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Evaluation of Sweet Cherry Fruit Firmness by Compression Testing and Penetrometer

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Abstract

Sweet cherry (*Prunus avium* L.) is considered a premium quality temperate fruit. Firmness is one of the most important fruit quality traits in sweet cherry, as it is a component of both consumer acceptance and storability. The traditional method utilized to determine firmness is by compression. We evaluated the relationship between a traditional compression-type firmness tester (Firmtech 2) and a programmable penetrometer (Mohr MDT-2). Firmness data from both instruments was successfully used to detect the combined effects of rootstock and spacing on firmness in a grower-focused trial. However, data from the Firmtech 2 was superior based on adjusted R^2 values of treatment effects models. Correlation analysis between the Firmtech 2 and MDT-2 revealed that the linear relationship between the firmness data was moderate overall and varied considerably between genotypes and between trees of the same genotype. This indicates that the two instruments are measuring different components of fruit firmness and suggests multiple genetic and environmental factors are involved. Fruit sampled later in the season in 2021 after a severe heat wave had no significant relationship between perceived texture and measurements from either instrument (nor between instruments), likely due to heat damage. The high throughput and non-destructive analysis of the compression test is better suited for use in early-stage selection in breeding programs or for commercial use to discard soft fruit. The penetrometer provides higher-dimensional data that may be useful for more thorough analysis of sweet cherry texture for research purposes.

Sweet cherry (*Prunus avium* L.) is considered a premium fruit with high economic value for farmers (Chauvin et al., 2009; Loescher 2016). Several attributes of sweet cherries contribute to their demand in the marketplace, including availability (they are generally the first temperate tree fruit of the season), size, color, flavor, and texture (Chauvin et al., 2009; Correia et al., 2017). While external characteristics such as size and color influence purchase decisions (Crisosto et al., 2003), internal factors such as sweetness and texture influence consumer acceptance and affect repeat purchase decisions. Consumers generally prefer firm-textured cherries over soft fruit (Dever et al., 1996; Guyer et al., 1993; Hampson et al., 2014), but there may be an optimal range in firmness, above which consumer appeal also declines (Kappel et al., 1996). According to Kappel et al. (1996), firmness along with size and sweetness constitute a "good" sweet cherry, placing this characteristic among the most important traits in many breeding programs around the world (Kappel et al., 1996, 2000; Crump et al., 2022). In addition, firm textured fruit better withstand impacts that occur during harvest, sorting, and shipping (Zoffoli et al., 2017). Due to its important effects on consumer acceptance and storability, the sweet cherry breeding program at Washington State University has established fruit firmness as one of its most important fruit quality traits.

While Contador et al. (2016) indicated that "There are no instruments that can re-

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veal the mouth's complexity, sensitivity, and range of movements", an objective measurement of fruit texture remains a desirable tool for research and quality assurance purposes. Traditionally, a compression-type firmness tester (e.g., Firmtech 2) has been employed to measure cherry firmness. The device measures the force required to compress the fruit for a defined distance.Compression firmness testers are easy to use, nondestructive, and results are reproducible (Mitcham et al., 1998). However, compression testers do not mimic the piercing of fruit skin and flesh by teeth, and there is some question as to whether other instrumental methods would provide a more realistic assessment (Abbott 1999). In a previous study (Chauvin et. al., 2009) utilizing sensory analysis by both trained and consumer panels, sweet cherry fruit texture (defined as a combination of firmness and juiciness) showed a moderate relationship with firmness as measured by a compression tester. While compression values separated fruit into three distinct firmness categories, neither group of panelists could differentiate fruit into three distinct categories. In blueberry (Vaccinium spp.), Saftner et al. (2008) found that lower compression values were associated with lower sensory scores for bursting energy and chewing texture, but the correlations were only moderate (0.44 and 0.33, respectively). In contrast, sweet cherry research by Hampson et al. (2014) identified strong linear relationships between compression values and sensory perception of both crispness (defined as the level of 'crunch' when biting with the front teeth) and firmness (determined by chewing with molars), with each relationship having a correlation of 0.87.

In contrast to compression-type firmness testers, penetrometers or texture analyzers use a probe to measure the forces involved in piercing fruit skin and flesh. Many instruments offer interchangeable probes with varying diameters, and with programmable penetrometers, the travel (distance and speed) of the probe can be defined depending on the fruit being tested. A lengthy review on the first texture analyzer developed for food texture measurements was reported by Friedman et al. (1962). Originally known as 'texturometers', texture analyzers were reported to better correlate between reported values and food texture perception (Friedman et al., 1962). In blackberry (*Rubus* L. subgenus *Rubus* Watson), Edgely et al. (2019) suggested that penetrometer values were a better measure of fruit quality than compression measurements. In another blueberry study, Blaker et al. (2014) found high correlations between bioyield force (the force required by a penetrometer to pierce skin at a constant speed) and sensory perceptions of bursting energy, chewing firmness, and skin roughness ($r = 0.86$, 0.82, and 0.78), albeit the correlations between these perceptions and compression values were essentially the same. The challenges encountered with texture analyzers are their potentially slower analysis speed, and that testing is a destructive process that can limit the amount of fruit available for evaluating additional parameters. This is particularly relevant in early stages of breeding programs where genotypes are represented by individual trees and small amounts of fruit.

The objective of this study was to compare firmness data generated by a traditional compression tester and a programmable penetrometer.

Materials and Methods

Evaluations were conducted in two independent sets of experiments. The first experiment was conducted during the 2018 harvest season on sweet cherry cv. 'Sweetheart' grown in a commercial orchard near Mattawa, WA. 'Sweetheart' was grown using three different rootstock/spacing combinations (treatments), with tree spacing nested within rootstock. At commercial maturity (skin color between 4 and 5 based on the Centre Technique Interprofessionnel des Fruits et Légumes (CTIFL) scale), four replicates containing between 60 to 198 fruit per treatment were harvested and placed in a cold room at 4°C overnight. The following day fruit were removed from the cold room and allowed to reach room temperature prior to evaluation of texture and firmness. The waiting period between measurements ranged between 15 to 30 min.

The second set of experiments were conducted over the next three harvest seasons (2019-2021) at the Washington State University Irrigated Agriculture Research and Extension Center in Prosser, WA (IAREC). Multiple genotypes were utilized (7 in 2019, 14 in 2020, and 15 in 2021). Each sample consisted of 25 fruit from a single tree. Samples were analyzed either the day of harvest or the day after. Harvested fruit were analyzed at room temperature (samples analyzed the day after harvest were allowed to equilibrate to room temperature after cold storage).

Texture and firmness evaluation

For both experiments, fruit were individually labelled and measured by the Bioworks Firmtech 2 (hereafter Firmtech 2) compression force tester (Bioworks Inc., Kameka, KS) and subsequently with the Mohr Digitest 2 (hereafter MDT-2) programmable penetrometer (Mohr Test and Measurement LLC, Richland, WA) to generate paired measurements. The Firmtech 2 is equipped with a flat disc (25 mm) connected to a stepper motor for compressing the fruit, and the resistance to deformation is measured by a load cell. Fruit were placed cheek (narrowest side) down in dimples in a 25-position carousel with the stems facing inward. The carousel rotates automatically to present fruit to the compression/load cell apparatus. The MDT-2 was equipped with a 4 mm flat probe. Fruit were positioned manually under the probe, which operates once the user presses the start button. The MDT-2 reports both average and maximum forces over a range of distances, which can be defined by the user. The MDT-2 is also able to perform measurements under constant rate (speed) or constant load. Both instruments can also be calibrated to measure fruit diameter, though this was not done for the MDT-2. The data collected by each instrument are shown in Table 1. For the MDT-2 analyses in the second set of experiments, only the M1 and A1 data were collected (Table 1). Probe travel in 2019 and 2020 was set to 6.4 mm. In 2021, a 'shallow' profile of 3.8 mm was used in the first group of 8 samples

Table 1. Parameters measured with the Firmtech 2 and MDT-2 instruments during the 2018 harvest season on 1500 'Sweetheart' sweet cherry fruit. The MDT-2 is also able to measure diameter but was not calibrated to do so in this or subsequent experiments. M2, A2, E2, and Cn were not used in subsequent years.

Firmtech 2	MDT-2
Firmness: maximum compression force (reported in g) required to compress the fruit by 1 mm	M1: Maximum force (reported in g) in first 3.8 mm of travel after fruit contact
Diameter (mm)	A1: Average force in first 3.8 mm of travel after fruit contact
	M2: Maximum force in second 2.5 mm of travel (i.e., after the first 3.8 mm)
	A2: Average force in second 2.5 mm of travel
	E2: Force at end of second 2.5 mm of travel
	Cn (Crispness): frequency-dependent fracturing of the fruit, calculated from forces encountered in the second 2.5 mm of travel

Table 2. Least-squares mean values for fruit firmness parameters of fruit harvested from 'Sweetheart' sweet cherry trees on three rootstocks (each with different tree spacing) measured with the Firmtech 2 and MDT-2 in 2018. In this table, the measurements from different methods are the dependent variables, and the rootstock/spacing treatments are the independent variables.

	Method						
	Firmtech 2	MDT-2					
Rootstock Treatment	g·mm^{-1}	M1	A1	M2	A2	E2	Cn
Krymsk-5	239 a[z]	666 a	395 a	905 a	480 a	660 a	21.1 a
Cass	230 b	669 a	391 a	873 b	458 b	595 b	21.6 a
GiSelA-5	218 c	647 b	377 b	826 c	431 c	502 c	20.5 a
Pr > F(Model)	<0.0001	0.01	0.0001	<0.0001	<0.0001	<0.0001	0.34
Adj. R^2	0.11	0.02	0.04	0.03	0.04	0.05	0.01

[z] Values within columns followed by common letters do not differ at the 5% level of significance, by Tukey's HSD.

(corresponding with the M1/A1 profile of the 2018 experiment), while the second group (7 samples) used a 'deep' travel profile of 6.4 mm (as for 2019 and 2020).

Results were subjected to correlation analyses between indicators and to one-way analysis of variance (ANOVA) to evaluate treatment effects (2018 only). For the ANOVA, the rootstock/spacing treatment effect was considered the independent variable, and the measure of firmness (Firmtech 2 or MDT-2 measurements) was considered the dependent variable. Furthermore, the ANOVA was conducted using individual fruit measurements. For the 2019-2021 experiments, correlations between instrumental data were calculated on all fruit combined, and separately for each 25-fruit sample. In 2021, all 25 fruit in a sample were sampled by a single individual following the instrument tests, with each fruit receiving its own perceived texture classification. All statistical analyses were performed in R (R Core Team 2021).

Results and Discussion

Prediction of firmness levels by testing method

Analysis of variance of the treatment (rootstock/spacing) effect on various firmness parameters of 'Sweetheart' in 2018 is summarized in Table 2. A significant effect of treatment was detected when firmness was measured by the Firmtech 2, and by MDT-2 parameters M1, A1, M2, A2, and E2. Multiple pairwise comparisons distinguished all three treatments when using Firmtech 2 firmness and MDT-2 parameters M2, A2 and E2. When utilizing parameters M1 and A1 no significant differences in firmness were detected between Krymsk-5 and Cass rootstocks Model fit (evaluated by adjusted R2 values) was highest for the Firmtech 2 (R2=0.11) and coefficients of determination ranged from 0.01 (non-significant) to 0.05 for MDT-2 parameters.

Correlations between instruments

In 2018, the MDT-2 parameters A1 and M1 correlated most strongly with Firmtech 2 firmness (r = 0.66 and 0.62, respectively) (Table 3). These stronger correlations between compression force (by Firmtech 2) and the penetration forces (A1 and M1) might reflect the similar tissues being analyzed between the two methods. The Firmtech 2 measures the force required to compress the fruit over a short distance (1 mm), while A1 and M1 parameters of the MDT-2 corresponded to the average and maximum forces measured while penetrating the first 3.8 mm of the fruit

Table 3. The relationship between firmness values obtained with the Firmtech 2 and six parameters obtained with the MDT-2 for 'Sweetheart' sweet cherry in 2018.[y]

Parameter	Correlation coefficient
M1	0.62[z]
A1	0.66[z]
M2	0.38[z]
A2	0.42[z]
E2	0.30[z]
Cn	0.13[z]

[z] Significant at $P < 0.0001$.
[y] N=1383

tissue. In contrast the A2, M2, E2, and Cn measurements were programmed to measure the forces required to penetrate the fruit to a deeper level (total 6.4 mm).

Correlations for parameters over all samples in the 2019-2021 experiments are shown in Table 4. With adjustments made to the MDT-2 for 2019 and 2020, the A1 and M1 parameters were equivalent in terms of total distance traveled to the A2/M2/E2 measurements utilized in 2018. However, the correlations between A1/M1 and the Firmtech 2 in 2019 and 2020 were similar to those observed between A1/M1 and the Firmtech 2 in 2018. This similarity suggests that the skin and outer regions of sweet cherry fruit are the firmest, i.e. average and maximum forces encountered in the first 3.8 mm of the fruit are similar to the average and maximum forces encountered in the first 6.4 mm. In the first group of 2021 experiments, M1/A1 were measured over the first 3.8 mm as in 2018, and overall correlations between these parameters and the Firmtech 2 were again very similar. However, the second group of experiments, sampled at 6.4 mm, had very low correlations with the Firmtech 2. The second group of samples were harvested on 25 June (4 samples), 28 June (2 samples), and 22 July (1 sample). Daily temperatures at the orchard in Prosser were abnormally high during this period, compared to the first group of samples (Table 4). Although temperatures had returned to normal levels by 22 July (the final harvest), the intervening period had seen maximum temperatures at or exceeding 37.8 °C for several days (data not shown). Excessive temperatures caused con-

Table 4. The relationship between fruit firmness values obtained with the Firmtech 2 and two parameters obtained with the MDT-2 for multiple sweet cherry genotypes, 2019-2021.

Year	Parameter	Depth	Overall Correlation	No. Observations	Range
2019	A1	Deep	0.69[y]	288	-0.18,0.80
2019	M1	Deep	0.75[y]	288	-0.22,0.83
2020	A1	Deep	0.59[y]	375	0.07,0.70
2020	M1	Deep	0.64[y]	375	0.08,0.71
2021	A1	Shallow	0.64[y]	200	-0.23,0.85
2021	M1	Shallow	0.63[y]	200	-0.20,0.78
2021	A1	Deep	0.18[z]	172	0.03,0.25
2021	M1	Deep	0.16[z]	172	-0.09,0.25

[z,y] Significant at $P < 0.05$, 0.0001, respectively.

Table 5. Daily minimum, average, and maximum temperatures (°C) for harvest dates in 2021. The first group was harvested on 23 and 24 June. Weather data are from Washington State University's AgWeathernet 'Roza2' station located in the Prosser orchard (weather.wsu.edu)

Date	Minimum	Average	Maximum
23 June	17.1	26.6	34.5
24 June	13.0	25.5	33.9
25 June	23.5	29.0	35.1
28 June	22.7	34.0	42.1
22 July	14.7	24.8	33.5

siderable damage to fruit this season (Hoang 2021; McCord, personal observation), and it is most likely that this damage to fruit structure obscured any relationships between Firmtech 2 and MDT-2 measurements.

Aside from the heat-damaged fruit, our overall correlations between the Firmtech 2 and MDT-2 across years and experiments were consistent, ranging from 0.62 to 0.75 (M1 parameter). Bound et al. (2013) found a very strong correlation in 'Van' and 'Sweetheart' cherries (r= 0.92) between compression (via the Firmtech 2) and flesh puncture measurements (via the GÜSS Fruit Texture Analyzer penetrometer). In comparison with the present research, Bound et al. (2013) removed the skin prior to penetrometer analysis, and a narrower penetrometer probe was used (2 mm vs. 4 mm). This suggests that the Firmtech 2 is primarily evaluating flesh firmness, although our data from 'Sweetheart' showed a higher correlation between the Firmtech 2 and shallow MDT-2 measurements which include the skin (Table 2). Brown and Bourne (1988) evaluated flesh and total (flesh plus skin) firmness in 29 sweet cherry genotypes and found a moderate correlation between the two (r=0.49). Furthermore, Brown and Bourne (1988) found that flesh firmness contributed only 15-34% of total firmness, although they suggested that the remaining components of firmness included interaction between skin and flesh, and not just skin firmness. Although the overall relationship between firmness (as measured by the Firmtech 2) and the MDT-2 is linear and positive, the two methods are not in strong agreement with each other. This can be seen clearly in Fig. 1, where the differences between firmness and M-1 are smaller at lower firmness values and increase at higher firmness values.

When correlations were separated by genotype or tree, considerable variability was apparent (Table 4, Figs. 2-4). It is also evident from Fig. 1 that the correlations vary between different trees of the same genotype (e.g. 'R50', r =0.11-0.48). Similarly, in plum (P. domestica L.), Seske and Wermund (2010) obtained correlations between compression and penetrometer readings ranging from 0.07-0.8, depending on cultivar and fruit maturity. As with the overall results above, these individual measurements suggest that while there is a linear relationship between compression and penetrometer values, it is not particularly strong nor constant. Since each device uses a different method (compression vs. penetration) to indirectly measure components of firmness such as cell wall composition (of different tissues) and turgor, each method is likely differentially affected by those components. These components include genetic factors (Cai et al., 2019; Campoy et al., 2015; Crump et al., 2022), environmental influences such as fruit maturity and excessive heat, and interactions between genetic and environmental effects.

In the 2021 experiments, preliminary analyses with a human taster identified some fruits (23/373) with more complex textures, such as firm fruit with a crunchy texture, or soft fruit with a tough skin. They were not assigned to an overall texture category (data not shown). Particularly for samples with

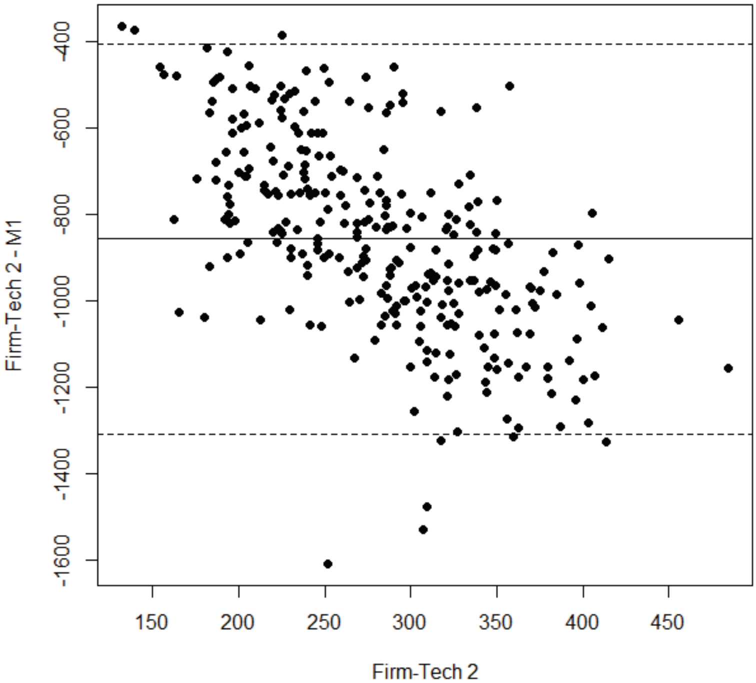

Figure 1. Scatter plot of the differences between Firmtech 2 and MDR-2 M1 measurements (y axis) and Firmtech 2 measurements (x axis). Data are from the 2019 experiments (n = 288) The solid horizontal line indicates the mean of the differences; upper and lower dotted lines delimit +/- two standard deviations, respectively.

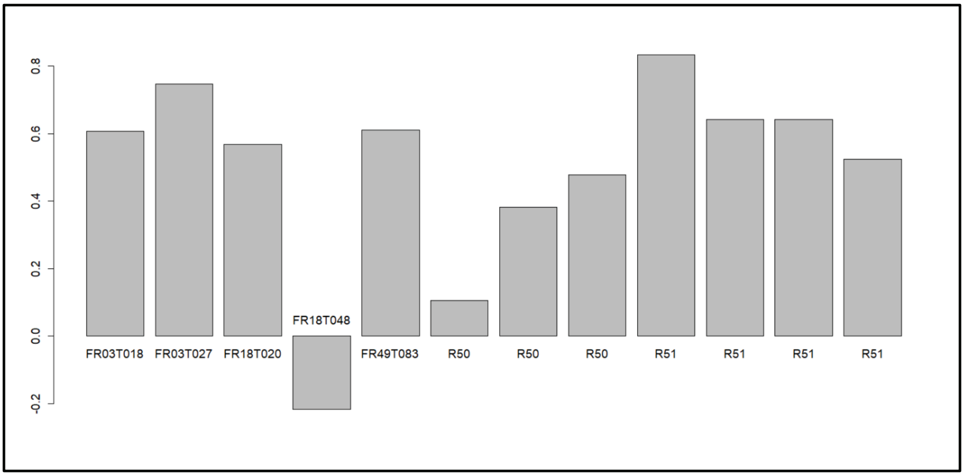

Figure 2. Correlation coefficients indicating the linear relationship between values obtained with the Firmtech 2 and M1 obtained with the MDT-2 for individual sweet cherry trees [n = 25 fruit per tree except the first tree of R51 (n=13)], 2019 season.

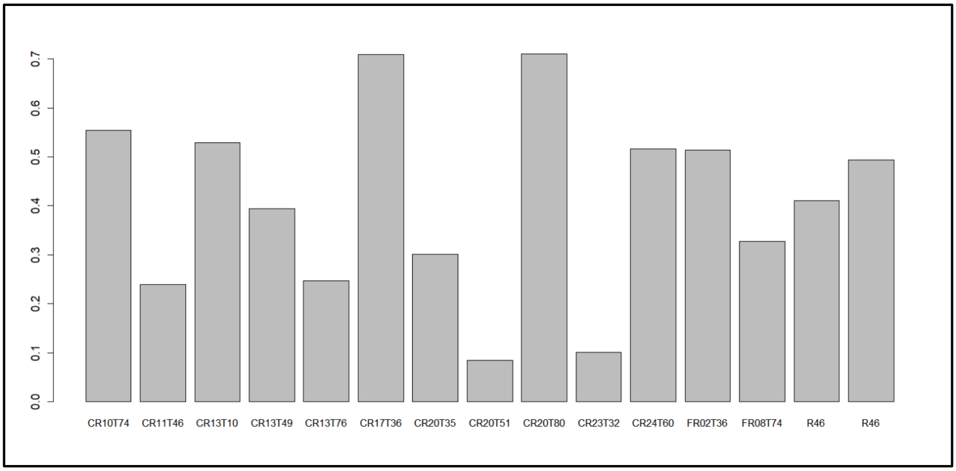

Figure 3. Correlation coefficients indicating the linear relationship between values obtained with the Firmtech 2 and M1 with the MDT-2 for individual sweet cherry trees, 2020 season. Coefficients were calculated based on measurements from 25 fruit per tree.

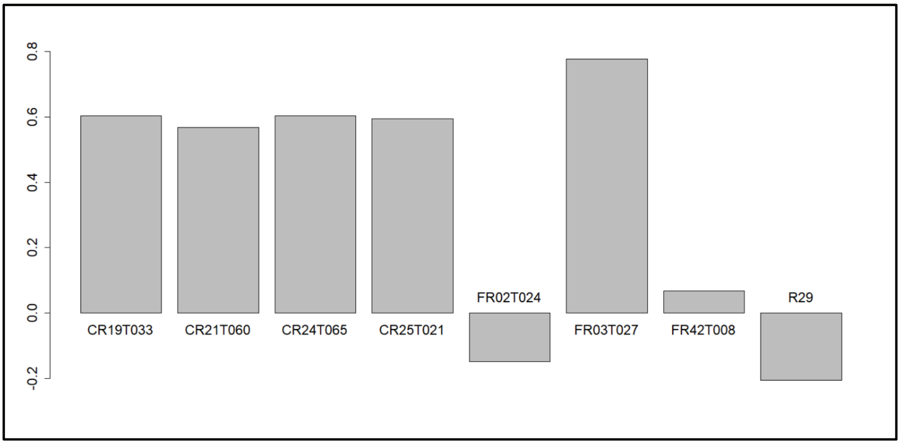

Figure 4. Correlation coefficients indicating the linear relationship between values obtained with the Firmtech 2 and MDT-2 M1 for sweet cherry fruit (shallow profile), 2021 season. Coefficients were calculated based on measurements from 25 fruit per tree.

not shown).Particularly for samples with complex texture, it is likely that more complex data will need to be collected to reliably distinguish them. Force curves can be generated from both the Firmtech 2 and MDT-2, although software modifications would be necessary to capture and/or analyze such data, particularly for the Firmtech 2. In the past, near-infrared spectroscopy (NIRS) was used with limited success to measure firmness in sweet cherry (Lu, 2001) and apricot (Bureau et al., 2009), but it is possible that spectroscopy methods could be improved to measure firmness as was done by Muhua et al. (2007) in peach and extended to predict more complex texture parameters.

Although both instruments were able to detect treatment effects in 2018, Firmtech 2 outperformed the MDT-2 in this regard. The correlation between Firmtech 2 and MDT-2 values was generally positive and statistically significant but varied significantly from genotype to genotype.This observation, combined with the facts that compression tests are non-destructive, correlate strongly with human perception of cherry texture (Hampson et al., 2014), and are widely used and understood by the industry, means compression testing remains the preferred instrument for fruit texture analysis. However, there is still texture variation that is unaccounted for by machine-based measurements. As mentioned above, analysis of the force curves generated in particular by the MDT-2 may allow for more accurate and thorough analyses of cherry texture.These analyses could be useful in the later stages of selection/variety development programs (where more fruit are available for characterization), to more thoroughly evaluate the effects of pre-harvest and post-harvest conditions on cherry fruit texture. The data could also be analyzed for relationships with other traits such as storability (including resistance to decay and pitting) or pathogen resistance. Alternatively, non-destructive spectroscopic methods, if sufficiently high throughput, could be developed for analysis of fruit texture, a key component of sweet cherry quality.

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References Cited

Abbott J. 1999. Quality measurement of fruits and vegetables. Postharvest Biol Technol. 15:207-225. https://doi.org/10.1016/S0925-5214(98)00086-6.

Blaker K, Plotto A, Baldwin E, Olmstead J. 2014. Correlation between sensory and instrumental measurements of standard and crisp-texture southern highbush blueberries (*Vaccinium corymbosum* L. interspecific hybrids). J Sci Food Agric. https://doi.org/10.1002/jsfa.6626.

Bound S, Close D, Quentin A, Measham P, Whiting M. 2013. Crop load and time of thinning interact to affect fruit quality in sweet cherry. J Agric Sci. 5:216-230. https://doi.org/10.5539/jas.v5n8p216.

Brown S, Bourne M. 1988. Assessment of components of fruit firmness in selected sweet cherry genotypes. HortScience 23:902-904. https://doi.org/10.21273/HORTSCI.23.5.902.

Bureau S, Ruiz D, Reich M, Gouble B, Bertrand D, Audergon J-M, Renard C. 2009. Rapid and non-destructive analysis of apricot fruit quality using FT-near-infrared spectroscopy. Food Chem. 113:1323-1328. https://doi.org/10.1016/j.foodchem.2008.08.066.

Cai L, Quero-García J, Barreneche T, Dirlewanger E, Saski C, Iezzoni A. 2019. A fruit firmness QTL identified on linkage group 4 in sweet cherry (*Prunus avium* L.) is associated with domesticated and bred germplasm. Sci Rep. 9:5008. https://doi.org/10.1038/s41598-019-41484-8.

Campoy, J, Le Dantec L, Barreneche T, Dirlewanger E, Quero-García J. 2015. New insights into fruit firmness and weight control in sweet cherry. Plant Mol Biol Rep. 33:783-796. https://doi.org/10.1007/s11105-014-0773-6

Chauvin M, Whiting M, Ross C. 2009. The influence of harvest time on sensory properties and consumer acceptance of sweet cherries. HortTechnology 19 (4): 748 – 754. https://doi.org/10.21273/HORTSCI.19.4.748.

Contador L, Diaz M, Hernandez E, Shinya P, Infante R. 2016. The relationship between instrumental tests and sensory determinations of peach and nectarine texture. Eur J Hortic Sci. 81:189-196. https://doi.org/10.17660/eJHS.2016/81.4.1.

Correia S, Schouten R, Silva A, Goncalves B. 2017. Factors affecting quality and health promoting compounds during growth and postharvest life of sweet cherry (*Prunus avium* L). Front Plant Sci. 8: 2166. https://doi.org/10.3389/fpls.2017.02166.

Crisosto C, Crisosto G, Metheney P. 2003. Consumer acceptance of 'Brooks' and 'Bing' cherries is mainly dependent on fruit SSC and visual skin color. Postharvest Biol Technol. 28:159-167. https://doi.org/10.1016/S0925-5214(02)00173-4.

Crump W, Peace C, Zhang Z, McCord P. 2022. Detection of breeding-relevant fruit cracking and fruit firmness quantitative trait loci in sweet cherry via pedigree-based and genome-wide association approaches. Front Plant Sci. 13: 823250. https://doi.org/10.3389/fpls.2022.823250.

Deve, M, McDonald R, Cliff M, Lane W. 1996. Sensory evaluation of sweet cherry cultivars. HortScience 31:150-153. https://doi.org/10.21273/HORTSCI.31.1.150.

Edgely M, Close D, Measham P. 2019. Effects of climatic conditions during harvest and handling on the postharvest expression of red drupelet reversion in blackberries. Sci Hortic. 253:399-404. https://doi.org/10.1016/j.scienta.2019.04.052.

Friedman H, Whitney J, Szczesniak A. 1962. The Texturometer - A new instrument for objective texture measurement. J Food Sci. 28:390-396. https://doi.org/10.1111/j.1365-2621.1963.tb00216.x.

Guyer D, Sinha N, Chang T, Cash J. 1993. Physicochemical and sensory characteristics of selected Michigan sweet cherry (Prunus avium L.) cultivars. J Food Qual. 16:355-370. https://doi.org/10.1111/j.1745-4557.1993.tb00121.x.

Hampson C, Stanich K, McKenzie D, Herbert L, Lu R, Li J, Cliff M. 2014. Determining the optimum firmness for sweet cherries using Just-About-Right sensory methodology. Postharvest Biol Technol. 91:104-111. https://doi.org/10.1016/j.postharvbio.2013.12.022.

Hoang M. 2021. Extreme heat takes out significant portion of Northwest cherry crop. Yakima Herald Republic. Extreme heat takes out significant portion of Northwest cherry crop | Local | yakimaherald.com. [Accessed 23 September 2021].

Kappel F, Fisher-Fleming B, Hogue E. 1996. Fruit characteristics and sensory attributes of an ideal sweet cherry. HortScience 31:443-446. https://doi.org/10.21273/HORTSCI.31.3.443.

Kappel F, MacDonald R, McKenzie D. 2000. Selecting for firm sweet cherries. Acta Hortic. 538:355-358. https://doi.org/10.17660/ActaHortic.2000.538.61.

Loescher W. 2016. Cherries (Prunus spp.): The fruit and its importance, p 10-13. In: Caballero B, Finglas P, Toldrá F (eds.). Encyclopedia of Food and Health. Academic Press (Elsevier), Cambridge, Mass. https://doi.org/10.1016/B978-0-12-384947-2.00138-0.

Lu R. 2001. Predicting firmness and sugar content of sweet cherries using near-infrared diffuse reflectance spectroscopy. Trans Amer Soc Agric Biol Eng. 44:1265-1271. https://doi.org/10.13031/2013.6421.

Mitcham E, Clayton M, Biasi W. 1998. Comparison of devices for measuring cherry fruit firmness. HortScience 33:723-727. https://doi.org/10.21273/HORTSCI.33.4.723.

Muhua L, Peng F, Renfa C. 2007. Non-destructive estimation of peach SSC and firmness by multispectral reflectance imaging. N Z J Agric Res. 50:601-608. https://doi.org/10.1080/00288230709510328.

R Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: https://www.R-project.org.

Saftner R, Polashock J, Ehlenfeldt M, Vinyard B. 2008. Instrumental and sensory quality characteristics of blueberry fruit from twelve cultivars. Postharvest Biol Technol. 49:19-26. https://doi.org/10.1016/j.postharvbio.2008.01.008.

Sekse L, Wermund U. 2010. Fruit flesh firmness in two plum cultivars: comparison of two penetrometers. Acta Hortic. 874:119-124. https://doi.org/10.17660/ActaHortic.2010.874.15.

Zoffoli J, Toivonen P, Wang Y. 2017. Postharvest biology and handling for fresh markets, p.460-484. In: J. Quero-García, A. Iezzoni J. Puławska, and G. Lang (eds.). Cherries: botany, production and uses. CABI, Wallingford, UK. https://doi.org/10.1079/9781780648378.0000.