Title: Optimizing texture assessment for muscadine grape breeding

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Introduction

Muscadine grapes (*Vitis rotundifolia* Michx.) are a disease-resistant specialty crop native to the southern United States. Muscadines have a loyal consumer base, but some fruit properties including thick skins, seedy pulp, and unstable aromas and flavors need improvement for successful market expansion. Texture is among the most important quality attributes for fresh-market grapes and has been studied extensively in V. vinifera grapes, which have a thin and tender skin that break down easily when chewed and adheres to the firm and meaty pulp (Sato et al. 1997; 2006). In contrast, muscadines typically have a thick, leathery skin, which slips from the soft pulp. While many consumers who grew up eating muscadine grapes discard the skins and/or appreciate the unique texture of this fruit, the soft pulp and leathery skin of many cultivars can be off-putting to consumers unfamiliar with muscadines. In fact, a recent consumer sensory study at the University of Florida showed that even consumer panelists familiar with muscadine grapes preferred thinner skins and concluded that breeding for thinner skins could increase the marketability of fresh-market muscadine grapes (Brown et al. 2016).

Developing new cultivars with improved flesh and skin texture is a major objective of the University of Arkansas and University of Georgia muscadine breeding programs. Selection for improved texture has already been successful; several newer cultivars such as ‘Supreme’ and ‘Lane’ have firmer flesh and more tender skins compared to older cultivars like ‘Scuppernong’ and processing types such as ‘Carlos’ and ‘Noble’ (Conner 2013). Both breeding programs have newer selections in the pipeline with even better texture than can be found in existing cultivars (Conner 2013, Barchenger 2015). Breeders initially characterize most new selections with quick sensory assessments in the field and ratings on a 1-9 scale. While these measures are quick and helpful, they are also subjective. Objective measurements of texture are helpful for supporting cultivar release decisions and choosing parents. Objective, quantitative measurements of fruit texture attributes could also be used to identify quantitative trait loci and molecular markers associated with thin skin or firm flesh that could be used in breeding programs to discard seedlings with poor texture or fast-track parents with superior texture alleles.

Berry texture characteristics are often assessed using universal testing machines that produce force deformation curves by taking precise measurements of force, time, distance, and deformation (Harker et al. 1997; Rolle et al., 2012). Penetration and compression tests are the most common tools used to assess fruit texture. In penetration tests, the arm of the texture analyzer moves down the berry to penetrate the skin and/or pulp to a fixed distance, while in compression tests the arm with attached implement compresses the whole berry and seed. Because of their slip-skin texture and large seeds, penetration tests have been used to measure muscadine firmness far more than compression tests.

Co-PI Conner (2013) used penetration tests with 2mm and 5mm flat cylindrical probes to evaluate a range of skin and flesh texture attributes in 26 muscadine cultivars and selections. Penetration tests of whole berries were used to measure berry deformation at first peak (mm) and berry maximum force (N) and to calculate berry penetration work (mJ). Fruit with a portion of the skin removed and a section of skin placed 1-mm thick polypropylene stage into which a 6-mm hole had been drilled were used to assess flesh maximum force (N) and skin break force (N) respectively. Firm fruit with tender skins are expected to have smaller berry deformation at first peak and lower berry maximum force than soft fruit or fruit with a tougher skin (Sato and Yamada, 2003). Conner (2013) found significant variation in muscadine berry texture for all attributes evaluated. As expected, older cultivars such 'Scuppernong' and 'Thomas' had higher berry deformation at first peak and lower flesh maximum force than firm fleshed cultivars like 'Lane' and newer breeding selections. Some newer selections were identified with a skin break force equivalent to *V. vinifera* (Conner 2013). Barchenger et al. (2015) also found a two-fold variation in berry maximum force among 17 muscadine genotypes in a similar study performed at the University of Arkansas.

Based on these results, Conner (2013) selected berry penetration work and flesh maximum force as the most useful attributes to measure for routine screening in breeding programs. Though skin break force seemed to be a useful measurement, it was too labor intensive to recommend for routine screening. Furthermore, the positive correlation between skin break force and berry deformation at first peak suggested that whole berry penetration tests were also a useful measure of skin tenderness or friability. Still, the time required to individually measure twenty berries per sample with penetration makes this method impractical for assessments of large segregating populations. Furthermore, other methods may better approximate human chewing of muscadine skins than penetration with a small flat probe.

The Kramer Shear cell is the most frequently used method for measuring the shear or extrusion properties of fruit tissue and may be a useful replacement or complement to penetration tests in muscadine grape (Harker et al. 1997). Shear is a strain in the structure of a substance, produced by pressure when its layers are laterally shifted in relation to each other. The Kramer shear cell simulates a single bite and provides information about bite characteristic, crispiness and firmness. The Kramer shear cell is a multi-bladed fixture that can be attached to universal testing device to measure compression, bulk shear, and extrusion forces for samples with irregular shapes and sizes. The shear cell consists of a small box with a grated base that is filled with a fixed amount of berries or other specimens. As five parallel blades move downward through the box at a constant speed, the berries are first compressed, then extruded, and finally sheared as the blades penetrate the bottom slots. The forces needed for the blades to move through the box relate to berry texture.

The Kramer Shear cell has been used to characterize fruit crispness in other small fruit including blueberry and raspberry (Sousa et al. 2005; Chiabrando et al. 2009). Shear cell measurements have also recently been adopted by the table grape community. Team members of the USDA-NIFA Specialty Crops Research Initiative funded project VitisGen II are using Kramer Shear cells to macerate grape berries twice and calculate gumminess, chewiness, and springiness of each cluster and applying these results for QTL mapping (Naegele, personal communication).

Methods

Plant Materials and Harvest

Five advanced selections from the University of Arkansas breeding program AM 9, AM 49, AM 83, AM 131, AM 154 and three commercially available cultivars ‘Carlos’, ‘Ison’ and ‘Nesbitt’ were selected for use in this project. Ten 1-lb clamshells of each cultivar were harvested from the University of Arkansas Fruit Research Station (FRS) in Clarksville, AR on September 17, 2018 and two table grape cultivars ‘Sugar Crunch’ and ‘Cotton Candy’ were purchased for use as checks in the analytical analysis.

Randomization

After harvest was complete, fruit was transported from the FRS to the Department of Food Science in Fayetteville, Arkansas. Fruit from each genotype was mixed and re-sorted into five 1-lb clamshells which were randomly assigned to the four analytical texture analysis methods and sensory analysis. During randomization immature and overripe fruit and any berries that displayed obvious deformity, wet picking scar, or other damage were discarded.

Descriptive Sensory Analysis

Descriptive sensory analysis of the muscadine genotypes was conducted at the Sensory Research and Consumer Center in the Food Science Department at the University of Arkansas on September 18, 2018. The descriptive panelists developed a fresh-market muscadine lexicon of sensory terms in 2017 (Felts et al. 2018). The panelists (n=9) used a modified Sensory Spectrum® method, an objective method for describing the intensity of attributes in products using references for the attributes. The descriptive panel evaluated each sample for 10 texture attributes (Table 1) and evaluate those attributes using a 15-point scale (0=less of an attribute, 15=more of an attribute). The descriptive sensory evaluation was performed in duplicate with randomized presentation order of each of the eight muscadine genotypes within each replication.

Breeders’ Ratings

University of Arkansas muscadine grape breeders, John Clark and Margaret Worthington, rate all breeding selections and check cultivars for attributes including skin and flesh texture on a 1-9 scale each year, with 1 = soft, mucilaginous flesh or thick skin that does not break apart when chewed and 9 = firm, meaty, non-slipskin flesh or thin, crisp skins that break apart easily when chewed. Breeders’ ratings from three years (2016-2018) for each of the muscadine genotypes were analyzed in this study.

Texture Analysis

Texture analysis with all four probes was performed within 24 hours of harvest. All berries used for texture analysis were individually weighed (g) and measured for diameter across the equatorial plane (mm).

Penetration Analysis: Fruit firmness was measured by penetration using a TA.XTPlus Texture Analyzer (Texture Technologies Corporation, Hamilton, MA) with a 5 kg load cell. Fifteen randomly selected berries per genotype were subjected to penetration tests with 2-mm flat cylindrical probe. Penetrations were made on the equatorial plane of each berry with a probe speed of 1 mm.sec^{-1}. Berry skin break force (N) was calculated as the force required to rupture the berry skin. Elasticity was calculated as mm the berry was compressed before the skin was ruptured. Skin firmness was calculated as skin break force (N) / elasticity (mm) following Felts et al. (2018). Berry penetration work (mJ) was calculated as the area under the curve from zero to the point of berry maximum force following Conner (2013). Because the genotypes varied significantly in size and diameter, additional variables were created for berry skin break force and skin firmness divided by berry diameter.

Compression Analysis: Compression tests were performed using a TA.XTPlus Texture Analyzer (Texture Technologies Corporation, Hamilton, MA) with a 5 kg load cell. Fifteen randomly selected berries per genotype were subjected to compression with a 10-mm flat cylindrical probe. Compressions were made on the equatorial plane of each berry with a probe speed of 1 mm.sec^{-1}. After the probe contacted the berry surface, it continued a further 9 mm to penetrate the skin. Berry hardness was calculated as the maximum force exerted by the probe (Sato et al. 1997).

Single Blade Analysis: Fifteen randomly selected berries per genotype were subjected to single blade shear tests performed using a TA-42 (knife blade with 45 degree chisel end) on a TA.XTPlus Texture Analyzer (Texture Technologies Corporation, Hamilton, MA) with a 5 kg load cell. The knife blade sheared each berry on the equatorial plane with a probe speed of 2 mm.sec^{-1}. The blade traveled a total of 8.0 mm or until the knife blade contacted the work surface. Berry skin shear force (N) was calculated as the maximum amount of force generated by the probe. Elasticity was calculated as the distance (mm) the berry was compressed before the skin was ruptured by the blade. Skin firmness was calculated as berry skin break shear force (N) / elasticity (mm). Because the genotypes varied significantly in size and diameter, additional variables were created by dividing skin shear force and skin firmness by berry diameter.

Kramer Shear Cell Analysis: Kramer shear tests were also performed on a TA.XTPlus Texture Analyzer (Texture Technologies Corporation, Hamilton, MA) with a 5 kg load cell. The box at the cell base was filled with six berries. The sample was then macerated in two cycles with a probe speed of 1 mm.sec^{-1}. This process was replicated three times for each genotype. While the first maceration cycle of the Kramer Shear Cell yielded data representative of compressing and shearing a berry, the second maceration cycle often resulted in the skins and seeds of the berries obstructing the blade outlet, resulting in a load cell overload and a second force measurement was often greater than that of the initial cycle and unrepresentative of the maceration of the fruit during consumption. Due to this complication, the second cycle measurement was not used for analysis. Shear force was calculated as maximum force (N) during the first maceration cycle. An additional variable was created by dividing shear force by berry diameter.

Statistical Analysis

Analytical texture data was analyzed using PROC GLM in SAS 9.2 (SAS Institute Inc., Cary, NC). Descriptive sensory data was analyzed using PROC MIXED with genotype considered a fixed effect and panelist and genotype x panelist interaction considered random effects. Breeders' ratings were also analyzed using PROC MIXED with genotype as a fixed effect and year and genotype x year interaction as random effects. Mean separation for significant factors was performed using Tukey's Honestly Significant Difference. PROC CORR was used to conduct Pearson correlations between the physical measurements of texture and sensory analysis and breeders' ratings.

Results and Discussion

Descriptive Sensory Analysis and Breeders' Ratings

The descriptive sensory panel identified significant differences among genotypes for visual separation, number of seeds, seed size, hardness, crispness and detachability (Table 2). AM-131 scored the highest and 'Ison' the lowest in visual separation, number of seeds, hardness, crispness and detachability. The eight muscadine genotypes also differed significantly for breeders' ratings (Table 3). AM-154 and 'Carlos' received the highest and lowest ratings, respectively, for skin and flesh texture attributes from 2016-2018. All attributes evaluated by the sensory panel with significant differences among genotypes were significantly correlated to breeders' flesh and skin texture ratings with the exception of the number of seeds (Table 4).

Texture Analysis

Significant differences in flesh and skin texture were found between genotypes using all four Texture Analysis probes.

Penetration Analysis: There were significant differences among genotypes for all of the textural characteristics measured using penetration tests with the 2 mm flat probe (Table 5). The table grapes 'Cotton Candy' and 'Sugar Crunch' had significantly lower berry skin break force, elasticity, skin firmness, and berry penetration work than any of the eight muscadine genotypes tested. However, most penetration measurements were not significantly correlated with breeders' ratings and descriptive sensory evaluations (Table 6). The lack of correlation between puncture measurements and breeder ratings is in contrast to Connor's findings in 2013, where the puncture measurements of improved muscadine germplasm were more closely related table grapes than to older cultivars such as Nesbitt. However, while Connor punctured the flesh and skin separately, we conducted the analysis on whole berries. The differences in results between the two methodologies may be due to the influence of flesh texture. It should also be noted that a lack of correlation between puncture measurements and breeder notes may be because the small surface area of the 2mm puncture probe compresses and punctures the berry differently than human teeth. Rupture/width was moderately correlated with the breeder skin score ($r = -0.54$, $P < 0.0014$). Elasticity was moderately correlated with both visual separation ($r = 0.45$, $P < 0.008$) and breeder skin score (*r* =-0.51, *P* <0.0025) and skin crispness was also moderately correlated with breeder skin score (*r* =-0.63, *P* <0.0001).

Compression Analysis: While the genotypes differed significantly in hardness measured by compression (Table 7), nine millimeters of compression was not significant enough to rupture the skin of all of the genotypes and some genotypes required less than 9 mm of compression for the skin to split. Differences in the amount of amount of compression or the distance travelled were taken into account by dividing the force measurement over the distance travelled. This adjustment appears to be unnecessary due to the unadjusted measurement being more closely correlated to both breeder and sensory panel scores (Table 8). Hardness was correlated with both visual separation (*r* =-0.62, *P* <0.0001) and detachability (*r* =-0.61, *P* <0.0001) as measured by the sensory panel. Indicating that the compression plate can be used to identify gelatinous flesh, which can be both easily separated from the skin and compressed. Further research into whether or not the compression plate can accurately measure differences in flesh texture among improved muscadine genotypes is needed.

Single Blade Analysis: Significant differences were found among genotypes for skin rupture, skin elasticity, skin firmness and skin crispness measured by the TA-42 single knife blade (Table 9). When the blade pressed against the skin of some of the slip-skin genotypes the, flesh was expelled from the skin instead of sheared (Figure 1a). However, genotypes with non-slip skin texture, such as AM-131 (Figure 1b), were sheared in a similar manner as the table grapes (Figure 1c). Interestingly, high skin firmness and skin shear force was correlated with high breeders' ratings for flesh texture (*r* =-0.85, *P* <0.001) and skin texture (*r* =-0.61, *P* <0.001) (Table 10).

Kramer Shear Cell Analysis

Significant differences in flesh and skin texture were found between genotypes using the first maceration cycle of KSC (Table 11) and first maceration cycle or bite was significantly correlated to the breeders' ratings all descriptive sensory panel attributes except number of seeds (Table 12). However, the skin and seeds of the muscadine berries presented a mechanical challenge to the use of the KSC. Where non-slip skin muscadine lines and the table grape checks were macerated twice (Figure 2a), the skin and seed of the slip skin lines obstructed the second maceration cycle resulting in a failed measurement (Figure 2b).

Conclusion

In this project we showed that there are multiple methods to evaluate muscadine skin and flesh texture. However, upon assessing correlations between these methods/probes with one another, breeder notes, and the results of the Descriptive Sensory Analysis, it is evident that some texture analysis probes better represent the first bite of human maceration of the fruit than others. Specifically, the TA-42 single knife blade that was very strongly correlated both with the breeder flesh texture notes (*r* = 0.85, *P* <0.0001) and the seed size measurements (*r* =-0.71, *P* <0.0001) from the sensory panels. Significant correlations across both the breeder notes and sensory panel were also observed for the initial maceration cycle of the KSC and while the KSC and single blade correlations for both hardness and crispness descriptors from the sensory panel and the breeder skin ratings were very similar the single knife blade was more closely (*r* = 0.84) correlated to the breeder texture notes than the KSC (*r* = 0.48). The differences in correlations may have been due to inclusion of slip-skin muscadines into the textural analysis. When a slip-skin muscadine is compressed during the initial bite of human maceration or by the single blade probe, the flesh is expelled from skin and not compressed/macerated. However, the multiple blades of the KSC do not allow for the flesh to escape compression/maceration and the flesh is accounted for in the corresponding measurement. Suggesting that while the single blade probe is more closely correlated to the breeder and sensory panel notes, the KSC more accurately measures the force needed to shear slip skin berries. Additional shear research with and without slip skin muscadines is needed to determine which shear probe is best suited for use in muscadine textural analysis.

However, this should not discourage further investigation into the use of the KSC for textural analysis of muscadine grapes. While the single knife blade has shown promise in measuring both skin and flesh texture it is limited to shear and compression measurements. Past research (R. Naegele, personal communication), has shown that the KSC can be used to measure hardness, gummy, and chewiness in table grapes. While the KSC has been successfully used in seedless table grapes (R. Naegele, personal communication), the slip-skin texture and large seeds of muscadine grapes may limit its use until significant improvements to the muscadine germplasm are made so that second maceration cycle of the KSC is not impeded by skins nor seeds. It is possible that modifications to the KSC protocol (e.g. modifying the amount of fruit used and the receptacle in which the macerations take place) may allow us to collect additional measurement on the second maceration cycle in follow-up experiments. Gumminess, chewiness, and springiness have been measured in blueberries (Chiabrando 2009) by analyzing multiple compression cycles of a 10mm disk. If further research determines that the same procedure can be used with muscadines it would eliminate the need to accommodate skins and seeds as well as well as decrease the amount of fruit needed for analysis.

Interestingly, the skin firmness and skin rupture measurements generated using the 2mm flat puncture probe were not correlated with breeders' skin or flesh texture ratings or the descriptive sensory panel crispness attribute. This may be due the gelatinous flesh of some genotypes failing to act as a spring and not exerting force upwards towards the point of contact of the probe, influencing both skin and flesh measurements. Past research has removed this effect (Connor, 2013) by removing a portion of the berries skin and measuring skin firmness and flesh texture separately; however, this procedure would not be appropriate for high through put screening. While breeders and sensory panelist are able to determine overall palatability of the cultivars, they may not be able to differentiate individual components that contribute to the palatability. Further investigation into penetration measurements is needed to determine which methods are accurately measuring improved skin texture and whether or not breeders and sensory panelists are able to distinguish skin crispness when macerating a whole berry.

As we continue to develop analytical methods to measure muscadine textural characteristics we plan to continuing to develop a standard operating procedure for the sensory panel that more accurately identifies differences among muscadine grapes as well as having the panel rate the skin and flesh separately. The continued development of textural analysis for muscadines will allow for a higher throughput of unbiased objective measurements that will help plant breeders identify QTL for skin and flesh texture attributes, release cultivars with improved skin and texture, and ultimately improve the marketability of fresh-market muscadine grapes.

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Table 1. Lexicon developed for descriptive sensory analysis of texture-related attributes in muscadine grape

Term	Definition	Technique	Reference	
Appearance (pulp of one berry cut in half)				
Visual separation	Detachability of pulp from skin of berry	Squeeze half of berry and observe the extent of which the pulp detaches from the skin. (none to much)	None=0 Much=15.0	
Amount of seeds	Number of seeds in the whole berry	Count the number of seeds in the whole berry	Number of seeds	
Seed size	Visual size of the seeds	Observe the seeds and determine the overall size. (small to large)	Photo reference of size A=12 (5.3 x 8.5 mm) B=7 (4.9 x 7.1 mm) C=3 (3.9 x 6.1 mm)	
Texture (whole berry)				
Berry hardness	Force required to compress the sample.	Place the sample in the mouth. Compress or bite through the sample one time with molars or incisors. (soft to hard)	Cream Cheese Egg White Am Cheese Beef Frank Olive Peanut Almond	1.0 2.5 4.5 5.5 7.0 9.5 11.0
Berry crispness	Unique, strong, clean, and acute sound produced in first bite of the food with incisors and open lips.	Place the sample in the mouth. Compress or bite through the sample one time with molars or incisors. Evaluate the sound intensity produced at the first bite. (none to much)	Ripe Banana Granny Smith Apple Carrot	0.0 7.5 15.0

Moisture release	Amount of wetness or moistness felt in the mouth after one bite or chew.	Compress the sample with molars one time only. (Dry to Wet)	Banana Carrot Mushroom Snap Beans Cucumber Apple Honeydew Orange (Chew refs 5 times)	1.0 2.0 4.0 7.0 8.0 10.0 12.0 15.0
Awareness of skins	How aware are you of the skins during mastication of the sample?	Place sample in mouth and chew 3-5 times. Can also be evaluated in first bite stage. (none to much)	Baked Beans Medium Lima Beans	4.0 8.0
Detachability	Ease with which the pulp separates from the skin of the berries	Place the sample in the mouth. Compress or bite through the sample one time with molars or incisors. Evaluate the ease that the pulp separates from the skin. (none to much)	None=0.0 Much=15.0	
Fibrousness between teeth	Amount of grinding of fibers required to chew through the sample (not including skins)	Place sample between molars and chew 3-5 times. Evaluate during chewing, but ignore the skin. (none to much)	Apple Apricot Salami Celery Toasted Oats (4-5) Bacon Beef Jerky	2.0 5.0 7.0 9.0 10.0 12.0 20.0
Seed separation	The ease with which the seeds separate from the pulp of the berry	Manipulate the pulp in the mouth for ease to separate seeds from pulp. (none to much)	None=0.0 Much=15.0	

Table 2. Muscadine texture characteristics measured by the descriptive sensory panel

Genotype	Visual separation	No. of seeds	Seed size	Berry hardness	Berry crispness	Moisture release	Awareness of skins	Detachability	Fibrousness	Seed separation
AM-131	7.32 a	3.89 ab	5.56 a	7.81 a	8.29 a	10.11 a	11.41 a	9.28 a	4.52	9.72
AM-154	9.79 abc	2.89 a	6.37 abc	7.70 ab	8.12 ab	10.78 ab	12.37 a	12.05 bc	4.48	10.66
AM-49	9.42 abc	3.33 ab	5.92 ab	7.66 ab	8.35 a	10.84 ab	11.49 a	10.54 abc	4.13	10.24
AM-83	11.42 bcd	3.33 ab	6.07 ab	7.71 ab	8.23 ab	10.38 ab	12.44 a	12.63 bc	4.20	10.16
AM-9	11.68 bcd	3.17 ab	6.41 abc	7.04 bc	7.41 ab	10.67 ab	12.26 a	12.61 bc	4.20	10.35
Carlos	12.12 cd	3.78 ab	7.57 c	7.00 bc	7.21 ab	10.42 ab	12.51 a	12.94 c	4.04	10.51
Ison	13.36 d	4.22 b	6.93 bc	6.71 c	7.09 b	11.12 b	12.17 a	13.39 c	4.48	10.39
Nesbitt	11.51 bcd	2.94 a	6.65 abc	7.69 ab	8.14 ab	10.66 ab	12.55 a	12.69 bc	4.50	9.63
P	<.0001	0.0081	<.0001	<.0001	0.0015	0.0389	0.0203	<.0001	0.4203	0.5868

[z] Mean separation within columns by Tukey's honestly significant difference ($P \leq 0.05$).

Table 3. Breeders' ratings of muscadine texture from 2016-2018

Genotype	Flesh texture	Skin Texture
AM-131	8.67 ab[z]	8.33 ab
AM-154	9.00 a	8.67 a
AM-49	7.67 ab	7.67 abc
AM-83	7.33 abc	6.00 cd
AM-9	7.33 abc	7.67 abc
Carlos	5.00 d	4.67 d
Ison	6.67 bcd	6.67 cd
Nesbitt	6.00 cd	6.00 cd
P	0.0002	<0.0001

[z] Mean separation within columns by Tukey's honestly significant difference ($P \leq 0.05$).

Table 4. Correlations among muscadine texture characteristics measured by descriptive sensory analysis and breeders' evaluations

	Visual separation	No. of seeds	Seed size	Berry hardness	Berry crispness	Moisture release	Detachability	Flesh texture[z]	Skin texture
Visual separation		0.15	0.78**[y]	-0.77**	-0.75**	0.54**	0.96**	-0.71**	-0.66**
No. of seeds	0.15		0.20	-0.53**	-0.50**	-0.02	-0.06	-0.23	-0.23
Seed size	0.78**	0.20		-0.72**	-0.80**	0.31	0.78**	-0.81**	-0.72**
Berry hardness	-0.77**	-0.53**	-0.72**		0.98**	-0.48**	-0.64**	0.55**	0.38*
Berry crispness	-0.75**	-0.50**	-0.80**	0.98**		-0.36*	-0.67**	0.58**	0.43*
Moisture release	0.54**	-0.02	0.31	-0.48**	-0.36*		0.49**	-0.07	0.08
Detachability	0.96**	-0.06	0.78**	-0.64**	-0.67**	0.49**		-0.63**	-0.61**
Flesh texture	-0.71**	-0.23	0.81**	0.55**	0.58**	-0.07	-0.63**		0.93**
Skin texture	-0.66**	-0.23	0.72**	0.38*	0.43*	0.08	-0.61**	.93**	

[z] Flesh texture and skin texture values from breeders' evaluations on a 1-9 scale from 2016-2018

[y] *, ** r significantly different from zero at $P \le 0.05$ and $P \le 0.001$, respectively

Table 5. Muscadine texture characteristics measured using penetration with a 2 mm flat probe

Genotype	Berry skin break force (N)	Berry skin break force (N) / berry diameter (mm)	Elasticity (mm)	Skin firmness ($N.mm^{-1}$)	Skin firmness ($N.mm^{-1}$) / berry diameter (mm)	Berry penetration work (mJ)
AM-131	56.98 ab[z]	2.46 a	8.37 cde	6.83 a	20.64 c	239.09 a
AM-154	50.79 d	2.05 b	7.70 e	6.60 a	15.76 ed	179.30 b
AM-49	44.19 f	1.82 c	7.99 de	5.57 b	14.66 e	181.74 b
AM-83	56.06 bc	2.53 a	12.63 a	4.52 c	31.95 a	149.89 c
AM-9	48.73 ed	1.90 bc	8.94 bcd	5.46 bc	17.00 ed	190.39 b
Carlos	52.54 cd	2.57 a	9.44 bc	5.59 b	24.25 b	220.49 a
Cotton Candy	11.49 g	0.53 d	4.83 f	2.33 d	2.64 f	27.13 d
Ison	45.17 ef	1.85 bc	10.02 b	4.67 bc	18.29 cd	177.85 b
Nesbitt	60.75 a	2.45 a	8.22 cde	7.58 a	20.17 c	242.84 a
Sugar Crunch	5.44 h	0.25 e	3.72 f	1.57 d	0.87 f	10.71 d
P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

[z] Mean separation within columns by Tukey's honestly significant difference ($P \leq 0.05$).

Table 6. Correlations among muscadine texture characteristics collected using the 2mm flat probe , Sensory panel analysis and breeder notes

	Visual sep	No. of seeds	Seed size	Hardness	Crispness	Detachability	Flesh texture [z]	Skin Score
Rupture	-0.21	-0.27	-0.10	0.52*	0.39*	-0.08	-0.12	-0.26
Rupture /width	-0.12	0.01	0.11	0.35	0.20	-0.03	-0.33	-0.54*
Elasticity	0.46*	0.28	0.10	-0.19	-0.17	0.42*	-0.26	-0.52*
Rupture/ Elasticity	-0.50*	-0.44*	-0.17	0.54*	0.44*	-0.38*	0.16	0.27
(Rupture*Elasticity)/width	0.21	0.15	0.09	0.11	0.04	0.24	-0.32	-0.62**
Skin work	-0.29	0.07	0.11	0.13	0.03	-0.31	-0.27	-0.11

[z] Flesh texture and skin texture values from breeders' evaluations on a 1-9 scale from 2016-2018

[y] *, ** *r* significantly different from zero at $P \leq 0.05$ and $P \leq 0.001$, respectively

Table 7. Muscadine texture characteristics measured by compression analysis

Genotype	Hardness (N)	Hardness (N) / elasticity (mm)
AM-131	1172.08 a[z]	119.82 a
AM-154	597.81 c	60.80 c
AM-49	532.00 cd	55.37 cd
AM-83	401.07 d	40.11 d
AM-9	524.60 cd	52.46 cd
Carlos	397.55 d	39.76 d
Cotton Candy	876.15 b	87.65 b
Ison	543.44 cd	55.06 cd
Nesbitt	954.71 b	100.68 b
Sugar Crunch	943.84 b	95.18 b
P	<0.0001	<0.0001

[z] Mean separation within columns by Tukey's honestly significant difference ($P \leq 0.05$).

Table 8. Correlations among muscadine texture characteristics collected using the using Compression Plate, Sensory panel analysis and breeder notes

	Visual sep	No. of seeds	Seed size	Hardness	Crispness	Detachability	Flesh texture [z]	Skin Score
Hardness	-0.62**	0.02	-0.47*	0.49*	0.44*	-0.61**	0.32	0.38*
Hardness /distance	-0.60**	0.01	-0.46*	0.49*	0.45*	-0.60**	0.30	0.37*

[z] Flesh texture and skin texture values from breeders' evaluations on a 1-9 scale from 2016-2018

[y] *, ** *r* significantly different from zero at $P \leq 0.05$ and $P \leq 0.001$, respectively

Table 9. Muscadine texture characteristics measured by TA-42 single knife blade

Genotype	Skin shear force (N)	Skin shear force (N) / diameter (mm)	Elasticity (mm)	Skin firmness (N.mm^{-1})	Skin firmness (N.mm^{-1}) / diameter (mm)
AM-131	1325.65 a[z]	58.64 ab	19.46 cd	70.90 a	1145.89 cb
AM-154	1381.50 a	56.36 b	22.49 ab	63.21 a	1279.13 ab
AM-49	994.43 bc	42.93 c	23.11 a	43.71 bc	1010.67 cd
AM-83	1372.18 a	62.40 a	20.90 bc	69.29 a	1316.83 a
AM-9	1012.42 b	42.32 c	21.90 ab	48.86 bc	909.94 ed
Carlos	776.49 d	39.67 cd	18.66 d	40.17 c	774.62 ef
Cotton Candy	628.98 e	31.70 e	21.66 ab	29.28 d	688.24 f
Ison	880.95 cd	36.74 de	18.53 d	49.41 b	683.52 f
Nesbitt	801.06 d	32.14 e	12.42 f	66.77 a	397.14 g
Sugar Crunch	380.73 f	18.33 f	16.30 e	23.66 d	300.10 g
P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

[z] Mean separation within columns by Tukey’s honestly significant difference ($P \leq 0.05$).

Table 10 Correlations among muscadine texture characteristics collected using the TA-42 single knife blade, Sensory panel analysis and breeder notes

	Visual sep	No. of seeds	Seed size	Hardness	Crispness	Detachability	Flesh texture [z]	Skin Score
Rupture	-0.60**	-0.21	-0.71**	0.61**	0.59**	-0.46*	0.85**	0.61**
Elasticity	-0.30	-0.04	-0.37*	0.03	0.10	-0.29	0.58**	0.52**
Skin Firmness	-0.43*	-0.28	-0.57**	0.70**	0.64**	-0.29	0.49**	0.29
(Rupture*Elasticity)/Width	-0.53*	-0.12	-0.58**	0.44*	0.45*	-0.43*	0.74**	0.50*

[z] Flesh texture and skin texture values from breeders' evaluations on a 1-9 scale from 2016-2018

[y] *, ** *r* significantly different from zero at $P \leq 0.05$ and $P \leq 0.001$, respectively

Table 11. Muscadine texture characteristics measured by Kramer Shear Cell

Genotype	Shear force (N)	Shear force (N) / berry diameter (mm)
AM-131	5962.40 ab [z]	264.18 a
AM-154	5608.60 bc	227.44 b
AM-49	4900.10 cde	210.66 bc
AM-83	4188.20 ef	190.11 c
AM-9	5007.30 cd	209.86 bc
Carlos	2873.10 g	137.34 d
Cotton Candy	3701.80 f	186.96 c
Ison	4759.50 de	198.39 bc
Nesbitt	6675.70 a	270.05 a
Sugar Crunch	1804.90 h	86.90 e
P	<0.0001	<0.0001

[z] Mean separation within columns by Tukey’s honestly significant difference ($P \leq 0.05$).

Table 12. Correlations among muscadine texture characteristics collected using the KSC, Sensory panel analysis and breeder notes

	Visual sep	No. of seeds	Seed size	Hardness	Crispness	Detachability	Flesh texture [z]	Skin Score
Bite-one / Width	-0.54* [y]	-0.33	-0.63**	0.60**	0.61**	-0.49*	0.52*	0.58**

[z] Flesh texture and skin texture values from breeders' evaluations on a 1-9 scale from 2016-2018

[y] *, ** *r* significantly different from zero at $P \leq 0.05$ and $P \leq 0.001$, respectively

Table 13 Correlations among select texture measurement collect from multiple texture probes

	Compression - Hardness	Puncture - Rupture/width	Puncture - Rupture/Elasticity	Single blade - Rupture /width	Single blade - (Rupture*elasticity)/width	KSC - Bite /width
Compression - Hardness		0.26	-0.21	0.14	0.61** ^{z}	0.86**
Puncture - Rupture/width	0.26		0.77**	0.10	0.46*	-0.03
Puncture - Rupture/Elasticity	-0.21	0.77**		0.21	0.35*	-0.34
Single blade - Rupture /width	0.14	0.10	0.21		0.65**	0.27
Single blade - (Rupture*elasticity)/width	0.61**	0.46*	0.35*	0.65**		0.69**
KSC - Bite /width	0.86**	-0.03	-0.34	0.27	0.69**	

^{z} *, ** *r* significantly different from zero at $P \le 0.05$ and $P \le 0.001$, respectively

Figure 1. TA-42 single knife blade slicing (a) ‘Nesbitt’, (b) ‘AM-131’, and (c) ‘Cotton Candy’ table grape

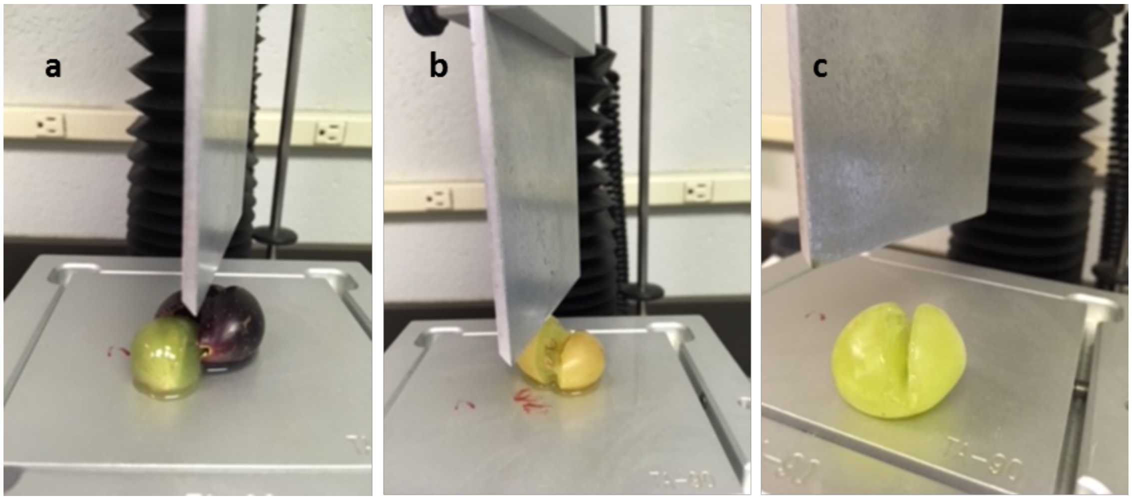

Figure 2. Samples of (a) ‘Cotton Candy’ table grape and (b) ‘Nesbitt’ muscadine after one cycle of shearing with the Kramer Shear Cell.