A Comparison of Firmness Assessment Instruments for Fresh Blueberry Fruit

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ADDITIONAL INDEX WORDS. durometer, fruit texture, ripening, SS/TA, *Vaccinium*

SUMMARY. Fresh fruit from northern highbush blueberry (*Vaccinium corymbosum*) and rabbiteye blueberry (*Vaccinium ashei*) are highly perishable, so reaching distant markets while maintaining superior quality and value is a challenge. Although firmness is one of the most critical traits of blueberries (*Vaccinium* sp.), most of the industry relies on a subjective-tactile assessment or on the use of low-cost texture analyzers, whereas scientists tend to rely on the FirmTech II instrument. In the present study, the FirmTech II was evaluated as a texture analyzer and compared with tactile estimation, two other FirmTech II devices, and three relatively inexpensive durometers (Penefel, Durofel, and DM1600). Tests were run for fruit previously segregated by tactile (T) measurements into three classes of firmness: Soft-T, Moderate-T, and Firm-T; fruit were classified into instrument-based (I) categories of texture: Soft-I, Moderate-I, and Firm-I using the FirmTech II instrument. The level of coincidence between T and I assessments were higher in the soft (90.7% to 92.6%) and moderate (69.6% to 78.2%) classes compared with the firm class (51.6% to 61.4%). Among firmness categories, T and I assessments tended to agree; none of the Soft-T fruit were classed as Firm-I. In comparisons between equivalently calibrated FirmTech II devices, concordance always decreased as fruit firmness increased, indicating that more reproducible readings for a given instrument could be expected from softer fruit. Dual measurements on a single fruit for FirmTech II and a second device yielded variable, but significant correlation coefficients (Penefel: $r^2 = 0.61$ to 0.67 ; Durofel: $r^2 = 0.48$ to 0.61 ; DM1600: $r^2 = 0.08$ to 0.49). The highest correlation existed between two FirmTech II devices ($r^2 = 0.94$ to 0.95). However, correlations between the FirmTech II and second devices among the three firmness classes yielded very low correlation coefficients (Penefel: $r^2 = 0.09$ to 0.40 ; Durofel: $r^2 = 0.05$ to 0.32 ; DM1600: $r^2 = 0.00$ to 0.25 ; FirmTech II: 0.03 to 0.33), suggesting that although all instruments were suitable for evaluating across broad ranges of fruit firmness, they were all similarly unsuitable within a narrow firmness range (e.g., for all soft or all firm fruit). Given the subjectivity of the tactile measurement and the range of variability between the evaluated alternatives, both FirmTech II and Penefel performed better in soft fruit but not as well in moderate or firm fruit. Therefore, among the more economical durometer devices, Penefel could be used by the industry to discriminate soft fruit from moderately firm or firm fruit. The results highlight the relevance of studying the predictive capacity of a particular instrument and to understand the performance of that instrument within a particular range of firmness values.

Participants in the industry of fresh-produce-marketing (e.g., producers, traders, and consumers) differ in the criteria used in the assessment of fruit quality (Abbott, 1999). Consumers perceive quality in terms of appearance, taste, texture, and aroma. To meet these expectations, traders tend to focus on appearance and texture, with the intent of maintaining these quality attributes until the product is sold to the consumer. In turn, producers are

expected to comply with the quality criteria imposed by traders (Abbott, 1999). Although the concept of what is meant by “quality” varies according to the target within the blueberry

(*Vaccinium* sp.) marketing chain (Abbott, 1999), fruit texture can be considered as the most relevant feature (Contador et al., 2015; Giongo et al., 2013).

Softening of blueberries between harvest (e.g., in the Southern Hemisphere) and delivery to retail markets (e.g., in the Northern Hemisphere) has been closely related to water loss and physiological firmness loss (Paniagua et al., 2013). Although firmness can vary widely among cultivars (Cappai et al., 2018), it is commonly used to estimate perishability (postharvest potential) of a given lot (Lobos et al., 2018).

Instruments to assess firmness of blueberry fruit are typically durometers or penetrometers. Mechanically, durometers estimate the force needed to attain a given deformation without skin ruptures, whereas penetrometers break the fleshy tissue (Armstrong et al., 1995; Li et al., 2011). Among durometers, FirmTech II (BioWorks, Wamego, KS) is considered the de facto standard instrument for firmness evaluation of small fruit, such as blueberries, and is commonly used by researchers and, to some extent, producers, and fruit exporters (Li et al., 2011; NeSmith et al., 2002). It is a stationary piece of equipment that uses an electric load cell to assess the fruit force–deformation curve under certain thresholds of deflection (e.g., the force needed to deflect the fruit by 1 mm). The main disadvantages are its current high cost ($\approx \$6500$) and lack of portability.

To maximize blueberry postharvest life, an instrument-based evaluation of fruit quality should be used to identify fruit lots less prone to deterioration and more able to undertake the rigors of shipping and handling (Lobos et al., 2018). This would be especially valuable for those cultivars with a tendency to deteriorate rapidly during shipment (Lobos et al., 2014; Moggia et al., 2017). At present, assessment of firmness in the blueberry industry relies mainly on the

Units			
To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
25.4	inch(es)	mm	0.0394
4.4482	lbf	N	0.2248
28.3495	oz	g	0.0353

tactile perception, both at origin (field and packaging lines) and at final destination (intermediaries and consumers). In this sense, when Ruíz et al. (2004) studied the relationship between sensorial assessment and the instrumental measurement of firmness in grapes (*Vitis vinifera*); a tactile segregation of grapes and the subsequent measurement in a FirmTech II showed that it was possible to differentiate berries between the extreme categories (firm and soft), but not between medium and soft fruit. Similar results were found by Brayovic (2011) on grape. Previously, Clayton et al. (1998) had reported that manual evaluations of cherry (*Prunus avium*) fruit were the most variable among eight different firmness methods; all instrument measurements were more precise than the tactile ones. Consequently, the global blueberry industry has attempted to use instruments to characterize blueberry firmness, often employing less costly devices (\$300–\$600) that are faster and easier to use than higher cost instruments, such as the FirmTech II or the mounted probe (Instron Corp., Norwood, MA).

Fruit firmness at harvest does not always permit one to predict the

firmness of fruit upon delivery to the consumer (Lobos et al., 2018). The rate and degree of softening is also a consequence of other relevant factors (e.g., cultivar, orchard orientation, extreme climatic events like heat waves and rainfalls, plant yield, nutritional status of the plant/fruit, harvest time, and frequency between pickings), which are not always considered when estimating the maximum travel capacity of a given fruit lot (Bailey, 1947; Ballinger et al., 1973; Finn and Luby, 1992; Galleta et al., 1971; Lobos and Hancock, 2015; Lobos et al., 2014, 2018; Moggia et al., 2017; Woodruff et al., 1960). Previous work, based on fruit segregated by firmness at harvest, has shown that postharvest softening rates are influenced by the fruit's initial firmness (Moggia et al., 2017). Therefore, a concern is that a subjective or imprecise measurement of initial firmness could exacerbate downstream risks of quality loss. Lack of knowledge of the accuracy and precision of a particular firmness-testing instrument (or procedure) therefore represents a latent risk for the blueberry industry, so the use of convenient but unreliable texture assessment instruments would lead to an unacceptable risk of quality loss.

Our objectives were first to understand the factors that affect the accuracy of a textural measurement in blueberry and thereafter to compare multiple instruments to determine performance and functionality. The first goal was to evaluate whether instrumental (FirmTech II) measurements were meaningful to human assessors by determining whether instrumental measures of texture correlated to sensory measures (tactile compression between fingers). A subsequent goal was to determine how much variation is associated with the device itself by comparing initial and repeat measurements of the same fruit. To do this also required that we learn the extent to which the first measurement affected the second measurement. Another goal was to answer the question of whether the performance of firmness measurement instrument was affected by fruit firmness (i.e., soft, moderate, and firm). Additionally, considering that there is growing interest among producers and exporters in having more objective tools to determine the firmness of blueberries, our final goal

was to evaluate the degree of association of the firmness measurements registered by a widely adopted instrument (FirmTech II) and those obtained by more economical durometer-type devices (Fig. 1). The current work adds to the current body of knowledge by establishing limits to the utility of each of the instruments for estimating firm, moderately firm, and soft blueberry fruit and by determining the most consistently accurate and useful of the more affordable firmness assessment instruments.

Materials and methods

For the different trials, the measurement of the equatorial firmness [i.e., the mean force (in Newtons) to deflect the fruit surface 1 mm] of northern highbush blueberry (*Vaccinium corymbosum*) and rabbiteye blueberry (*Vaccinium ashei*) fruit were considered. A durometer (FirmTech II) was used as the control instrument with the following setting: force thresholds (15–200 g), load cell speed (16 mm·s⁻¹), rotation speed of the sample plate (1.57 rotations/s), and time delay between sampling (500 ms). The instrument delivers data as grams force, and therefore values were converted to Newtons (×0.0098). At the Plant Breeding and Phenomics Center (Universidad de Talca, Talca, Chile) facilities, three FirmTech II instruments (designated as FT_{#1}, FT_{#2}, and FT_{#3}) were used. A power-stabilizing device was used to provide a constant operational voltage. The FT_{#1} was used to perform Expts. 1 and 3, whereas instruments FT_{#1}, FT_{#2}, and FT_{#3} were used for Expt. 2 (discussed subsequently).

Firmness classes are not necessarily related to commercial thresholds of the evaluated cultivars (Saftner et al., 2008). Additionally, according to each experiment, when fruit were sorted using FirmTech II, two scales were considered: 1) continuous, with no gaps between classes as might be used in the commercial world, and 2) discontinuous, as a way of better recognizing instrument performance in well-defined classes.

EXPT. 1. CONSISTENCY BETWEEN SENSORY AND INSTRUMENTAL ASSESSMENTS. During the 2015–16 season, fully ripe (100% blue coverage) fruit from 8-year-old ‘Elliott’ northern highbush blueberry plants of a commercial field in Chile [Freire, de la Araucanía

Received for publication 27 Sept. 2021. Accepted for publication 16 Dec. 2021.

Published online 11 February 2022.

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This work was funded by the National Commission for Scientific and Technological Research CONICYT (FONDECYT 1191818), the Chilean Blueberry Committee (branch of the Asociación de Exportadores de Frutas de Chile, A.G. ASOEX or Fruit Exporters Association of Chile) and Top-Quality SpA.

Author Contributions: Gustavo A. Lobos, Claudia Moggia, and Randolph Beaudry contributed to the conception and design of the work. Yeldo Valdés, Alejandra Arancibia, Marcelo Valdés, Gustavo A. Lobos, Claudia Moggia, and Randolph Beaudry performed the analysis and interpretation of data for the work. Gustavo A. Lobos, Claudia Moggia, and Randolph Beaudry collaborated to generate and validate the version to be published.

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<https://doi.org/10.21273/HORTTECH04960-21>

Fig. 1. Comparison of different instruments used to measure firmness of fresh blueberry fruit. (A) Texture analyzer (FirmTech II; BioWorks, Wamego, KS); (B) durometer (Penefel; Setop-Giraud Technologies, Cavaillon, France); (C) durometer (Durofel, Setop-Giraud Technologies); (D) durometer (DM1600; Rex Gauge Co., Buffalo Grove, IL).

region (lat. 38°57'42.9"S; long. 72°35'27.9"W)] were harvested at the peak of the season (5 Jan. 2016) and manually segregated into three sensory-based firmness classes based on tactile assessments of trained panelists. The tactile (T) firmness categories into which the fruit were classed were Soft-T, Moderate-T, and Firm-T. To classify firmness, each fruit received a gentle compression using the distal phalanx of the index finger and the thumb applied at the equator of the fruit. Assessments were performed until there were 450 berries per firmness category. Each tactilely segregated fruit was then given a single instrumental measurement using the FT_{#1} and assigned to their corresponding instrumental firmness classes using the continuous scale (Soft-I < 1.3 N; Moderate-I ≥ 1.3 and ≤ 1.7 N; Firm-I > 1.7 N) or the discontinuous scale (Soft-I ≥ 1.0 and ≤ 1.3 N; Moderate-I ≥ 1.4 and ≤ 1.7 N; Firm-I ≥ 1.8 and ≤ 2.1 N). The latter was used to better separate instrument-based classes and avoid uncertainties for fruit that might be marginally misidentified. Sensory evaluation was contrasted with instrumental measurements, on both continuous and discontinuous scales.

For statistical assessments, a completely randomized design was used. The percentage of coincidences between tactile categorization (Soft-T, Moderate-T, Firm-T) and instrumental firmness categorizations (Soft-I, Moderate-I, Firm-I) was determined using continuous and discontinuous scale ranges. With this information an inter-rater agreement (kappa) analysis was performed; the kappa statistic is frequently used to test interrater reliability, for classifications on ordinal or nominal scales; kappa coefficient (k) values are: 0 (poor or random), 0.01–0.2 (slight), 0.21–0.4 (fair), 0.41–0.6 (moderate), 0.61–0.8 (substantial), and 0.81–1.00 (almost perfect to perfect) (Landis and Koch, 1977; McHugh, 2012; Rigby, 2000). All statistical analyses were performed using statistical software [R (ver. 3.1.1; R Foundation for Statistical Computing, Vienna, Austria) and SigmaPlot (ver. 12.0; Systat Software, Palo Alto, CA)].

EXPT. 2. CONCORDANCE BETWEEN FIRMTECH II INSTRUMENTS (FT#1, FT#2, AND FT#3). During 2016–17, ‘Elliott’ northern highbush blueberry fruit coming from the same field as Expt. 1 were harvested on 8 Jan.

2017 to study the ability of repeat instrumental measurements to render the same firmness class. Blueberry fruit were evaluated twice, once on each of two FirmTech II instruments using the discontinuous ranges previously described. In all, FT_{#1}, FT_{#2}, and FT_{#3} were evaluated. There was no effort to obtain specific numbers of fruit per firmness category. The order of evaluation (initial and final measurements) was included as a testing factor to determine whether final fruit firmness might be affected by a prior initial measurement. No more than 5 min were allowed between measurements because reverse readings were done immediately after the forward sampling. The “forward” comparisons (i.e., first FT_{#1} then FT_{#2}, first FT_{#2} then FT_{#3}, and first FT_{#3} then FT_{#1}) each used lots of 25 fruit, and the tests were replicated three times (225 fruit total). To assess the effect of prior measurement, additional lots of fruit (3 replicates × 25 fruit) were measured in the “reverse” order to those previously listed (i.e., first FT_{#2} then FT_{#1}, FT_{#3} then FT_{#2}, and first FT_{#1} then FT_{#3}). For concordance estimates, only cases in which both firmness measurements fell within the discontinuous firmness ranges of the classes under study were considered, resulting in slightly different sample numbers in the “forward” and “reverse” comparisons.

To compare the performance of FirmTech II devices to discriminate fruit firmness within a particular firmness class, Lin concordance analysis (Lin, 1989) was performed. For this, firmness between the first (initial firmness) and the second (final firmness) measurement of each paired-equipment comparison were contrasted by obtaining the Lin concordance index (rho), the maximum value of which is 1 (total equality). To determine whether the first measurement of firmness by the FirmTech II instrument affected the second measurement on the same fruit, *t* tests were performed for the paired instrument tests described for fruit across all firmness categories and within the three continuous instrumental firmness categories of Soft-I, Moderate-I, and Firm-I.

EXPT. 3. DEGREE OF ASSOCIATION OF FIRMNESS REGISTERED BY THE FIRMTECH II AND LESS COSTLY DEVICES. The correlation of firmness values measured by three durometers with those

measured by the FT_{#1} was determined. Two durometers employed a cylindrical, flat-tipped contact surface on the probe: Durofel and Penefel (Setop-Giraud Technologies, Cavaillon, France), and one used a hemispherical contact surface (DM1600; Rex Gauge Co., Buffalo Grove, IL) (Fig. 1). Both Durofel and DM1600 deliver measurements on a 0 to 100 scale without units. Penefel was the only durometer that could be configured; therefore, a preliminary study was conducted to ensure a meaningful response from blueberry fruit (data not shown). To minimize the potential for fruit injury, the minimum threshold force value of 100 (units unknown) was used. Using this force setting, an appropriate probe depth setting was then determined. For this, 50 fruit of 'Brigitta Blue' northern highbush blueberry (not segregated by firmness) were measured, first in FT_{#1}, and then in the Penefel for six working depth settings (80, 40, 20, 10, 5, and 2). The manufacturer recommends a default depth parameter value of 80, which corresponds to 2.5 mm of deformation. The coefficients of determination (r^2) ranged from 0.43 to 0.67. However, the highest coefficients were for the working depths of 5, 10, and 20 ($r^2 = 0.59$ to 0.67). Using same procedure, 200 non-segregated fruit for depth settings of 5, 10, and 20 were evaluated again; depth 5 had the highest coefficient of determination ($r^2 = 0.68$). All subsequent tests described using the Penefel instrument used a force threshold value of 100 and a depth setting of 5.

Correlation analyses between the FT_{#1} and the durometers were performed for fruit aggregated across Soft-T, Moderate-T, and Firm-T classes and disaggregated within each firmness class. From the same orchard from Expt. 1, during the 2016–17 season fully ripe 'Brigitta Blue' northern highbush blueberry fruit (collected on 28 Dec. 2016) and 'Ochlockonee' rabbiteye blueberry (25 Jan. 2017) were used for this study. Fruit were initially measured with FT_{#1} and subsequently measured with one of the durometers. As previously noted, firmness measurements were made at the fruit equator. On the basis of the initial measurement from FT_{#1}, each fruit was assigned a particular firmness class (Soft-I, Moderate-I, or Firm-I) as previously described. Initial firmness assessments with FT_{#1} were performed until there

were 400 fruit per durometer for 'Ochlockonee' rabbiteye blueberry and 800 fruit per durometer for 'Brigitta Blue' northern highbush blueberry.

To determine the correlation between measurements of firmness by FT_{#1} and the durometers, a regression analysis was performed and the adjusted coefficient of determination of each comparison was calculated; the degree of association was analyzed with data combined for all the firmness classes and then for disaggregated data within each class. For comparison of the FirmTech II instrument against itself, the 520 comparisons generated in Expt. 1 among FT_{#1}, FT_{#2}, and FT_{#3} on 'Elliott' northern highbush blueberry were included in the regression analyses.

Results

CONSISTENCY BETWEEN SENSORY AND INSTRUMENTAL ASSESSMENTS. The k for sensory and FirmTech II firmness measurements was moderate ($k = 0.57$, $P < 0.0001$) and substantial ($k = 0.66$, $P < 0.0001$) for continuous and discontinuous scales, respectively (Table 1). Despite the overall moderate/substantial agreement between tactile and instrumental analyses, the consistency between the two assessments depended on the firmness class. There were higher rates of agreement between tactile and instrumental measurements for soft fruit (90.7% and 92.6% coincidence for continuous and discontinuous scales, respectively) than for moderate and firm fruit. Less than 10% of soft fruit were classed as moderate and none were classed as firm. However, coincidence levels tended to diminish as fruit became firmer. Fruit rated initially as Moderate-T had 69.6% and 78.2% coincidence with the Moderate-I category for continuous and discontinuous scales, respectively. For the fruit initially rated in the Firm-T category, only 51.6% and 61.4% were coincident with Firm-I for continuous and discontinuous scales, respectively. However, a significant portion of the Firm-T fruit were placed in the Moderate-I category, with 46.9% and 38.6% assigned to the Moderate-I category for continuous and discontinuous scales, respectively. Finally, only a small portion of the Firm-T fruit (<1.6%) was assigned to the Soft-I category by instrumental analysis via

the continuous scale data and 0% was incorrectly assigned to Soft-I using the discontinuous scale.

CONCORDANCE BETWEEN SAME FIRMTECH II DEVICES (FT_{#1}, FT_{#2}, AND FT_{#3}). The performance of individual FirmTech II devices for the nine forward and reverse comparisons of paired instruments tended to be similar for Soft-I, Moderate-I, and Firm-I fruit classes. An exception was for the paired comparison of FT_{#1} vs. FT_{#3} and FT_{#3} vs. FT_{#1}, where firmness difference was 0.036 N higher when FT_{#3} was used for the first measurement of a given berry for the Moderate-I class fruit (Supplemental Table 1). When the data for the three firmness classes was aggregated, the same comparison resulted in slightly different forward and reverse results, with the FT_{#3} vs. FT_{#1} order yielding a 0.03 N higher firmness difference than the reverse order. When the information from the three FirmTech II instruments (i.e., FT_{#1}, FT_{#2}, and FT_{#3}) was combined, comparing the first instrument (initial measurement) and the final instrument (final measurement), the Lin coefficient of concordance (ρ) decreased as the firmness increased (Fig. 2); for soft, moderate, and firm classes, ρ values were 0.47, 0.34, and 0.18, respectively (Fig. 2A–C), indicating that more accurate and reproducible readings between equipment could be expected from soft fruit.

There appeared to be a modest impact of the first measurement of firmness on the second measurement for FirmTech II operated as described herein. For the Soft-I firmness class, five of the six comparisons yielded firmness readings that were firmer on the first measurement compared with the second measurement (Supplemental Table 2). In this case, the average difference between first and second firmness assessments was ≈ 0.04 N. For the Moderate-I fruit firmness class, however, only one of the six paired comparisons yielded a higher firmness for the first measurement with a decline in firmness being ≈ 0.037 N upon the second measurement. For the Firm-I firmness class, one of the six comparisons yielded a 0.05 N lower firmness reading for the first measurement, and one comparison yielded 0.029 N higher firmness reading for the first

fruit measurement. Across the full range of firmness measurements, the first measurement was firmer than the second for six of the instrument comparisons; overall, the average drop in firmness was 0.043 N for the reverse measurement. Analysis of the data from all FirmTech II devices, contrasting initial vs. final values, showed that on average, 64% of initial firmness measurements (first device) were higher than the second measurement, whereas 36% of the values were higher on the final firmness (second device). These proportions occurred mainly for Soft-I and Moderate-I classes; for the Firm-I class the ratio was 58% to 42%.

The concordance analyses for specific FirmTech II paired comparisons, regardless of which instrument was used for the first measurement showed that, in general, the highest rho values were found for the Soft-I firmness class (Fig. 3). Results depended somewhat on the instrument, however. The highest rho values were obtained for FT_{#1} vs. FT_{#2} and FT_{#1} vs. FT_{#3} (0.503 and 0.415, respectively) comparisons, but the rho value for the comparison FT_{#2} vs. FT_{#3} was only 0.24. For fruit classed moderate and firm, rho values were lower than for fruit classed as soft, ranging from 0.126 to 0.297 and 0.048 to 0.223, respectively.

CORRELATIONS BETWEEN THE FIRMTECH II AND DUROMETERS. Regardless of the cultivar, regression analyses yielded a higher coefficient of determination when data from all firmness classes were aggregated, than

for any individual class (Table 2). A high r^2 was obtained between the three FirmTech II instruments ($r^2 = 0.94$ to 0.95). However, the coefficients of determination between FT_{#1} and the various durometers were lower [FirmTech II vs. Penefel ($r^2 = 0.61$ to 0.67); FirmTech II vs. Durofel ($r^2 = 0.48$ to 0.61) and FirmTech II vs. DM1600 ($r^2 = 0.08$ to 0.49)]. When data were analyzed by firmness category, r^2 values dropped dramatically [FirmTech II vs. Penefel ($r^2 = 0.09$ to 0.40); FirmTech II vs. Durofel ($r^2 = 0.05$ to 0.32); FirmTech II vs. DM1600: ($r^2 = 0.00$ to 0.25); between FirmTech II instruments ($r^2 = 0.03$ to 0.33)] (Table 2).

The association within each firmness class, regardless of the durometer being compared, decreased considerably at the higher firmness levels. The highest r^2 were found in Soft-I ($r^2 = 0.01$ to 0.40 ; average = 0.21) followed by those of Moderate-I fruit ($r^2 = 0.04$ to 0.26 ; average = 0.16), whereas the r^2 of for comparisons within the Firm-I class were quite low and, in some cases, nonsignificant ($r^2 = 0.00$ to 0.25 ; average = 0.10). The same situation was observed when FirmTech II instruments were compared for Soft-I ($r^2 = 0.18$ to 0.33 ; average = 0.28), Moderate-I ($r^2 = 0.03$ to 0.21 ; average = 0.14), and Firm-I ($r^2 = 0.03$ to 0.07 ; average = 0.04) firmness classes.

The coefficient of determination between the durometers and the FirmTech II differed somewhat for the two cultivars evaluated. When all

firmness classes were aggregated, the r^2 for firmness estimates for ‘Ochlockonee’ rabbiteye blueberry were highest with Penefel, whereas for ‘Brigitta Blue’ northern highbush blueberry, both Durofel and Penefel yielded high coefficients of determination. The DM1600 yielded lowest coefficients of determination for both cultivars. For the disaggregated firmness classes, DM1600 also performed poorly, with no significant associations between its measurements and those of the FirmTech II for ‘Ochlockonee’ rabbiteye blueberry for soft, moderate, or firm fruit and no significant relationship for firm ‘Brigitta Blue’ northern highbush blueberry fruit. The coefficients of determination between the three FirmTech II instruments using ‘Elliott’ northern highbush blueberry fruit were similar to those reported for ‘Brigitta Blue’ northern highbush blueberry and ‘Ochlockonee’ rabbiteye blueberry and, as with the DM1600, there was no correlation between measurements for firm fruit.

Discussion

Although softening of the fruit is considered one of the major barriers limiting the export of fresh blueberries to distant markets (NeSmith et al., 2002; Vicente et al., 2007), there is no international standard methodology for this quality trait. Throughout the entire value chain of blueberry production, decisions are based, for the most part, on the use of tactile perception as an indicator of fruit firmness (Mitcham et al., 1998). Due

Table 1. Contingency table of success (%) and kappa coefficient for Expt. 1 between firmness of ‘Elliott’ northern highbush blueberry fruit, harvested 5 Jan. 2016, first segregated by tactile (T) assessment into Soft-T, Moderate-T, and Firm-T firmness categories, and then measured instrumentally (I) using a texture analyzer FirmTech II (BioWorks, Wamego, KS) and assigned to Soft-I, Moderate-I, and Firm-I categories, considering continuous and discontinuous scale ranges.

Instrumental class	Firmness range (N) ^z	Tactile class		
		Soft-T	Moderate-T	Firm-T
Coincidence, continuous scale (%)				
Soft-I	<1.3	90.7	22.7	1.6
Moderate-I	1.3–1.7	9.3	69.6	46.9
Firm-I	>1.7	0.0	7.8	51.6
k (<i>P</i> value) ^y		0.57 (<i>P</i> < 0.0001)		
Coincidence, discontinuous scale (%)				
Soft-I	1.0–1.3	92.6	9.3	0.0
Moderate-I	1.4–1.7	7.4	78.2	38.6
Firm-I	1.8–2.1	0.0	12.5	61.4
k (<i>P</i> value)		0.66 (<i>P</i> < 0.0001)		

^zThe FirmTech II instrument designated as FT_{#1} was used; 1 N = 0.2248 lbf.
^yk = kappa coefficient (0–1) from an interrater agreement (kappa) analysis.

Fig. 2. Concordance analysis for the firmness measures of northern highbush 'Elliott' northern highbush blueberry that, for the same fruit, compares the evaluation performed first on one of the three texture analyzers (FirmTech II; BioWorks, Wamego, KS) (initial firmness), and then on a second instrument (final firmness), according to three discontinuous firmness classes: soft: 1.0 to 1.3 N (A); moderate: 1.4 to 1.7 N (B); and firm: 1.8 to 2.1 N (C). Lin coefficient of concordance (ρ ; blue line) ranges from 0 (poor or random agreement) to 1 (perfect agreement; red line 1:1). The combined results of the comparisons made with three FirmTech II devices are presented; 1 N = 0.2248 lbf.

to the imprecision of this methodology (Nunes, 2015; Ruiz et al., 2004), it is likely that any two quality control teams assessing the same fruit, may have a different appreciation not only about the firmness of a lot but also about its storage potential. Additionally, no matter how trained a person is, the problem regarding the ability to adequately estimate firmness will remain considering that 1) the wide frequency distribution of firmness prevents a clear recognition of thresholds between classes (Lobos et al., 2018; Moggia et al., 2017) and 2) since environmental conditions vary between seasons (Allen and Ingram, 2002), so does the frequency distribution of firmness (Lobos et al., 2018; Moggia et al., 2017). Thus, it is difficult to recognize the aforementioned thresholds. After performing a tactile firmness segregation of grape berries, Ruiz et al. (2004) were able to recognize only those extreme categories (the firmest and softest fruit), but not an intermediate one.

Given that the kappa index values were "moderate" to "substantial" in this study and that the tactile estimation of firmness (Soft-T, Moderate-T, or Firm-T) showed relatively high rates of coincidence (between 51.6% and 92.6%) within the equivalent instrumental firmness categories (Soft-I, Moderate-I, and Firm-I), it is not surprising that tactile analysis remains the preferred procedure throughout the whole market chain of fresh berries. However, there is still significant risk in identifying a lot of fruit as being

higher in quality than it actually is. In the present study, 22.7% and 9.3% of berries that were initially rated as Moderate-T were identified as being soft via objective analysis, for continuous and discontinuous scales, respectively. This is relevant because firmness declines between harvest and the end of storage period occurs at similar rates regardless of the initial firmness of a particular cultivar. Moggia et al. (2017) found that 'Duke' northern highbush blueberries exhibited 39.8%, 33.6%, and 38.6% softening (after 35 d at 0 °C) for, respectively, soft, moderate, and firm fruit, whereas in 'Brigitta Blue' northern highbush blueberry values averaged 17.3%, 24.4%, and 23.8%, respectively. Nevertheless, only 1.6% of fruit initially rated as Firm-T were identified as being soft using instrumental analysis. Conversely, less than 10% of the fruit classified as Soft-T were objectively determined to be moderate, and none were determined to be firm.

In this study, the first assessment of firmness had a small negative impact on the second measurement, but because the impact was so minor (e.g., only 0.04 N), the added bias would only be meaningful within narrow ranges of firmness. The effect of prior measurement would be expected to have a modest impact on the three firmness classes used herein, which had a range of 0.3 N in the discontinuous scales, but there would be little impact on measurements made over broader firmness ranges such as those

encountered in most blueberry sample populations.

Although the tactile assessment of blueberry fruit firmness is a widely accepted practice, during the past couple of decades there has been a growing interest among producers and exporters in having more objective tools to determine fruit firmness. The relatively high r^2 found in this study between FirmTech II and two of the durometers (especially Penefel, $r^2 = 0.61$ to 0.67) when fruit from all firmness categories were pooled, could seem promising. However, the high correlation is the result of the analysis across a firmness range of 1.1 N or greater, and considerably lower values were obtained when r^2 were estimated within a particular firmness class.

Given that soft fruit typically comprise the target group used to define the travel capacity of a fruit lot (Lobos et al., 2018; Moggia et al., 2017), the elevated Lin concordance indexes fruit in the Soft-I firmness class (Fig. 2) suggests that individual FirmTech II instruments that are properly calibrated can operate in a highly equivalent manner. Nevertheless, the low concordance values among FirmTech II devices are of some interest, suggesting that there may be physiological or structural differences at different positions within a single berry that may yet need to be accounted for.

The FirmTech II could be considered an affordable device for a medium-

Fig. 3. Concordance analysis for paired measurements of fruit firmness of ‘Elliott’ northern highbush blueberry on equivalent texture analyzers (FirmTech II; BioWorks, Wamego, KS) instruments according to three discontinuous firmness classes: soft: 1.0–1.3 N (left column: A, D, G); moderate: 1.4–1.7 N (middle column: B, E, H); and firm: 1.8–2.1 N (right column: C, F, I). Within each firmness category, comparisons between FirmTech II instruments (FT_{#1}, FT_{#2}, and FT_{#3}) were performed as follows: FT_{#1} vs. FT_{#2} (top row), FT_{#1} vs. FT_{#3} (middle row), and FT_{#2} vs. FT_{#3} (bottom row). The order in which a particular instrument was used (e.g., first or second of the paired measurements) was not considered. The Lin coefficient of concordance (rho; blue line) ranges from 0 (poor or random agreement) to 1 (perfect agreement; red line 1:1); 1 N = 0.2248 lbf.

sized packing and shipping organizations and has, to some extent, found some use among growers and exporters. Currently, it has become the de facto standard instrument for blueberry firmness evaluation within the global blueberry research community (Li et al., 2011), mainly due to the ability

of the operator to adjust analysis parameters. Nevertheless, as with any equipment that allows configuration before measurement, the same hardware, misused with different settings, can deliver completely different firmness values (Prussia et al., 2006). It is therefore important to emphasize the need for

detailed research for the FirmTech II or any firmness analysis device to settle on optimal or preferred configurations for specific applications. In the current study, the three FirmTech II devices performed comparably in paired comparisons, providing assurance that results from different studies, seasons,

Table 2. Determination coefficients (r^2) and sample size (n) for the simple regression analysis of continuous scale blueberry firmness measurements between texture analyzer FirmTech II (BioWorks, Wamego, KS) (instrument FT_{#1}), and less costly durometers (Penefel, Durofel, and DM1600) for ‘Brigitta Blue’ northern highbush blueberry (harvested on 21 Dec. 2016) and ‘Ochlockonee’ rabbiteye blueberry fruit (harvested on 25 Jan. 2017); and between equivalent, calibrated FirmTech II instruments (designated as FT_{#1}, FT_{#2}, and FT_{#3}) for ‘Elliott’ northern highbush blueberry (harvested on 8 Jan. 2017).

Comparison: FirmTech II	Brigitta Blue	Ochlockonee	Elliott
r^2 (n): all firmness classes combined			
FT _{#1} vs. Penefel	0.61** (735)	0.67** (370)	
FT _{#1} vs. Durofel	0.61** (764)	0.48** (380)	
FT _{#1} vs. DM1600	0.49** (745)	0.08* (374)	
FT _{#1} vs. FT _{#2}			0.95** (192)
FT _{#1} vs. FT _{#3}			0.94** (177)
FT _{#2} vs. FT _{#3}			0.94** (152)
FT _{#1} + FT _{#2} + FT _{#3}			0.94** (520)
r^2 (n): Soft class (<1.3 N) ^z			
FT _{#1} vs. Penefel	0.25** (317)	0.40** (88)	
FT _{#1} vs. Durofel	0.24** (209)	0.32** (77)	
FT _{#1} vs. DM1600	0.09* (259)	0.01 NS (65)	
FT _{#1} vs. FT _{#2}			0.33** (81)
FT _{#1} vs. FT _{#3}			0.31** (70)
FT _{#2} vs. FT _{#3}			0.18* (57)
FT _{#1} + FT _{#2} + FT _{#3}			0.29* (208)
r^2 (n): Moderate class (1.3–1.7 N)			
FT _{#1} vs. Penefel	0.09* (247)	0.26** (182)	
FT _{#1} vs. Durofel	0.11* (274)	0.20* (195)	
FT _{#1} vs. DM1600	0.25** (258)	0.04 NS (198)	
FT _{#1} vs. FT _{#2}			0.20* (73)
FT _{#1} vs. FT _{#3}			0.03 NS (72)
FT _{#2} vs. FT _{#3}			0.21* (62)
FT _{#1} + FT _{#2} + FT _{#3}			0.12** (207)
r^2 (n): Firm class (>1.7 N)			
FT _{#1} vs. Penefel	0.11* (130)	0.25** (110)	
FT _{#1} vs. Durofel	0.12* (132)	0.05 NS (107)	
FT _{#1} vs. DM1600	0.07 NS (107)	0.00 NS (112)	
FT _{#1} vs. FT _{#2}			0.03 NS (38)
FT _{#1} vs. FT _{#3}			0.07 NS (35)
FT _{#2} vs. FT _{#3}			0.04 NS (32)
FT _{#1} + FT _{#2} + FT _{#3}			0.03 NS (105)

^z1 N = 0.2248 lbf.

NS, *, **Nonsignificant or significant at $P \leq 0.05$ or 0.01, respectively.

and regions would be comparable if operational parameters were similar.

There has been an increasing interest in expanding control points along the value chain for blueberry using more affordable devices to assess firmness, such as those evaluated in this study. While Durofel has been reported as an alternative to FirmTech II, albeit with lower predictive capacity (Clayton et al., 1998), in this study, Penefel was somewhat more reliable than Durofel when all firmness classes were combined as well as for Soft-I and Firm-I classes. Nevertheless, the determination coefficients between the FirmTech II and the Penefel durometer were much lower than for the FirmTech II when the

latter was compared against itself. Likely, this is a function of differences in the compression process between instruments. The FirmTech II uses a flat compressive disk that has a contact surface that increases during compression, whereas the durometer has full contact of the sensor head throughout the compression process (Armstrong et al., 1995; Li et al., 2011; NeSmith et al., 2002).

There has been great progress in blueberry breeding programs to improve fruit firmness as new cultivars are released (Blaker et al., 2014; Capai et al., 2018). Nevertheless, due to the wide range of physiological ages that are present in a particular picking date due to a long blooming period,

poor understanding or assessment of harvest index, delays between harvests due to labor shortage, and the impact of climatic conditions during fruit development (Galleta et al., 1971; Lobos et al., 2014, 2018), a high variability in firmness of harvested blueberries of a given cultivar can be expected (Lobos et al., 2018). Given the multiplicity of external forces acting on the blueberry fruit in the orchard, it would be reasonable to expect that two boxes of the same cultivar, having the same initial inspection grade, may undergo differing rates of deterioration during storage. At its most extreme, one could envision two adjacent berries with similar firmness at harvest, but differing positions within a

cluster, may soften differently during storage. In grapes, fruit cluster thinning alters the maturation rates of the remaining fruit, increasing variability at harvest (Gamero et al., 2014; Guidoni et al., 2002; Palliotti and Cartechini, 2000; Reščič et al., 2015). In blueberry, seasonal macroenvironmental (e.g., maximum temperatures, rains) and microenvironmental characteristics (fruit position within the plant) impact both the plant and the fruit (Estrada et al., 2015; Lobos et al., 2018). Finally, postharvest management and shipping conditions may vary between otherwise comparable harvested lots.

Conclusions

Given the subjectivity of the tactile measurement and the lack of consistency between the evaluated alternatives, within the three categories of firmness, both FirmTech II and Penefel performed better in fruit classed as soft, compared with moderate or firm classes. Given its lower cost and ease of use, the Penefel could be used more extensively across the various levels within the blueberry value chain, permitting better standardization of evaluation criteria and a better ability for the actors within the blueberry value chain to clearly communicate their understanding and expectations of fruit firmness, especially for soft fruit.

Additionally, the results indicate the relevance of studying the predictive capacity of any firmness assessing equipment within a particular firmness class; user manuals generally report regression values for populations with a wide range of firmness levels. Use of an overly broad range of firmness levels for instrument assessment can mask the ability of the instruments to perform over a narrow range in firmness levels. Further, the absolute firmness levels impact the ability to generate correlations. Blueberry fruit, for instance, seem to require more than 0.3 N range in firmness to discern correlative trends for the firmer fruit, but correlations emerge within this narrow range for softer fruit.

Finally, the data and associated analysis herein highlight the risk associated with the use of different methodologies to evaluate firmness in blueberries and provide a path forward to implement standardized

fruit firmness measurement along the whole value chain for this valuable fruit.

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Supplemental Table 1. *t* tests evaluating whether the order of the three texture analyzers FirmTech II (BioWorks, Wamego, KS) instruments (designated as FT_{#1}, FT_{#2}, and FT_{#3}) affected the firmness difference between first and second measurement on individual blueberry fruit. There were 75 measurements made per comparison in each firmness class and 225 per comparison for the three firmness classes combined.

First instrument	Second instrument	Firmness absolute difference (N) ^z	SE
Soft class (<1.3 N)			
FT _{#1} vs.	FT _{#2}	0.049	0.007
FT _{#2} vs.	FT _{#1}	0.069	0.008
Significance ^y		0.063	
FT _{#1} vs.	FT _{#3}	0.059	0.008
FT _{#3} vs.	FT _{#1}	0.076	0.009
Significance		0.193	
FT _{#2} vs.	FT _{#3}	0.066	0.008
FT _{#3} vs.	FT _{#2}	0.079	0.009
Significance		0.307	
Moderate class (1.3–1.7 N)			
FT _{#1} vs.	FT _{#2}	0.069	0.009
FT _{#2} vs.	FT _{#1}	0.065	0.009
Significance		0.763	
FT _{#1} vs.	FT _{#3}	0.058	0.011
FT _{#3} vs.	FT _{#1}	0.094	0.013
Significance		0.039	
FT _{#2} vs.	FT _{#3}	0.064	0.010
FT _{#3} vs.	FT _{#2}	0.081	0.009
Significance		0.215	
Firm class (>1.7 N)			
FT _{#1} vs.	FT _{#2}	0.086	0.012
FT _{#2} vs.	FT _{#1}	0.090	0.013
Significance		0.871	
FT _{#1} vs.	FT _{#3}	0.080	0.018
FT _{#3} vs.	FT _{#1}	0.116	0.016
Significance		0.132	
FT _{#2} vs.	FT _{#3}	0.107	0.015
FT _{#3} vs.	FT _{#2}	0.087	0.017
Significance		0.406	
All firmness classes combined (n = 225)			
FT _{#1} vs.	FT _{#2}	0.066	0.006
FT _{#2} vs.	FT _{#1}	0.073	0.006
Significance		0.404	
FT _{#1} vs.	FT _{#3}	0.064	0.007
FT _{#3} vs.	FT _{#1}	0.094	0.007
Significance		0.003	
FT _{#2} vs.	FT _{#3}	0.077	0.006
FT _{#3} vs.	FT _{#2}	0.082	0.006
Significance		0.617	

^zN = g·mm⁻¹ × 0.0098; 1N = 0.2248 lbf.

^yP > 0.05 = nonsignificant.

Supplemental Table 2. *t*-tests evaluating whether the first firmness measurement affected the firmness reading of the second measurement on individual blueberry fruit with texture analyzer FirmTech II (BioWorks, Wamego, KS) instrument. There were 75 measurements made per comparison in each firmness class and 225 per comparison for the three firmness classes aggregated.

First device	Second device	Real Difference (N) ^z	SE	<i>t</i> test ^y	Higher firmness (%)	
					First device	Second device
Soft class (<1.3 N)						
FT _{#1}	FT _{#2}	0.015	0.066	NS	52.5	47.5
FT _{#2}	FT _{#1}	0.051	0.068	*	75.0	25.0
FT _{#1}	FT _{#3}	0.032	0.072	*	63.2	36.8
FT _{#3}	FT _{#1}	0.069	0.068	*	81.3	18.8
FT _{#2}	FT _{#3}	0.036	0.072	*	71.4	28.6
FT _{#3}	FT _{#2}	0.051	0.083	*	66.7	33.3
Moderate class (1.3–1.7 N)						
FT _{#1}	FT _{#2}	0.003	0.086	NS	55.9	44.1
FT _{#2}	FT _{#1}	0.022	0.086	NS	68.6	31.4
FT _{#1}	FT _{#3}	0.017	0.074	NS	66.7	33.3
FT _{#3}	FT _{#1}	0.038	0.122	NS	64.0	36.0
FT _{#2}	FT _{#3}	0.037	0.072	*	63.6	36.4
FT _{#3}	FT _{#2}	0.026	0.090	NS	61.5	38.5
Firm class (>1.7 N)						
FT _{#1}	FT _{#2}	−0.050	0.094	*	38.5	61.5
FT _{#2}	FT _{#1}	0.009	0.113	NS	57.1	42.9
FT _{#1}	FT _{#3}	0.058	0.087	*	81.8	18.2
FT _{#3}	FT _{#1}	0.026	0.149	NS	55.6	44.4
FT _{#2}	FT _{#3}	0.035	0.128	NS	60.9	39.1
FT _{#3}	FT _{#2}	0.047	0.104	NS	66.7	33.3
All firmness classes combined						
FT _{#1}	FT _{#2}	−0.006	0.085	NS	50.0	50.0
FT _{#2}	FT _{#1}	0.031	0.088	*	68.5	31.5
FT _{#1}	FT _{#3}	0.033	0.077	*	68.8	31.2
FT _{#3}	FT _{#1}	0.046	0.115	*	67.9	32.1
FT _{#2}	FT _{#3}	0.035	0.090	*	66.3	33.8
FT _{#3}	FT _{#2}	0.041	0.091	*	64.8	35.2

^zN = g·mm^{−1} × 0.0098; 1N = 0.2248 lbf.

^y*t* test: NS = nonsignificant; **P* ≤ 0.05.