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Inter-correlation of apple firmness determinations and development of cross-validated regression models for prediction of sensory attributes from instrumental and compositional analyses

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ABSTRACT

The texture of apples is paramount for determining fruit quality. This research explored the correlations among firmness determinations from the Sinclair iQ™ Firmness Tester (SiQ™), the Aweta Acoustic Firmness Sensor (AFS), and eight measurements from the Mohr Digi-Test-2 (MDT) instrument. Assessments were conducted on a collection of nine apple cultivars (Ambrosia, Aurora Golden Gala™, Honeycrisp, Fuji, Imperial Gala, McIntosh, Pink Lady™, Silken, Salish™), with a broad range of firmness values, in each of two years. Sensory analysis of the apples was conducted using a semi-trained panel ($n = 10$) to evaluate crispness, hardness, juiciness and skin toughness, in quadruplicate at two testing dates, providing eight data points per cultivar per year. Inter-correlations of the instrumental firmness determinations (SiQ™, AFS, MDT) revealed that most values were highly correlated with one another ($r > 0.500$ $n = 72$). This suggested that the instruments were tracking similar, but not identical, underlying characteristics. Multiple regression models were developed using the 2016 data to predict the sensory attributes from the instrumental and compositional (titratable acidity, soluble solids concentration, absorbed juice) analyses. Models with the highest R^2 were cross-validated using the 2015 data. Accuracy of these models was evaluated using R^2 and prediction standard errors (*PSEs*) - an index quantifying the difference between the predicted and actual values. In general, simple 1- and 2-variable models satisfactorily predicted hardness and crispness, with the R^2 values ranging between 85 and 89%, while more complex non-linear models were required to predict juiciness and skin toughness. Correlations coefficients reported in this research allow for interconversion of experimental firmness data, as determined by the SiQ™, AFS and MDT. Regression models predicting hardness, crispness and juiciness from instrumental/compositional analyses, revealed that the quality factor (QF) variable was particularly important for estimation of textural characteristics. Therefore the MDT, among the instruments evaluated, was the instrument of choice for quality assessment of apples. Since cross-validation of the models accounted for a high proportion of the variance (70–82%) in a new data set with small *PSEs* (2.67–6.36) (on a 100-unit scale), the developed models were appropriate for estimating the apple textural attributes.

1. Introduction

Fruit texture has a critical influence on consumers' choice for apples (Bonany et al., 2013; Harker, Kupferman, Marin, Gunson, & Triggs, 2008; Hoehn, Gasser, Guggenbuhl, & Kunsch, 2003; Tu & De Baerdemaeker, 1996). Consumers prefer crisp and juicy apples that are dependent on cellular structure and response of cells to applied forces (Szczesniak, 2002). Since the assessment of foods by humans is very labour intensiveness, much research has been devoted to predict sensory and consumer perception using instrumental determinations (Ross, 2009).

Mehinagic, Royer, Symoneaux, and Jourjon (2006) studied the

Abbreviations: SiQ™, Sinclair iQ™ Firmness Tester; AFS, Aweta Acoustic Firmness Sensor; MDT, Mohr Digi-Test-2; n.d., not dated; *PSEs*, prediction standard errors; *SD*, standard deviation; *SE*, standard error; *r*, correlation coefficient; R^2, coefficient of determination; *B*, regression coefficient; *β*, beta coefficient; RMSECV, root-mean-square-error-of-cross-validation; standardized DF_{Beta}, difference between the fitted and predicted values; standardized DfFit, the change in the predicted value when a point is left out of the regression; VIF, variance inflation factor; TS, tolerance statistic; TA, titratable acidity; SSC, soluble solids concentration; AJ, absorbed juice; M1, maximum firmness for R1; A1, average force for R1; M2, maximum firmness for R2; A2, average force for R2; E2, average force of the last 20 reading in R2; C_0, creep deformation; Cn, crispness measurement; QF, quality factor

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Table 1
List of determinations, abbreviations and units of measure associated with the independent and dependent variables.

Type of determination	Type of statistical variable	Name of variable	Abbreviation for variable	Abbreviation for mean	Units of measure
Compositional	Independent	Titratable acidity	TA	MTA	Grams/liter, g/L
Compositional	Independent	Soluble solids concentration	SSC	MSSC	Percent, %
Compositional	Independent	Absorbed juice	AJ	MAJ	Grams, g
Instrumental	Independent	Sinclair firmness[a]	SiQ	MSiQ	Unitless
Instrumental	Independent	Aweta firmness[b]	AFS	MAFS	Unitless
Instrumental	Independent	Maximum firmness for R1[c]	M1	MM1	Newtons, N
Instrumental	Independent	Average force for R1[c]	A1	MA1	Newtons, N
Instrumental	Independent	Maximum firmness for R2[c]	M2	MM2	Newtons, N
Instrumental	Independent	Average force for R2[c]	A2	MA2	Newtons, N
Instrumental	Independent	Average force of last 20 readings in R2[c]	E2	ME2	Newtons, N,
Instrumental	Independent	Creep deformation[c]	C_0	MC_0	Millimeters, mm
Instrumental	Independent	Crispness measurement[c]	Cn	MCn	Unitless
Instrumental	Independent	Quality factor[c]	QF	MQF	Unitless
Sensory	Dependent	Perceived crispness	Crispness	$M_{crispness}$	Value out of 100, unitless
Sensory	Dependent	Perceived hardness	Hardness	$M_{hardness}$	Value out of 100, unitless
Sensory	Dependent	Perceived juiciness	Juiciness	$M_{juiciness}$	Value out of 100, unitless
Sensory	Dependent	Perceived skin toughness	Skin toughness	$M_{skin\ toughness}$	Value out of 100, unitless

[a] As determined using the Sinclair iQ™ Firmness Tester (SiQ™) (Sinclair International Ltd., Norwich, England).
[b] As determined using the Acoustic Firmness Sensor (AFS) desktop system (Aweta, Nootdorp, The Netherlands).
[c] As determined using the Mohr Digi-Test-2 (MDT) (Mohr and Associates Inc., Richland, WA, USA).

relationship between apple sensory attributes and instrumental parameters for three apple cultivars. They found that a combination of some penetrometry measurements were highly correlated with crunchiness, and the acoustic stiffness coefficient was significantly correlated with fruit resistance and mealiness.

Harker, Gunson, and Triggs (2006) used sensory-instrumental relationships to create a tool for apple firmness evaluation. They concluded that instrumental firmness determinations were satisfactory when textural differences were large, but that sensory testing was necessary when instrumental differences were small (~5 N puncture force). They also noted that there was variability among measurements between apples of different orchards, pre- and post-harvest, but fruit from adjacent locations on the same tree may also differ (Harker et al., 2006). While fruit characteristics are modified by orchard architecture, the textural properties are primarily determined by the cultivars' genetic makeup (Harker, Redgwell, Hallett, Murray, & Carter, 2010).

This study aimed: 1) to examine the correlations among firmness determinations from three commercially available fruit firmness testing instruments, 2) to develop multiple regression models to predict sensory textural attributes (hardness, crispness, juiciness and skin toughness) from instrumental and compositional analyses and 3) to cross-validate the best regression models to evaluate their appropriateness in predicting the sensory textural attributes.

2. Materials and methods

2.1. Apples

Nine apple cultivars were utilized for the study. In both years (2015, 2016), seven cultivars (Ambrosia, Aurora Golden Gala™, Fuji, Imperial Gala, McIntosh Silken, Salish™) were grown at the Summerland Research and Development Centre (Summerland RDC) and the remaining two (Honeycrisp and Pink Lady™) were purchased from a local fruit stand. The cultivars selected encompassed a broad range of textural attributes (Cliff, Li, & Stanich, 2014; Cliff, Stanich, Lu, & Hampson, 2015; Stanich, Cliff, Hampson, & Toivonen, 2014). All fruit were produced in accordance with commercial practices, and harvested at commercial maturity (BC Fruit Growers Association, 2016). Fruit from each cultivar was sorted to remove damaged apples and matched for size and colour to ensure, as much as possible, the uniformity of the samples for the sensory panel (Cliff et al., 2015; Cliff & Toivonen, 2017). All fruit were stored in air at 0.5 °C.

2.2. Compositional determinations

Titratable acidity (TA), soluble solids concentration (SSC) and absorbed juice (AJ), were determined on four replicate samples of three fruit each, on the same day as the sensory assessment.

TA and SSC were measured after firmness and juice absorption determinations. Juice was extracted from the bottom half of each apple. TA was determined using Model 848 Titrino Plus titrator (Metrohm, Herisau, Switzerland) and reported as g/L malic acid. SSC were measured using the Refracto 30PX refractometer (Mettler Toledo, Columbus, OH, USA) and reported as percent (%).

AJ was determined using the method described by Harker, Stec, Hallett, and Bennett (1997). A 21 mm disk of apple flesh was excised from the top half of each fruit. The disc was cut in half and the weight of juice absorbed by two layers of Kimwipes™ tissue (Kimberly-Clark Worldwide Inc., Rosswell, GA, USA) in 60 s was recorded.

2.3. Instrumental determinations

Firmness was measured non-destructively using the Sinclair iQ™ Firmness Tester (SiQ™) (Sinclair International Ltd., Norwich, England) and the Acoustic Firmness Sensor (AFS) desktop system (Aweta, Nootdorp, The Netherlands). The SiQ™ determined fruit firmness by taking four low-mass impact determinations around the equatorial plane of the fruit. AFS determined fruit firmness by measuring the vibration pattern (resonance attenuated vibration) associated with tapping the fruit with a probe at two locations around the equatorial region of the fruit.

Destructive testing was performed using the Mohr Digi-Test-2 (MDT) (Mohr and Associates Inc., Richland, WA, USA) equipped with a Magness-Taylor probe of 11.1 mm in diameter. The MDT instrument output eight values (Table 1) associated with the outer region of the fruit nearest the skin (R1) (between 0-~8.13 mm) and the inner region of the fruit between R1 and the core (R2) (between 8.13 and ~15.24 mm) (Mohr and Associates, not dated (n.d.)). The eight values were: maximum firmness for R1 (M1), average force for R1 (A1), maximum firmness for R2 (M2), average force for R2 (A2), average force of the last 20 reading in R2 (E2), creep deformation (C_0), crispness measurement (Cn) and quality factor (QF).

The M1 values are "equivalent" to the penetrometry-type measurements - the industry standard. M1 and A2 were determined at constant velocity; whereas, C_0 was obtained using a constant force (10 lbs) for given time (usually 0.5–2.5 s) (Mohr and Associates, n.d.).