively large grouping of crisp texture genotypes with bursting energy, firmness during chewing and skin toughness (Figs 1 and 2) may be due to the panelists' inability to differentiate between them, or to these traits being biologically linked with one another. As one might expect, juiciness and mealiness were inversely proportional to one another. Collectively, there was considerable overlap between Tukey groupings for all texture attributes (Tables 2 and 3). The lack of perceptual differences among genotypes suggests that sensory analyses may be

J Sci Food Agric 2014; **94**: 2785–2793
Journal of the Science of Food and Agriculture published by John Wiley & Sons Ltd on behalf of Society of Chemical Industry.

Table 4. Pearson correlation coefficient (*R*) values between sensory and quantitative scores for all southern highbush blueberry genotypes (*n*=36) evaluated in 2010

	Firmness during chewing[a]	Skin toughness	Mealiness	Juiciness	Compression force	Bioyield force
Bursting energy	0.94***	0.83***	−0.41**	0.27	0.81***	0.86***
Firmness during chewing		0.86***	−0.31*	0.15	0.85***	0.82***
Skin toughness			−0.16	0.10	0.75***	0.78***
Mealiness				−0.75***	−0.28	−0.37*
Juiciness					0.20	0.38*
Compression force						0.78***

[a] Significant statistical differences are indicated by asterisks:
*$P < 0.05$,
**$P < 0.01$, and
***$P < 0.001$.

Table 5. Pearson correlation coefficient (*R*) values between sensory and quantitative scores for all southern highbush blueberry genotypes ($n = 47$ to 55)[a] evaluated in 2011

	Firmness during chewing[b]	Skin toughness	Mealiness	Juiciness	Graininess	Overall flavor intensity	Compression force	Bioyield force
Bursting energy	0.93***	0.72***	−022	0.09	−0.01	0.07	0.72***	0.81***
Firmness during chewing		0.70***	−0.10	−0.03	0.05	0.04	0.72***	0.75***
Skin toughness			−0.05	−0.05	0.12	0.01	0.60***	0.78***
Mealiness				−0.75***	0.43*	−0.43*	−0.02	−0.31*
Juiciness					−0.40*	0.55***	−0.08	0.10
Compression force								0.71***

[a] $n = 55$ for sensory attributes (bursting energy, firmness during chewing, skin toughness, mealiness, juiciness, graininess and overall flavor intensity); $n = 47$ for compression force measurements; $n = 54$ for bioyield force measurements.
[b] Significant statistical differences are indicated by asterisks:
*$P < 0.05$,
**$P < 0.01$, and
***$P < 0.001$.

difficult to employ for the phenotypic evaluation of blueberry texture attributes necessary for breeding selection. Sensory analyses grouped the cultivars 'Kestrel' and 'Raven' with the subjectively identified crisp texture genotypes. Breeder evaluations of both 'Kestrel' and 'Raven' have not included them in the crisp texture grouping but, in light of the results from this study, that characterization warrants further examination. It remains unclear whether crisp texture is a new trait or the extreme expression of already characterized traits in blueberry such as firmness and skin toughness. Observing segregation patterns from putative crisp texture parents would help to elucidate the genetic basis of these cultivars considered to have a unique texture.

Analysis of variance of the instrumental measurements revealed a significant year × genotype interaction. The use of different-size probes (4 mm and 3 mm in 2010 and 2011, respectively) likely contributed to the significant year × genotype interaction for bioyield. However, the same equipment and parameters were used for compression force measurements in both years. The 2010 harvest was delayed by approximately 3 weeks due to unusually cool spring temperatures compared to 2011, and may have resulted in instrumentally measured differences, while the relative yearly differences were not apparent to the trained panel. The significant compression and bioyield force differences found between replicated genotypes within a season may result from changes in management and environmental conditions that can occur rapidly within a growing season. A similar increase in precision over sensory analysis was documented in sweet cherry, where a difference of $0.39\ \mathrm{N\ mm^{-1}}$ was required before a trained sensory panel could perceive a significant difference in cherry firmness.[27] With this potential incongruence between trained panel evaluations and instrumental measures, we used a correlative approach to align trained panel results with common instrumental measurements.

In a 2008 study of 12 highbush blueberry cultivars, compression firmness, also measured with a FirmTech 2, best correlated with juiciness ($R = 0.48$), bursting energy ($R = 0.44$) and texture during chewing ($R = 0.33$), but was not associated with skin toughness.[12] Compared to the present study, lower correlation values could be due to differences among panels or experimental design, but probably due to the narrow range of cultivar textures evaluated, which did not include crisp texture cultivars.

CONCLUSION

The objective of this study was to develop descriptors for textural traits in blueberry using a trained sensory panel, and survey a broad range of germplasm, including crisp texture genotypes to detect differences in firmness and the extent of correlation between trained panel rating and instrumental measurements of blueberry texture. We found three descriptors that align sensory evaluation of fruit texture and firmness with instrumental measures that could be used for quantitative measurements during breeding selection. Instrumental measures of compression and bioyield forces were significantly different among cultivars and correlated with sensory scores for bursting energy, flesh firmness and skin toughness. The results of sensory and instrumental measures support the distinction of crisp texture and standard texture cultivars in blueberry, and suggest that crisp texture is related to both higher compression and bioyield force measurements and to sensory perception of increased bursting energy, flesh firmness and skin toughness.

ACKNOWLEDGEMENTS

This work was supported by funding from the Florida Department of Agriculture and Consumer Services and USDA-NIFA Specialty Crop Research Initiative Award # 2008-51180-19579. The authors thank Straughn Farms for the use of their plant material, and Dr Steve Sargent for critical review of the manuscript.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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