Folia Hort. 34(2) (2022): 139–150

DOI: 10.2478_fhort-2022-0011

Folia Horticulturae

Published by the Polish Society
for Horticultural Science since 1989

SHORT COMMUNICATION | Open access | http://www.foliahort.ogr.ur.krakow.pl

Mathematical modelling of Hass avocado firmness by using destructive and non-destructive devices at different maturity stages and under two storage conditions

Virgilio Gavicho Uarrota, Romina Pedreschi**

Pontificia Universidad Catolica de Valparaiso, Escuela de Agronomia, Department of Postharvest and Industrialization,
Calle San Francisco S/N, La Palma, Quillota, Chile

ABSTRACT

Devices which are used to determine firmness of non-destructive nature do not penetrate the skin or damage the underlying flesh of the fruit and do provide real-time results, avoid raw biomass loss and allow the testing of every individual fruit and repeated testing of the same fruit, thus providing many advantages for researchers and the industry alike. Contrarily, destructive methods puncture the fruit and thus only a subsample, selected to represent all fruit, can be tested. In addition, different operators can generate quite different values for the same fruit using a hand-held penetrometer. Hass avocado from two commercial orchards was collected, and fruit firmness was measured at harvest, during two storage conditions controlled atmosphere (CA) and regular air (RA), during shelf-life and at the ready-to-eat stage using both destructive (Fruit Pressure Tester, mod. FT327, Wagner Instruments, Greenwich, USA) and non-destructive devices (Model TA.XT plusC, Stable Micro Systems Ltd, England). Then, the mathematical relationship between these two devices was assessed using Spearman Correlation coefficient (rho) and *p*-values adjusted by Benjamini-Hochberg and Bonferroni procedures. Thus, 3,200 fruits were evaluated during two harvests and two subsequent seasons. A moderate and positive association between destructive and non-destructive devices was found (rho coefficient ranging from 0.41 to 0.51). The variance explained by the regression models ranged from 0.53 to 0.63; all of them were significant with good accuracies (i.e., 0.79; 0.78; 0.73; 0.76). The results prompt us to conclude that a non-destructive texture analyser device can be used to accurately predict firmness measured by a penetrometer in Hass avocado fruit and contribute to avoiding fruit discards.

Keywords: destructive fruit firmness, mathematical modelling, non-destructive device, *Persea americana*, relationships

INTRODUCTION

Avocado is rich in fatty acids and has high economic and health importance globally (Dreher and Davenport, 2013; Pedreschi et al., 2019). Fruit firmness is an important quality attribute which is used to assess the ripeness stage of the fruit during storage (Penchaya et al., 2015). It is the most reliable parameter for determining if the fruit is ripe to eat and plays a critical role in controlling postharvest shelf-life. The firmness at which fruit is consumed or assessed for quality is also very important since rots and internal disorders of Hass avocado develop rapidly during the later stages of fruit ripening (White et al., 1999; Zhang et al., 2019). Firmness can be measured by conventional destructive (fruit penetrometers) and recently by non-destructive texture analysers. Comparison of non-destructive methods indicates that each method is probably assessing different textural attributes; hence, the softening patterns may also differ (Goldberg et al., 2019). Fruit firmness and the rate of softening vary greatly, both between and within fruit batches, especially during shelf-life. Since

*Corresponding author.
e-mail: uaceleste@yahoo.com.br (Virgilio Gavicho Uarrota), romina.pedreschi@pucv.cl (Romina Pedreschi).

the conventional methods for assessing the progress of fruit ripening with a penetrometer are destructive, they require many fruits (Goldberg et al., 2019). Knowledge of textural properties is important for stakeholders in the food value chain including producers, postharvest handlers, processors, marketers and consumers (Chen and Opara, 2013).

The fruit penetrometer is used to monitor the ripeness stage and to check the consistency of the inner fruit flesh. It is very useful in the field for determining the best harvest time. Moreover, it can be used for quality control during storage or after transport. First, the fruit skin and flesh are removed, and the penetrometer is then pushed into the exposed fruit flesh (Khalaj et al., 2016; Souri and Dehnavard, 2017). Usually, each fruit is measured twice at the equator, with measurements made at 90° to each other. The average value is then taken as the firmness of that fruit (Li et al., 2016). Non-destructive devices allow repeated measurements of the same fruit or even the possibility of all fruit being assessed on a grading line. A key aspect of non-destructive measurement is that the whole fruit is assessed, although the particular technology applied will determine whether a specific part of the fruit has a large impact on the measurement made (Li et al., 2016).

There are significant amounts of studies in the literature comparing firmness by a penetrometer and non-destructive devices in different fruit such as in mango (Penchaiya et al., 2015), apple (Peleg, 1993), kiwifruit (Li et al., 2016; Goldberg et al., 2019), blueberries (Giongo et al., 2013) and watermelon (Abbaszadeh et al., 2015). Significant heterogeneity of maturities is frequently observed in Hass avocado fruit depending on the harvest season, environmental and agronomic factors (Fuentealba et al., 2017; Hernandez et al., 2016, 2017). It would be advantageous to have a reliable non-destructive method for measuring Hass avocado fruit firmness. Such a tool will be optimal for determining optimal harvest, monitoring periodic firmness in controlled atmosphere (CA) storage and regular air (RA). If a higher positive relationship is found, then non-destructive measurement can be used in the routine laboratory to assess Hass avocado firmness. The main goals of this study were to study the relationships between the Hass avocado fruit firmness measured by destructive (fruit penetrometer) and non-destructive devices (texture analyser) from harvest to ready-to-eat (RTE) stage and in two storage conditions (CA and RA).

MATERIALS AND METHODS

Orchard selection, fruit sampling and storage conditions

Fruits of Hass avocado (400 fruits per orchard) were sampled from two commercial orchards (Bartolillo and Quilhuica) at early (23–26% dry matter) and middle harvest (>27–30% dry matter) during two subsequent seasons (2018/2019 and 2019/2020) from Valparaiso region, Chile, and then transported to the Postharvest Laboratory, Faculty of Agriculture and Food Sciences, Pontificia Universidad Católica de Valparaíso for subsequent analysis. Before storage, fruit were numbered, and four small batches of 50 fruit each were marked randomly. Two hundred (200) fruit were stored for 55 days at 5 °C, 4 kPa O_2 and 6 kPa CO_2 in CA, and the other 200 fruit were stored at 5 °C for 30 days in RA conditions. At harvest, 50 fruit were evaluated for their firmness using destructive and non-destructive devices. Fruit stored in CA were sampled (50 fruit each batch) for firmness measurement at day 20, 35, 55 and at the RTE stage. Those fruit stored in RA were sampled for firmness measurement at harvest and at day 10, 20 and 30 and at RTE stage. In total, 3,200 fruits were evaluated in this experiment.

Destructive firmness measurement

At each day of sampling, 50 fruits from each orchard were measured for their firmness using a penetrometer (Fruit Pressure Tester, mod. FT327). Two sets of measurements per fruit were performed at two equidistant points on the equatorial region of each whole fruit, and results were expressed in Newton (N). The penetrometer was equipped with a 4 mm plunger tip. At RTE, a plunger tip of 8 mm was used, and all values were converted to Newton (Rivera et al., 2017).

Non-destructive firmness measurement

The firmness of each fruit was evaluated as described by Ochoa-Ascencio et al. (2009) with small modifications to it using a non-destructive texture analyser (Model *TA.XT plus C*, Stable Micro Systems Ltd) fitted with a cylinder probe of 10 mm diameter (Ø), trigger threshold of 0.50 N and measuring speed of 8 mm · s^{-1}. The compression force was recorded in Newton (N) at 2 mm deformation and was determined at two equidistant points on the equatorial region of each whole fruit, and results were expressed in N.

Data mining and statistics

Data were summarised, subjected to normality (Shapiro–Wilk test) and homogeneity tests (Levene test), to check the correlation assumptions and finally the correlation analysis. Kruskal–Wallis (1952) rank sum test was performed to test for differences in firmness during the storage time and where differences were observed a Dunn's test (1964) was used as multiple comparison test and p-values adjusted using Benjamini-Hochberg (1995) and Bonferroni procedure as powerful tools to decrease the false discovery rate (false positives or type I error). All performed tests were done in R software (R Core Team, 2021), using scripts elaborated by the research group.

RESULTS AND DISCUSSION

The results of normality tests (i.e., normal Q-Q plots and histograms with normal curves of fruit firmness measured by non-destructive and destructive devices for fruit stored in RA and CA of Quilhuica and Bartolillo orchards) are summarised in Supplementary Figures 1–4. Independently of the storage technique, all variables tested (firmness by a penetrometer and firmness by a texture analyser) did not follow a Gaussian distribution, and the variances tested by Levene's test ($p < 0.05$) between the groups were different (not homogeneous). Supplementary Figures 1 and 2 present the normal Q-Q plot of fruit firmness measured by non-destructive and destructive devices for fruit stored in RA and CA for Quilhuica and Bartolillo orchards, respectively. Supplementary Figures 3 and 4 show a histogram with a curve of normal distribution for Quilhuica and Bartolillo orchards, respectively. As it can be observed, the variables tested did not follow a normal distribution, confirming previous results of Shapiro–Wilk test ($p < 0.05$). Spearman correlation was then chosen as the normality assumptions were not satisfied and the rho was calculated using Equation 1 below:

$$\left\{ \text{rho} = \frac{\sum(x-m_x)(y-m_y)}{\sqrt{\sum(x-m_x)^2 \sum(y-m_y)^2}} \right\}$$

where x = rank (x) and y = rank(y).

Results of spearman correlations (Figure 1) showed a positive moderate association between the firmness measured by penetrometer (destructive device) with non-destructive fruit firmness in all storage conditions and orchards. Higher positive association (rho = 0.51) was found for Bartolillo orchard (Figure 1C) fruits stored in RA, while for those fruits stored in CA (Figure 1D), a coefficient of 0.46 was observed. The lowest coefficients found were 0.41 (Figure 1B) and 0.45 (Figure 1A) for Quilhuica fruit stored in CA and RA, respectively.

Regression analysis was also performed, and models were built. Four models were built for Quilhuica and

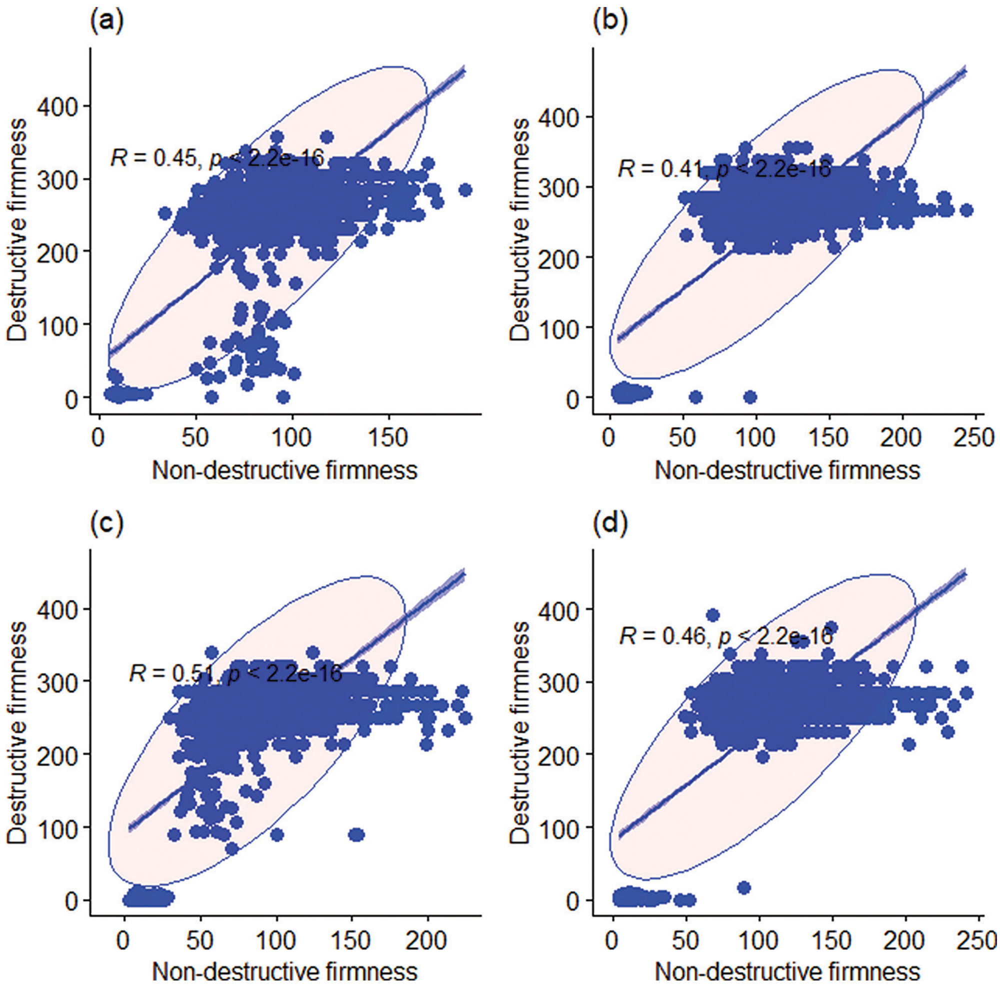

Figure 1. Spearman correlations of firmness data between destructive and non-destructive devices for Quilhuica (A,B) and Bartolillo (C,D) orchards.The firmness of the fruit stored in RA decreased rapidly once removed from cold storage conditions (day 30). The firmness of the fruit was not easily lost under CA storage and remained unaltered during the prolonged storage stage, and the fruit lost firmness faster after removal from storage at day 55. Figure 2A, 2C show the firmness loss measured by a texture analyser while Figure 2B, 2D show the firmness by a destructive device for Quilhuica and Bartolillo orchards, respectively. Differently from non-destructive devices, little change in firmness was observed when the penetrometer was used (Figure 2B, 2D).

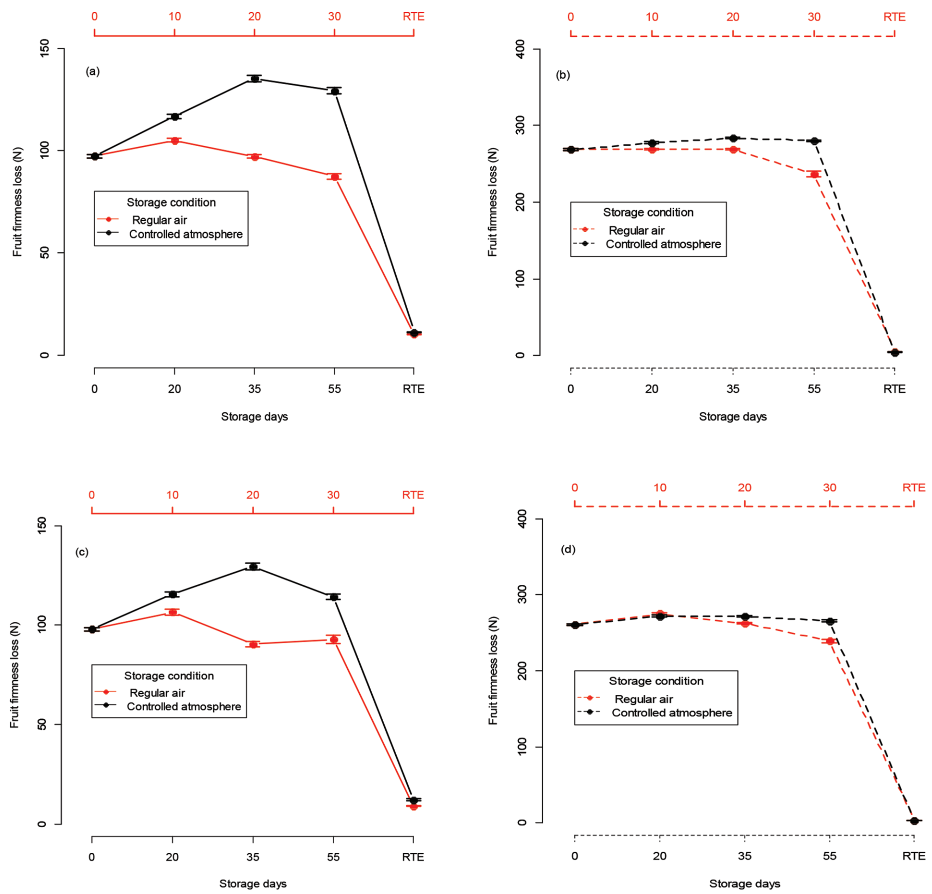

Figure 2. Changes in firmness from harvest until RTE stage of fruit stored in RA and CA storage of both orchards, Quilhuica (A,B) and Bartolillo (C,D). CA, controlled atmosphere; RA, regular air; RTE, ready-to-eat.

Bartolillo for samples stored in RA and CA conditions, respectively. The accuracy of the first model (Q_RA) was 0.79, and the variance explained by the model (coefficient of determination) was 0.63. The second model (Q_CA) expressed a variance of 0.61 with model accuracy of 0.78, the third model expressed a variance of 0.53 with accuracy of 0.73 and finally the fourth model expressed a variance of 0.57 with accuracy of 0.76. All tested models were statistically significant ($p < 0.05$). Table 1 presents the prediction intervals of all tested models with 95% confidence intervals. As it can be observed, the fitted values of firmness by a penetrometer were within the range of the confidence intervals, and according to the model equations, it is possible to predict firmness by a penetrometer using a non-destructive device in Hass avocado fruit.

$$[F_{PE} = 50.66 + 2.09\mathrm{F}_{TA}](\mathrm{Q\_RA})$$
$$[F_{PE} = 75.18 + 1.59\mathrm{F}_{TA}](\mathrm{Q\_CA})$$
$$[F_{PE} = 93.28 + 1.58\mathrm{F}_{TA}](\mathrm{B\_RA})$$
$$[F_{PE} = 83.34 + 1.52\mathrm{F}_{TA}](\mathrm{B\_CA})$$

Analysis of variance (ANOVA) by Kruskal–Wallis (non-parametric ANOVA) was also performed to assess if there were significant differences in firmness changes during the storage period. For Quilhuica fruit stored in RA storage and measured by a non-destructive device (Table 2), Dunn's test revealed significant statistical differences of firmness during the storage time. No differences from harvest until day 20 were observed using the penetrometer. For Bartolillo orchard (Table 2) and using non-destructive devices, firmness at day 0 and 10 differed from day 20 and 30 and RTE, whereas significant differences at each day of sampling were observed when using a penetrometer. Significant differences during the sampling time were also observed for samples stored in CA storage (Table 3).

Results presented in this study agree with those reported by Li et al. (2016) in kiwifruit. A decline in firmness during storage was also observed, and a good relationship between standard penetrometer and non-destructive device was reported. The firmness change depended on the storage technique and while measuring by penetrometer depends also by the speed approach measurement. Higher speed tends to give higher values of firmness. Peleg (1993) found positive association while comparing destructive and non-destructive firmness in apple fruit but claimed that linear regression and correlation coefficients depended strongly on the firmness range of the inspected sample. As the firmness may vary from sample to sample, correlation coefficient

Table 1. Model prediction intervals from each regression analysis performed. Four models were tested from different datasets.

Model	F_{TA}	F_{PE}	Fitted F_{PE}	lwr	upr
	97.79	302.60	255.13	146.99	363.27
	86.84	267.00	232.24	124.10	340.38
	93.92	249.20	247.05	138.91	355.19
Q_RA	91.70	281.24	242.40	134.26	350.54
	95.96	267.00	251.31	143.17	359.46
	82.85	249.20	223.89	115.75	332.03
	121.22	252.76	304.13	195.95	412.31
	86.14	249.20	230.79	122.65	338.93
Model	F_{TA}	F_{PE}	Fitted F_{PE}	lwr	upr
	97.79	302.60	231.53	120.30	342.76
	86.84	267.00	214.03	102.80	325.26
	157.88	284.80	327.62	216.33	438.90
Q_CA	92.81	267.00	223.58	112.35	334.81
	120.86	267.00	268.42	157.20	379.65
	82.85	249.20	207.64	96.41	318.88
	101.42	284.80	237.34	126.12	348.56
	86.14	249.20	212.92	101.68	324.15
Model	F_{TA}	F_{PE}	Fitted F_{PE}	lwr	upr
	68.01	234.96	200.50	83.41	317.60
	103.33	252.76	256.18	139.09	373.27
	96.82	284.80	245.92	128.83	363.01
B_RA	81.22	284.80	221.33	104.24	338.41
	80.86	284.80	220.76	103.67	337.84
	83.43	267.00	224.81	107.73	341.90
	113.48	284.80	272.18	155.08	389.29
	114.79	267.00	274.25	157.14	391.36
Model	F_{TA}	F_{PE}	fitted F_{PE}	lwr	upr
	10.69	5.34	99.55	-7.85	206.96
	83.80	252.76	210.40	103.19	317.62
	88.70	238.52	217.84	110.62	325.05
B_CA	89.11	249.20	218.46	111.25	325.67
	83.48	249.20	209.92	102.70	317.14
	78.88	284.80	202.95	95.73	310.17
	209.33	284.80	400.75	293.28	508.21
	8.82	5.34	96.71	-10.70	204.12

Q_RA and Q_CA are model prediction intervals from Quilhuica firmness data of RA and CA, respectively, and B_RA and B_CA for Bartolillo orchard. F_{TA} and F_{PE} are the observed firmness values measured by a texture analyser (non-destructive device) and penetrometer, respectively. Fitted F_{PE} is the fitted penetrometer firmness by the linear regression model; lwr and upr means lower and upper prediction interval of the model, respectively.
CA, controlled atmosphere; RA, regular air.

is not suitable for comparisons of firmness measurement methods. The results of our study are also in agreement with those reported by Plocharski et al. (2000) who found positive association between destructive and non-destructive firmness in pear and apple fruit stored in CA and RA conditions. They concluded that correlation coefficient varies with cultivar and growing season; these results that corroborate with those of our study. Significant correlations in firmness measurement methods were also found according to fruit type in peaches, nectarines and plums (Valero et al., 2007). As it was observed in our study, the rugosity of the peel

Table 2. Mean comparisons of firmness during storage time after ANOVA by Kruskal–Wallis (non-parametric ANOVA).

	Quilhuica		Bartolillo	
Storage time*	F_{TA}	F_{PE}	F_{TA}	F_{PE}
0	b	a	a	b
10	a	a	a	a
20	b	a	b	b
30	c	b	b	c
RTE	d	c	c	d

p values were adjusted by Bonferroni test. Analysis was performed for fruit stored in RA.

*Samples stored in RA.

ANOVA, analysis of variance; RA, regular air; RTE, ready-to-eat.

Table 3. Mean comparisons of firmness during storage time after ANOVA by Kruskal–Wallis (non-parametric ANOVA).

	Quilhuica		Bartolillo	
Storage time*	F_{TA}	F_{PE}	F_{TA}	F_{PE}
0	d	c	c	c
20	c	b	b	a
35	a	a	a	a
55	b	ab	b	b
RTE	e	d	d	d

p values were adjusted by Bonferroni test. Analysis was performed for fruit stored in CA.

*Samples stored in CA

ANOVA, analysis of variance; CA, controlled atmosphere; RTE, ready-to-eat.

and its characteristics also influence the results of the measurement. How might it affect the correlations between these two devices is a matter to be considered.

The technique of CA can provide different concentrations of gas, such as low O_2 and high CO_2 levels, which are always used with the appropriate temperature and relative humidity (RH) for fruit storage. Ma et al. (2019) reported that CA storage with the suitable conditions proves to be better than RA as a storage regimen to keep the quality of fruit. In their research, they found that fruit stored under CA showed lower contents of weight loss and malondialdehyde (an indicator of lipid peroxidation, membrane injury and cellular oxidation) and a higher content of total soluble solids, titratable acidity, total phenolic contents and vitamin C, and in contrast, the alcohols, malondialdehyde and esters displayed elevated levels in RA conditions of stored lemon fruit (Ma et al., 2019). McDonald and Harman (1982) also reported that CA conditions delay the rate of kiwifruit softening and increased storage life up to 3–4 months beyond normal air-storage life (RA). Enhancement of quality attributes (firmness and weight loss) in mango fruit by CA technology was also found by Hailu et al. (2016) and by Santana et al. (2011) in peaches. Ethylene production was also found to be lower in CA storage conditions (Golias et al., 2016) in pear fruits. Recently, a study by Hernandez et al. (2021) using mechanistic models clearly showed that CA storage retains the firmness of the fruit when compared to RA. Different non-destructive firmness measurements have been previously reported in other fruits such as in apples (Osinenko et al., 2021), in tomato (Alenazi et al., 2020), in peach fruit (Minas et al., 2021) and in avocado (Landahl and Terry, 2020), and this was recently extensively reviewed by Arunkumar et al. (2021). The results presented here are important, and the models built can be used in the routine laboratory to rapidly measure the firmness, thus contributing to decrease fruit discards commonly observed while using destructive devices.

CONCLUSIONS

The results prompt us to conclude that there is positive association between firmness measured by the destructive method (fruit penetrometer) and non-destructive measurement by a texture analyser during the maturity stages and under different storage conditions. The rho coefficient was dependent on the orchard and storage technique. There was less loss of firmness in fruit stored in CA than that stored in RA. The models built are robust and can be used to predict penetrometer firmness from non-destructive measurement. The models were built from sufficient data and can be extended to model firmness of any Hass avocado fruit via non-destructive measurements. In addition, using non-destructive methods to account for quality parameters contributes to decrease fruit discards while firmness by penetrometer depends on the penetration speed and the trigger force at which the penetration measurements commence.

AKNOWLEDGEMENTS

The authors are thankful to Pontificia Universidad Católica de Valparaíso for providing research facilities, Sociedad Gardiazabal y Mena Ltda, Hass avocado-associated producers and exporters of Chile for providing avocado fruit.

FUNDING

The study is fully funded by the ANID-FONDECYT postdoctoral project N° 3190055 (Chile).

AUTHOR CONTRIBUTIONS

V.U. designed the experiment, performed all laboratory and statistical analysis and drafted the manuscript. R.P. supervised and performed the critical revision of the manuscript and final considerations.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Abbaszadeh, R., Rajabipour, A., Ying, Y., Delshad, M., Mahjoob, M., and Ahmadi, H. (2015). Nondestructive determination of watermelon flesh firmness by frequency response. *LWT – Food Science and Technology*, *60*, 637–640, doi: 10.1016/j.lwt.2014.08.029.

Alenazi, M., Shafiq, M., Alsadon, A., Alhelal, I., Alhamdan, A., and Solieman, T. (2020). Non-destructive assessment of flesh firmness and dietary antioxidants of greenhouse-grown tomato (*Solanum lycopersicum* L.) at different fruit maturity stages. *Saudi Journal of Biological Sciences*, *27*(10), 2839–2846.

Arunkumar, M., Rajendran, A., Gunasri, S., Kowsalya, M., and Krithika, C. (2021). Non-destructive fruit maturity detection methodology – A review. *Materials Today: Proceedings*, doi: 10.1016/j.matpr.2020.12.1094.

Benjamini, Y., and Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society, Series B (Methodological), 57*, 289–300.

Chen, L., and Opara, U. (2013). Texture measurement approaches in fresh and processed foods: A review. *Food Research International, 51*, 823–835.

Dreher, M., and Davenport, A. (2013). Hass avocado composition and potential health effects. *Critical Reviews in Food Science and Nutrition*, *53*, 738–750.

Dunn, O. J. (1964). Multiple comparisons using rank sums. *Technometrics, 6*, 241–252.

Fuentealba, C., Hernández, I., Olaeta, J., Defilippi, B., Meneses, C., and Campos, R. (2017). New insights into the heterogeneous ripening in Hass avocado via LC–MS/MS proteomics. *Postharvest Biology and Technology, 132*, 51–61.

Giongo, L., Poncetta, P., Loretti, P., and Costa, F. (2013). Texture profiling of blueberries (*Vaccinium* spp.) during fruit development, ripening and storage. *Postharvest Biology and Technology, 76*, 34–39.

Goldberg, T., Agra, H., and Ben-Arie, R. (2019). Non-destructive measurement of fruit firmness to predict the shelf-life of 'Hayward' kiwifruit. *Scientia Horticulturae*, *244*, 339–342.

Goliáš, J., Létal, J., Balík, J., and Kožíšková, J. (2016). Effect of controlled atmosphere storage on production of volatiles and ethylene from cv. Zaosuli pears. *Horticultural Science*, *43*(3), 117–125.

Hailu, Z. (2016). Effects of controlled atmosphere storage and temperature on quality attributes of mango. *Journal of Chemical Engineering & Process Technology*, *7*(5), 1000317, doi: 10.4172/2157-7048.1000317.

Hernández, I., Fuentealba, C., Olaeta, J., Lurie, S., Defilippi, B., Campos-Vargas, R., and Pedreschi, R. (2016). Factors associated with postharvest ripening heterogeneity of 'Hass' avocados (*Persea americana* Mill). *Fruits, 71*(5)*,* 259–268.

Hernández, I., Fuentealba, C., Olaeta, J., Poblete-Echeverría, C., Defilippi, B., González-Agüero, M., Campos-Vargas, R., Lurie, S., and Pedreschia, R. (2017). Effects of heat shock and nitrogen shock pre-treatments on ripening heterogeneity of Hass avocados stored in controlled atmosphere. *Scientia Horticulturae, 225*, 408–415.

Hernández, I., Uarrota, V., Paredes, D., Fuentealba, C., Defilippi, B., Campos-Vargas, R., Meneses, C., Hertog, M., and Pedreschia, R. (2021). Can metabolites at harvest be used as physiological markers for modelling the softening behaviour of Chilean "Hass" avocados destined to local and distant markets? *Postharvest Biology and Technology*, *174*, 111457, doi: 10.1016/j.postharvbio.2020.111457.

Khalaj, K., Ahmadi, N., and Souri, M. K. (2016). Improvement of postharvest quality of Asian pear fruits by foliar application of boron and calcium. *Horticulturae, 3*(1), 15, doi: 10.3390/horticulturae3010015.

Kruskal, W. H., and Wallis, A. (1952). Use of ranks in one-criterion variance analysis. *Journal of the American Statistical Association*, *47*, 583–621.

Landahl, S., and Terry, L. (2020). Non-destructive discrimination of avocado fruit ripeness using laser Doppler vibrometry. *Biosystems Engineering*, *194*, 251–260.

Li, H., Pidakala, P., Billing, D., and Burdon, J. (2016). Kiwifruit firmness: Measurement by penetrometer and non-destructive devices. *Postharvest Biology and Technology, 120*, 127–137.

Ma, Y., Li, S., Yin, X., Xing, Y., Lin, H., Xu, Q., Bi, X., and Chen, C. (2019). Effects of controlled atmosphere on the storage quality and aroma compounds of lemon fruits using the designed automatic control apparatus. *BioMed Research International*, *2019*, 6917147, doi: 10.1155/2019/6917147.

Mcdonald, B., and Harman, J. (1982). Controlled-atmosphere storage of kiwifruit. I. Effect on fruit firmness and storage life. *Scientia Horticulturae*, *17*(2), 113–123.

Minas, I., Blanco-Cipollone, F., and Sterle, D. (2021). Accurate non-destructive prediction of peach fruit internal quality and physiological maturity with a single scan using near infrared spectroscopy. *Food Chemistry*, *335*, 127626, doi: 10.1016/j.foodchem.2020.127626.

Ochoa-Ascencio, S., Hertog, M., and Nicolaï, B. (2009). Modelling the transient effect of 1-MCP on 'Hass' avocado softening: A Mexican comparative study. *Postharvest Biology and Technology 51*(1)*,* 62–72.

Osinenko, P., Biegert, K., Mccormick, R., Göhrt, T., Devadze, G., Streif, J., and Streif, S. (2021). Application of non-destructive sensors and big data analysis to predict physiological storage disorders and fruit firmness in 'Braeburn' apples. *Computers* *and Electronics in Agriculture*, *183*, 106015, doi: 10.1016/j.compag.2021.106015.

Pedreschi, R., Uarrota, V., Fuentealba, C., Alvaro, J., Olmedo, P., Defilippi, B., Meneses, C., and Campos-Vargas, R. (2019). Primary metabolism in avocado fruit. *Frontiers in Plant Science, 10*, 795, doi: 10.3389/fpls.2019.00795.

Peleg, K. (1993). Comparison of non-destructive and destructive measurement of apple firmness. *Journal of Agricultural Engineering Research*, *55*(3), 227–238.

Penchaiya, P., Uthairatanakij, A., Srilaong, V., Kanlayanarat, S., Tijskens, L., And Tansakul, A. (2015). Measurement of mango firmness by non-destructive limited compression technique. *Acta Horticulturae*, 1088, 73–78.

Plocharski, W. J., Konopacka, D., And Zwierz, J. (2000). Comparison of magness-taylor's pressure test with mechanical, non-destructive methods of apple and pear firmness measurements. *International Agrophysics, 14*, 311–318.

Rivera, S., Ferreyra, R., Robledo, P., Selles, G., Arpaia, M., Saavedra, J., and Defilippi, B. (2017). Identification of preharvest factors determining postharvest ripening behaviors in 'Hass' avocado under long term storage. *Scientia Horticulturae*, *216*, 29–37.

Santana, L., Benedetti, B., Sigrist, J., Sato, H., and Anjos, V. (2011). Effect of controlled atmosphere on postharvest quality of 'Douradão' peaches. *Ciência e Tecnologia de Alimentos*, *31*(1), 231–237.

Souri, M. K., and Dehnavard, S. (2017). Characterization of tomato growth and fruit quality under foliar ammonium sprays. *Open Agriculture, 2*(1), 531–536.

Valero, C., Crisosto, C., and Slaughter, D. (2007). Relationship between nondestructive firmness measurements and commercially important ripening fruit stages for peaches, nectarines and plums. *Postharvest Biology and Technology*, *44*(3), 248–253.

White, A., Woolf, A., Harker, R., and Davy, M. (1999). Measuring avocado firmness: Assessment of various methods. *Revista Chapingo Serie Horticultura, 5*, 389–392.

Zhang, C., Xiong, Z., Yang, H., and Wu, W. (2019). Changes in pericarp morphology, physiology and cell wall composition account for flesh firmness during the ripening of blackberry (*Rubus* spp.) fruit. *Scientia Horticulturae, 250*, 59–68.

Received: March 1, 2022; accepted: June 14, 2022

SUPPLEMENTARY MATERIALS

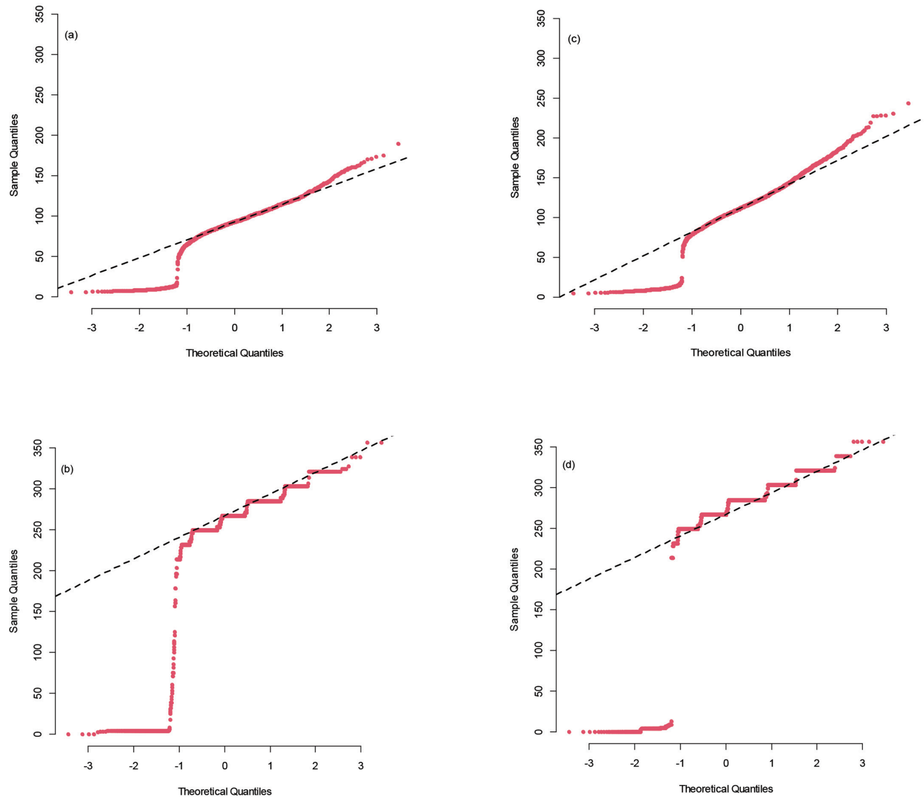

Figure S1. Normal Q-Q plots of fruit firmness measured by non-destructive (A,C) and destructive (B,D) devices. (A,B): Fruit stored in RA and (C,D) stored in CA of Quilhuica orchard. CA, controlled atmosphere; RA, regular air.

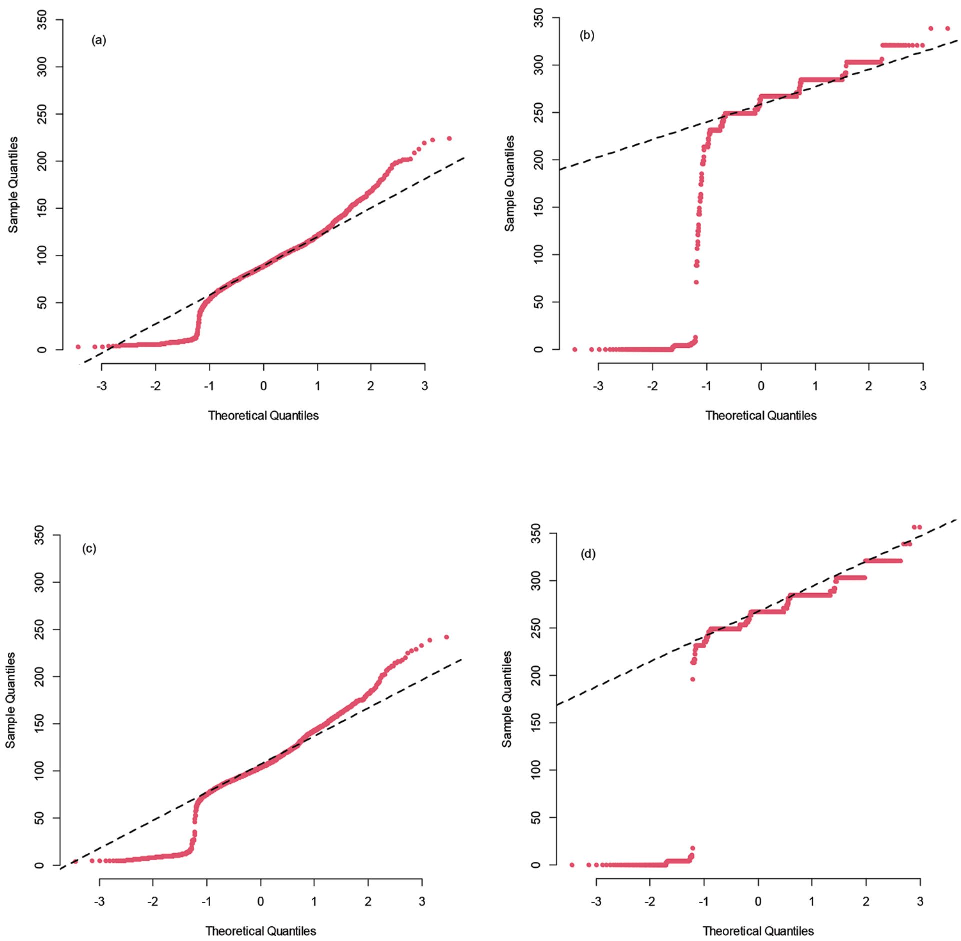

Figure S2. Normal Q-Q plots of fruit firmness measured by non-destructive (A,C) and destructive (B,D) devices. (A,B): Fruit stored in regular air (RA) and (C,D) stored in the controlled atmosphere (CA) of Bartolillo orchard.

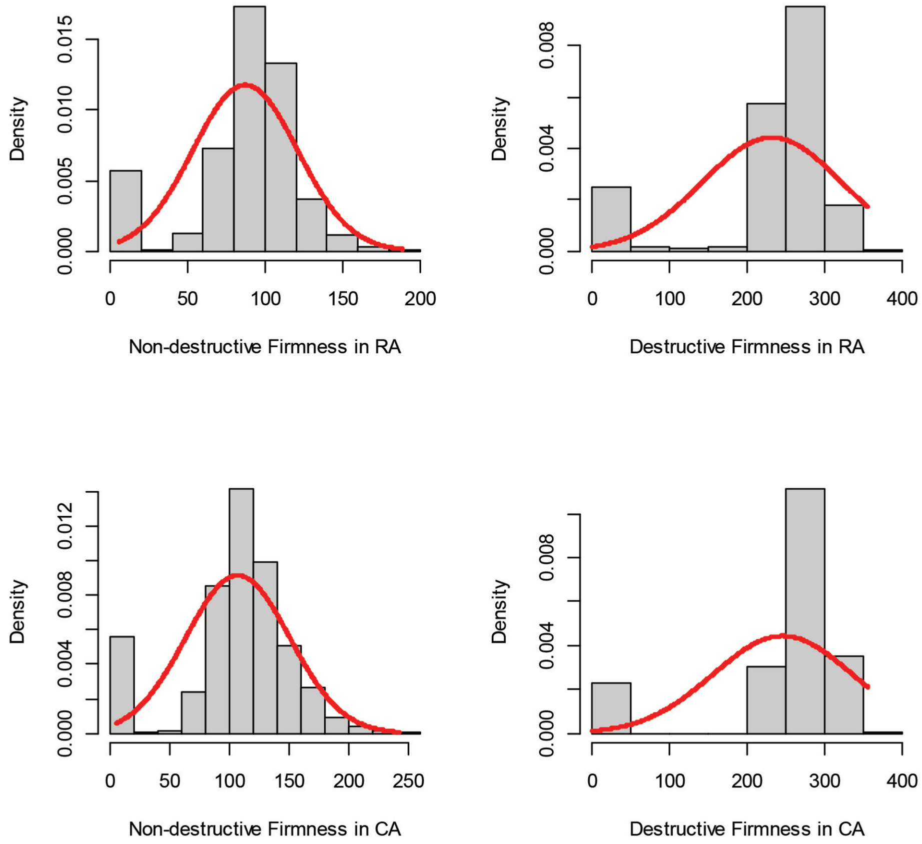

Figure S3. Histograms of normal distributions of firmness measured by non-destructive device and destructive device for both fruit stored in regular and CA of Quilhuica orchard. CA, controlled atmosphere; RA, regular air.

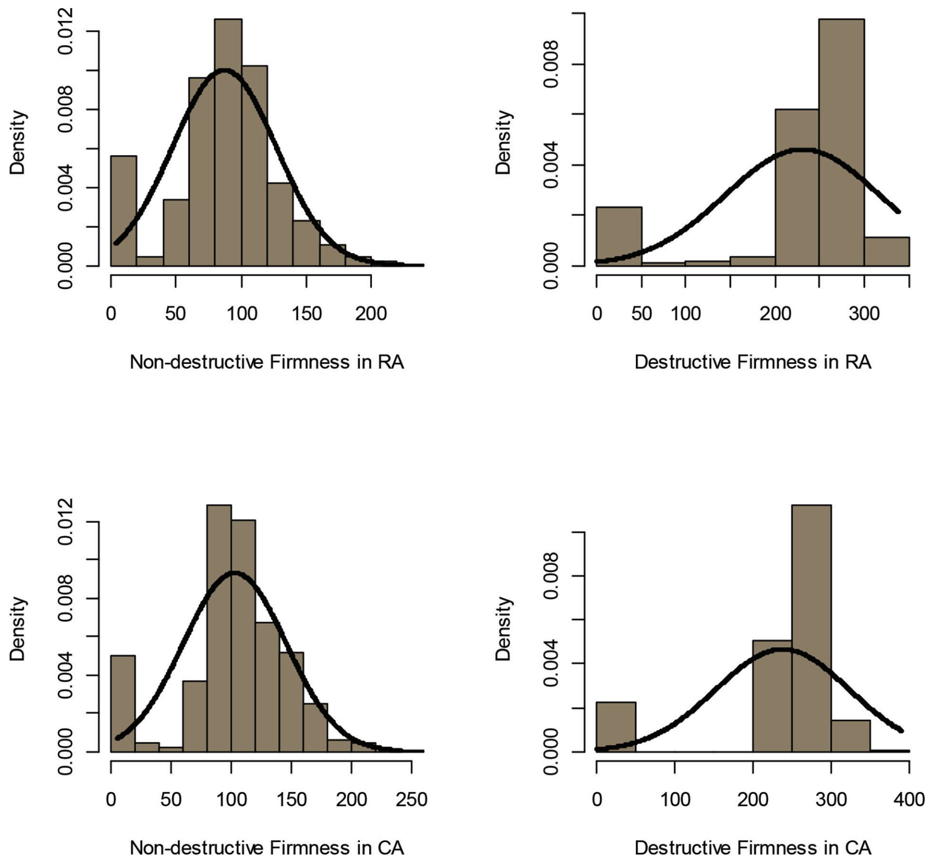

Figure S4. Histograms of normal distributions of firmness measured by non-destructive device and destructive device for both fruit stored in regular and CA of Bartolillo orchard. CA, controlled atmosphere; RA, regular air.