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RESEARCH ARTICLE

Method for in-field texture analysis of sugar beet roots using a handheld penetrometer

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ABSTRACT

Methodology for analysing textural properties of sugar beet roots in the laboratory has previously been established. It has been shown to be reliable and of value in exploring relationships between textural properties, damage rates, and storability of varieties. In this paper, a methodology for the assessment of textural properties in-field, prior to harvest, using an inexpensive handheld penetrometer is examined. Three sugar beet varieties were grown in Belgium, the Netherlands, and Sweden during 2019. Textural properties were assessed in-field with the handheld penetrometer 2, 1 and 0 months prior to harvest, and with the laboratory penetrometer directly after harvest. Comparison of the results showed generally strong correlations. A power analysis suggests a difference in mean Handheld Pressure of 0.10 MPa could be found significant within a large trial with a block design. The reliability of the handheld penetrometer was further assessed in the Swedish national variety trials over three years (2019-2021). Correlation coefficients of 0.86 and 0.94 were found between mean Handheld Pressure for 2019 and 2020, and 2020 and 2021 respectively. The handheld penetrometer can be applied as an economic means of quantifying differences in textural properties of sugar beet varieties. Clear operating procedure and training must exist.

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Mechanical properties; textural properties; firmness; pre-harvest measurement; post-harvest losses

Introduction

Mechanical damage to sugar beet, *Beta vulgaris* ssp. *vulgaris* L., occurs during harvest and handling, and generally leads to increased rates of sugar loss during storage (Kenter et al. 2006; Huijbregts et al. 2013; Kleuker and Hoffmann 2021). The ability of a sugar beet root to withstand mechanical damage varies with its textural properties (Kleuker and Hoffmann 2020, 2022). Textural properties analysed for sugar beet roots include puncture resistance, compressive strength, and deformation (Gorzelany and Puchalski 2000; Nedomová et al. 2017; Kleuker and Hoffmann 2019, 2022). Differences of these traits between varieties have been shown to be strong and stable (Kleuker and Hoffmann 2020, 2021).

The determination of textural properties of sugar beet has been achieved using laboratory equipment. The specific metrics sort and methodology applied varies. For example, resistance to penetration was analysed by Gorzelany and Puchalski (2000) using an 8 mm diameter steel probe at a crosshead speed of 30 mm min^{-1} during the loading process, with samples taken somewhere in the top third and middle third of the sugar beet root. Nedomová et al. (2017) used a 6 mm diameter steel probe at 20 mm min^{-1} with samples taken at an unspecified point. The forces at puncture from Nedomová et al. (2017) are approximately one-fifth the magnitude of those of Gorzelany and Puchalski (2000). Neither publication specified a sampling depth. Identifying gaps and variability in the applied methodology, Kleuker and Hoffmann (2019) sort to develop a standardised and repeatable method that would permit 'uniform and comparable implementation in future studies'. The method they developed is tightly specified. For Puncture Resistance, the method involves taking three penetration samples per harvested and washed sugar beet root, using a 2 mm diameter cylindrical probe, at a speed of 60 mm min^{-1}, at the widest point of the beet, not in the root furrow, and to a depth of 5 mm. This method has subsequently been adopted in Kleuker and Hoffmann (2020), Schäfer et al. (2020), Kleuker and Hoffmann (2021) and Hoffmann et al. (2022).

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Operating procedures for the testing of fruit with penetrometers are well established and standardised. They require the harvest, often the removal of skin, and then the insertion of a probe of given diameter into the fruit to a given depth (Blanpied et al. 1978). A slow and consistent speed of insertion is required to ensure a consistent testing force across samples (Abbott 1999). Magness and Taylor (1925), Feng et al. (2011) and Li et al. (2016) have all shown that a high measurement speed of a penetrometer consistently lead to higher readings than a slower speed. For Li et al. (2016) the difference was only significant for soft fruit, and for Feng et al. (2011) resistance increased with measurement speed at a decreasing rate.

The use of handheld mechanical penetrometers to assess textural properties of fruits and vegetables dates back at least to the 1920s and Murneek (1921) and Magness and Taylor (1925). There is, however, no known application to sugar beet. Handheld penetrometers are a widely adopted version of the technology owing in large to their ease of use, their accessibility owing to their low cost, and the ability to apply them rapidly during the growing season. Small mechanical handheld penetrometers fit easily in the hand, weigh as little as 100 g, and cost less than €300. They have also been shown to be as reliable as laboratory equipment when applied correctly (Harker et al. 1996; Lehman-Salada 1996).

Handheld penetrometers are often analog, and in the large can only report the single metric of maximum resistance force. In contrast to laboratory texture analyser methods, they have issues around variability in the application of the testing procedure between operators resulting primarily from variability in application speed, depth, and angle. Harker et al. (1996) showed a consistent inter-operator variation of 10% among well-trained operators testing apples and kiwifruit. DeJong et al. (2000) reported that softer fruit was indicative of greater operator variability but were unable to find significant differences. In a comparison of penetrometers in kiwifruit, Feng et al. (2011) reported that the handheld penetrometer was occasionally applied at a speed of 600 mm sec^{-1} when the recommended speed was 240 mm sec^{-1}. Controlling the depth of insertion was noted as an issue by both Harker et al. (1996) and DeJong et al. (2000). Jantra et al. (2018) highlight the importance of a consistent probe angle to maintain a consistent contact area and loading rate, although Harker et al. (1996) could not find differences resulting from angle of application.

Further limitations in the application of a handheld variant of a penetrometer pre-harvest are foreseeable in the case of sugar beet. Sampling in the field introduces a greater risk for soil contamination at the sampling point. Uniform selection of a sampling point can also be challenging. This is required to avoid the variations in strength that are present along the length of the root (Kleuker and Hoffmann 2019). The widest part of the sugar beet root – the sampling point in Kleuker and Hoffmann (2019) – is often situated under the soil surface until harvest. The root surface area that is accessible above the soil surface will vary with time, growing conditions, and variety. No roots are accessible during early stages in the growth cycle. For some varieties, the lack of access to a sampling point in the root could extend across the full commercial growth cycle, precluding the pre-harvest use of a handheld penetrometer entirely. These drawbacks notwithstanding, the usability of handheld penetrometers makes them an attractive tool in the assessment of food crop quality if standardised, efficient, and proven methods exist.

In this study, comprehensive tests were conducted to assess the reliability of a method to measure mechanical strength of sugar beet roots that employs a handheld penetrometer applied pre-harvest. Measurements taken with a handheld penetrometer during the growing season were assessed against the results of measurements taken post-harvest in the laboratory, applying the method of Kleuker and Hoffmann (2019). An analysis of the sample size needed with the handheld penetrometer to find expected differences in mean strength as significant is presented. The inter-operator variation in the application of the handheld penetrometer is also briefly assessed. The reliability of the handheld penetrometer is then assessed in the Swedish national sugar beet variety trials. The description of the methods will allow uniform and comparable implementation in future research applications.

Materials and methods

Field trials and plant material

Sugar beets for this experiment were taken from field trials undertaken during the 2019 growing season. Trial plots were established for three varieties of differing yield formation, chosen to give variation in textural properties. These varieties can be classified as Variety 1: E-type, Variety 2: N-type, and Variety 3: Z-type (Bosemark 1993), but should not be considered as representative of these type classes. For each variety at each trial site, there were six replicates. Three agronomic treatments were also applied in these trail in a split-plot design. This gave a total of 18 plots per variety, and 54 plots total, per trial site. The agronomic treatments are

Table 1. Description of trial site and growing conditions, season 2019.

Country	BE	NL	SE
Location	Lens	Lelystad	Löddeköpinge
Latitude	50.569	52.544	55.768
Longitude	3.899	5.543	13.035
Soil type	Loam	Clay-loam	Clay-loam
Sowing date	1 April	9 April	10 April
In-season rainfall	390 mm	395 mm	359 mm
Plot size	14.3 m^2	36.0 m^2	46.1 m^2
Plant population	79 140 ha^{-1}	109 500 ha^{-1}	99 900 ha^{-1}

BE = Belgium, NL = the Netherlands, SE = Sweden.

not considered in this work, but are described in Hoffmann et al. (2022) and the ParentProjectDesign.pdf document in the project's data repository.

The trials were established in the sugar beet growing regions of Belgium (BE), the Netherlands (NL), and Sweden (SE). Table 1 summarises each trial site and the growing conditions. All trials were grown in accordance with national standards of Good Agronomical Practice.

Field textural properties analysis – handheld penetrometer

Field measurements of the sugar beet root mechanical strength were taken with an Effegi type FT011 handheld penetrometer (QA Supplies, Norfolk, Virginia, U.S.A.) with a 2 mm diameter cylindrical probe (Figure 1(b)). Measurements were taken in situ at a soil and damage free point on the root directly below all petiole insertions (Figure 1 (a)). This sampling point was chosen as it was deemed the only point on the root that would be consistently assessable on all varieties and during all sampling occasions. The probe tip was placed on the root surface, then the probe inserted perpendicular to the root surface, by hand, at a slow and constant speed, and to approximately 5 mm. The maximum resistance force was recorded. Force was recorded as pounds and to the nearest single decimal place, then converted to pressure as megapascals through a conversion factor of 1.4159. While measurements from handheld penetrometers are usually referred to as Firmness (Abbott 1999), to distinguish the in-field measurement from the laboratory measurements, it is here termed Handheld Pressure.

Ten sugar beet plants per plot were randomly selected for sampling. Each root was measured once as the restricted sampling area precluded the ability to take multiple samples per root. Excessively small or large roots were excluded from measurement. No strict criteria of size were applied, with instruction given to select only roots of a normal size for a fully populated stand at the given stage of development. This assessment made was at the discretion of the operator, all of whom were experienced with sugar beet cultivation. Field measurements were taken at three occasions; two months prior (−2 Months), one month prior (−1 Month), and directly prior (−0 Months) to the planned harvest date (Table 2). The same beets were not necessarily included at each occasion. To provide insight to the magnitude of inter-operator variability, a second operator (SE-2) assessed all plots independently in SE in occasions −1 Month and −0 Months. This data is only applied in the Effect of operators analysis – all other data for SE is from operator SE-1.

Successful sampling with the handheld penetrometer was achieved at all sampling locations and occasions, with the exception of SE during the earliest (−2 Months) occasion. At this time, sampling was not possible in 12 of the 54 plots owing to the sugar beet roots being too small for a sampling point to be accessible. Of the 18 plots per variety, 16, 12 and 14 plots were sampled for Variety 1, 2 and 3 respectively. All other Handheld Pressure results for each variety are presented as the mean of 10 roots per plot and 18 plots per site. A limited amount of soil was observed to adhere to the surface of individual roots, but was not prohibitive in the selection of a soil and damage free sampling point. Roots were not observed to move during sampling. Sampling took approximately 3 h per field and occasion, for a sampling rate of 180 observations per hour.

Laboratory texture analysis

Assessment of textural properties in the laboratory was undertaken to provide benchmark data against which the reliability of the handheld penetrometer was assessed. After harvest, the sugar beet roots were directly transported to IfZ in Göttingen, Germany for assessment. Owing to travel distances and the size of the experiment, assessment in the laboratory occurred between 2 and 7 days after harvest. Roots were stored at 6°C, then washed and stored at room temperature (20°C) one day prior to assessment. Laboratory assessment employed a texture analyzer equipped with a 100 kg load cell (TA.XTplus100, Stable Micro Systems, Godalming, UK). Assessment was made of Puncture Resistance, Tissue Firmness, and Compression Strength (Kleuker and Hoffmann 2019). Compression Strength is not reported further in this paper. Puncture Resistance is defined as the force required to rupture the sugar beet root periderm. This value is usually the maximum resistance force recorded in any one sample. Tissue Firmness is taken as the mean resistance over the distance from 0.5 mm after rupture to 5 mm into the sugar beet root. Both Puncture Resistance and Tissue Firmness were measured using a 2 mm diameter cylindrical probe, employed at the widest part of the sugar beet

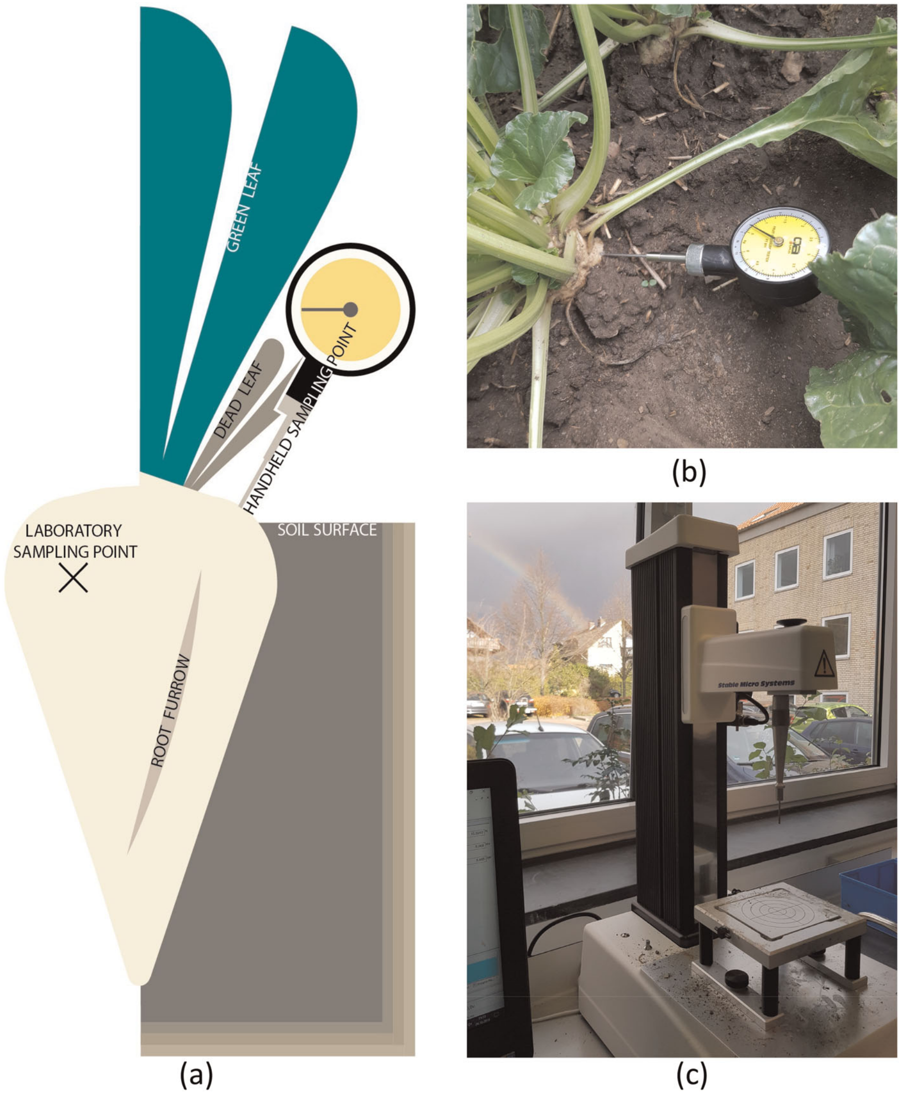

Figure 1. Sampling of textural properties of sugar beet. (a) Schematic of sampling points on the sugar beet root, (b) Handheld penetrometer placed at the sampling point of a sugar beet in the field with a limited sampling area, Sweden August 2019, (c) TA.XT Plus 100 with 2 mm diameter plunger in a laboratory at IfZ, Göttingen.

root, in an area free from damage and not in the root furrow. In the roots in which a handheld penetrometer sampling point was visible, no damage from a disease or insect incursion was observed to have developed and thus handheld sampling did not interfere with the laboratory sampling. Five sugar beet roots per plot were assessed, with three measurements taken per root, for a total of 15 samples per plot. Two hundred seventy measurements were taken per variety × country for each of these metrics. Successful sampling in the laboratory was achieved for all plots. Sampling rate with the laboratory analyzer when running only penetration tests is estimated at 95–115 observations per hour. This does not include the time to harvest, transport, store, or wash material.

Table 2. Sample occasion (2, 1, & 0 months prior to planned harvest date) and harvest dates of sugar beet at each of the three trial sites in 2019.

Country	BE	NL	SE
−2 Months	29 August	22 August	16 August
−1 Month	3 October	23 September	11 September
−0 Months	13 November	17 October	18 October
Harvest	15 November	25 October	24 October

BE = Belgium, NL = the Netherlands, SE = Sweden.

Reliability study

To assess the reliability of the handheld penetrometer in providing stable rankings of Handheld Pressure between years, an assessment of the national variety trials in SE was undertaken over three years. The same field textural properties analysis methodology was applied. The assessment was conducted within the constraints of the national variety trials, and as such a reduced sampling strategy was applied. Varieties were assessed at one, two, and two sites, in 2019, 2020 and 2021 respectively. Each trial had four replicates. Ten observations per plot were taken in 2019, five in 2020, and six in 2021. The final sample consisted of nine varieties assessed in both 2019 and 2020, and 18 varieties assessed in both 2020 and 2021. A sampling rate of 130–170 observations per hour was achieved, with the slower rate occurring in 2020 when relatively more time was spent moving between plots.

Statistics

Comparison of measurement procedures

Statistical analysis was carried out with the program R v4.1.2 (R Core Team 2021) within RStudio v2021.09.0 (RStudio Team 2021). Results are presented as the Least square means at the variety × country × measure level for the laboratory measures, and variety × country × occasion level for Handheld Pressure. Means were computed with plot level observations and the emmeans package. A linear mixed effects model including a random block effect was employed. Significant differences in means were assessed with an analysis of variance (ANOVA) using post-hoc Tukey tests, $\alpha \leq 0.05$. For visualisation of the comparison of Handheld Pressure and the laboratory measures, plot level observations were standardised using country and occasion (handheld), or country and measure (laboratory) specific means and standard deviations. Pearson's Correlation was used as the measure of association between the handheld and laboratory measures.

Effect of sample size

A power analysis was conducted to find the number of samples required to find statistical significance based on both a survey research design and a block design. The differences of mean Handheld Pressure used in this analysis were taken from the reliability study in 2020, plus some marker mean differences and sample sizes. The standard deviation applied to the analysis of a survey design was taken as the mean of the three within variety standard deviations for SE at −0 Months, for observations at the level of the individual root: s.d. = 0.2836. This is the most conservative mean standard deviation on Handheld Pressure from this occasion (BE: s.d. = 0.2218, NL: s.d. = 0.2378). The standard deviations applied to the analyses of the block design were taken as the average within site and between plot values from the two extreme cases of samples per plot in the reliability study. For 2020 – five samples per plot – s.d. = 0.1826. For 2019 – ten samples per plot – s.d. = 0.1389. In a power analysis, α represents the willingness to accept statistical Type I error, and Power is the inverse of willingness to accept statistical Type II error. α was set to 0.05, Power set to 0.90.

Effect of operators

Comparison of mean Handheld Pressure of the two operators in SE was done with a linear mixed effects model including an operator-variety interaction term and a random block effect. Assessment was made of the significance of the main operator effect and operator × variety interaction. Significant differences were assessed using post-hoc Tukey tests, $\alpha \leq 0.05$.

Reliability study

Statistical analysis in the reliability study followed the comparison of measurement procedures methodology for the calculation of means and correlations.

Results

Average textural properties

The textural properties for each variety in each country are presented as laboratory measurement or Handheld Pressure at each occasion (Figure 2). The Puncture Resistance for Variety 1 was less than for Variety 2 and 3 in all countries. For Tissue Firmness, the three varieties were ranked Variety 1: Variety 2: Variety 3 in all countries. This ranking was also found for Handheld Pressure in seven of the nine country × occasion combinations. The exceptions were NL during occasion −0 Months and SE during occasion −2 Months, where no significant difference was found between Variety 2 and Variety 3.

Values of Puncture Resistance ranged from 5.98 MPa for Variety 1 in NL, to 6.73 MPa for Variety 3 in SE. Tissue Firmness ranged from 4.42 MPa for Variety 1 in NL to 5.51 MPa for Variety 3 in BE. The Handheld Pressure values ranged from 5.06 MPa for Variety 1 in BE in occasion −2 Months, to 7.18 MPa for Variety 3 in SE in occasion −0 Months. The range of values within country are shown in Table 3. The range of Handheld Pressure was lowest at occasion −0 Months for both BE and NL, while this occasion had the largest range for SE. Occasion −2 Months also tended to have the largest standard deviations for Handheld Pressure (Figure 2) and standard deviations for Handheld Pressure were generally larger than for the laboratory measures.

Handheld Pressure values tended to increase with time. In both BE and SE, this increase was from occasion −2 Months and through the −1 Month occasion to the

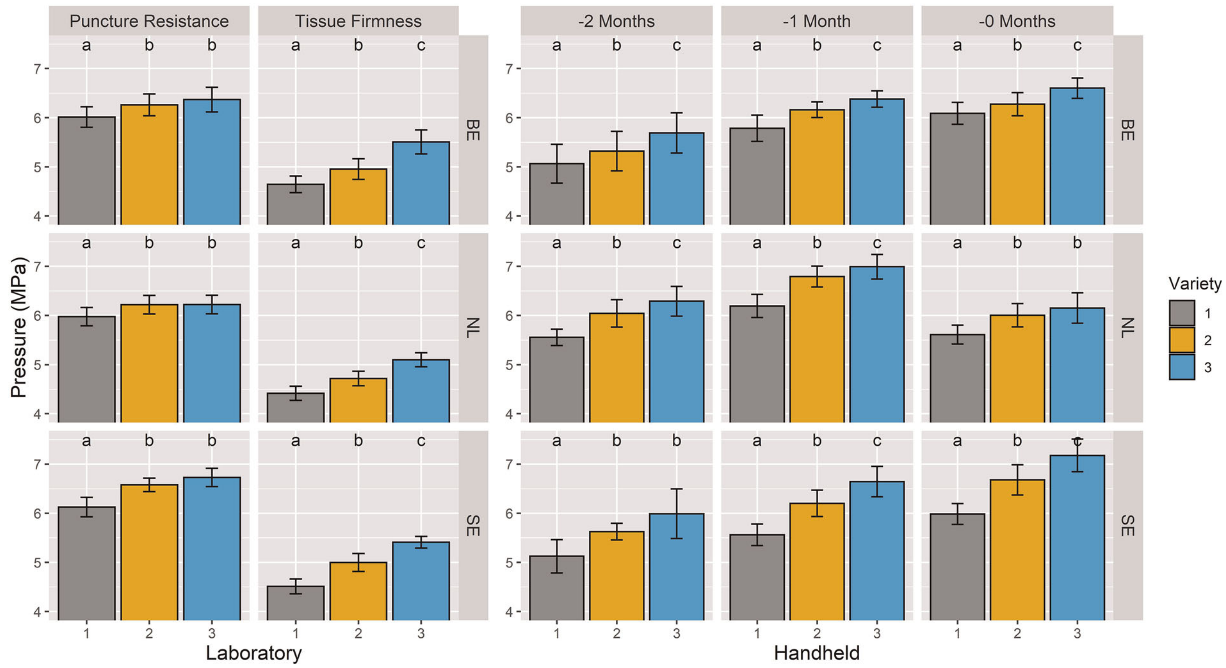

Figure 2. Textural properties of roots of three sugar beet varieties for laboratory measures (left) and Handheld Pressure at field sampling occasion (right), by country, 2019. Vertical bars indicate standard deviation. Letters indicate significance grouping within country and measure (laboratory) or occasion (handheld), post-hoc Tukey test, $a = 0.05$. $N = 18$ per variety. BE = Belgium, NL = the Netherlands, SE = Sweden.

−0 Month occasion. For NL, the values from the −0 Months occasion were on average comparable to −2 Months.

Comparison of measurement procedures

Comparisons of the laboratory Puncture Resistance and Tissue Firmness measurements to the Handheld Pressure measurements at the plot level are presented in Figures 3 and 4 respectively. The 1:1 line in these figures indicates the ideal agreement of measurements. Any point above the line tested relatively stronger in the field than in the laboratory. Correlation coefficients for each sub-figures show that all comparisons were found to have a significant association at $a = 0.05$, with the exception of Puncture Resistance in BE at −2 months.

Both Figure 3 and 4 show a general trend of Variety 1 with lower values to Variety 3 with higher. Correlation coefficients are above 0.60 in 12 of the 18 comparisons. Handheld Pressure showed better agreement with Tissue Firmness than with Puncture Resistance, as indicated by the higher correlation coefficients. Eight of nine correlation coefficients for Handheld Pressure and Tissue Firmness were greater than 0.60. Only four of nine correlation coefficients are above 0.60 for the comparison with Puncture Resistance. All correlation coefficients for NL were less than 0.35 in the comparison with Puncture Resistance.

Effect of sample size

The power analysis shows that at an a of 0.05, Power of 0.90, and the standard deviation calculated for a survey design with the data from SE in occasion 3 (s.d. = 0.2836), a mean difference of 0.100 MPa is expected to be found significant with a sample size of 86.5 per variety (Table 4). 30.0 samples per variety would find differences to be significant when the mean difference

Table 3. Range of textural properties of roots of three sugar beet varieties, by country, measure (laboratory) or sampling occasion (handheld) (MPa).

	Laboratory		Handheld pressure			
	Puncture resistance	Tissue firmness	−2 Months	−1 Month	−0 Months	All occasions
BE	0.36	0.87	0.63	0.60	0.51	1.54
NL	0.24	0.68	0.73	0.80	0.54	1.43
SE	0.51	0.90	0.87	1.08	1.19	2.06
All countries	0.75	1.09	1.23	1.43	1.57	2.12

Sampling occasions were 2, 1 and 0 months prior to planned harvest date. BE = Belgium, NL = the Netherlands, SE = Sweden.

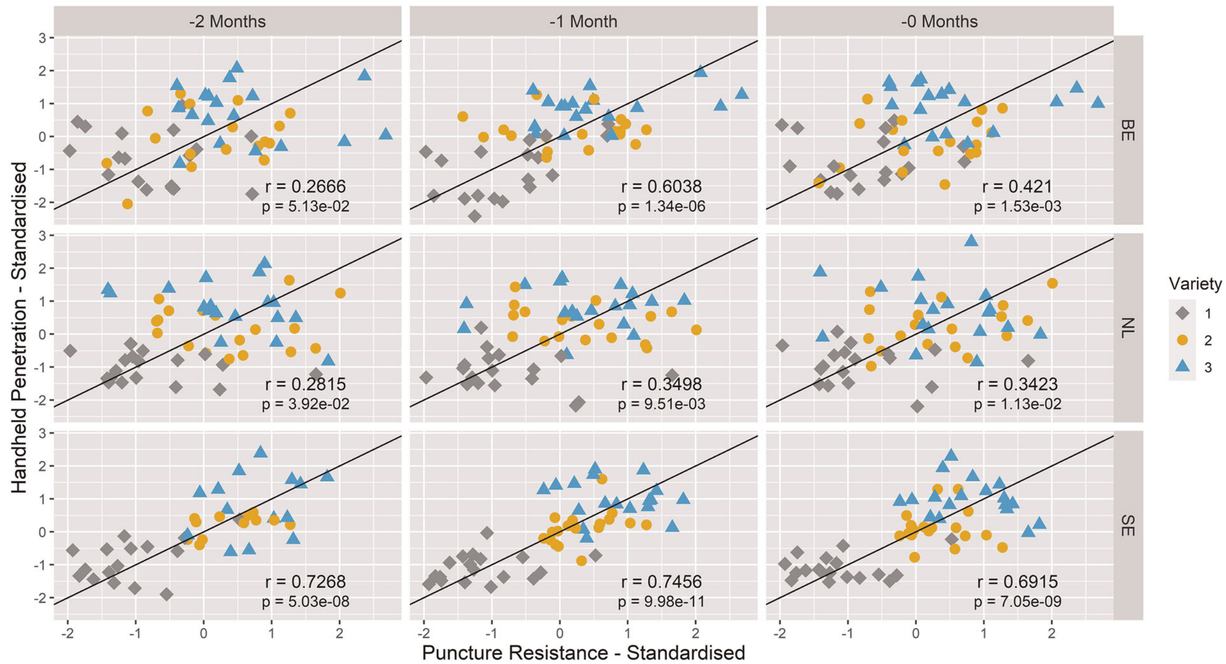

Figure 3. Comparison of handheld pressure and puncture resistance of roots of three sugar beet varieties, by country and field sampling occasion, 2019. Plot level standardised values. Pearson's r correlation and associated p-values shown. 1:1 line shown. N = 10 per plot and occasion (Handheld Pressure), 15 per plot (Puncture Resistance). BE = Belgium, NL = the Netherlands, SE = Sweden.

was 0.174 MPa. For the standard deviations from the SE national variety trials in 2019 and 2020, with the block design in four replicates (s.d. = 0.1389 and s.d. = 0.1826), a difference of 0.100 MPa is expected to be found significant with a sample size of 22.3 and 37.0 per variety respectively. At a sample size of four plots per variety, a difference of 0.35 and 0.46 MPa, respectively, would be expected to be found significant.

Effect of operators

Operator SE-2 had a tendency to measure higher Handheld Pressure values than operator SE-1 (Figure 5). The exception was for Variety 3. In the linear mixed effects models, the operator effect was significant at both sampling occasions; $t(102) = 4.85$, $p =$ 4.63e-6, and $t(102) = 3.86$, $p =$ 1.98e-4. The operator SE-2x Variety 3 interaction was significant in both sampling occasions; $t(102) = -3.97$, $p =$ 1.38e-4, and $t(102) = -2.92$, $p = 0.043$. Other interaction effects were not significant at $\alpha = 0.05$. Operator SE-1 tended to have a higher standard deviation in their measurements than operator SE-2.

When the data from operator SE-2 replaces operator SE-1 in the above comparisons of methods, some changes in the results are found. The mean differences for Handheld Pressure in SE (Figure 2) remain highly significant. The highest p-value on the post-hoc contrast for mean difference when using the data from operator SE-2 is equal to 0.0040 for Varieties 2 and 3 in occasion −1 Month; this was 2.97 e-5 for operator SE-1. The correlations between Handheld Pressure and the laboratory measures weakened slightly, at 0.7179 and 0.6934 with Puncture Resistance in occasions −1 Month and −0 Months respectively, and at 0.7645 and 0.7699 with Tissue Firmness during these occasions. There was a large change in the standard deviation used in the power analysis. This would decrease from 0.2836 to 0.1711, resulting in the need for much smaller sample sizes in the analysis of a survey design. For the mean differences of 0.100 MPa, samples of 32.7 and 18.4 respectively would be required for operator SE-2 – down from 86.5 and 47.0.

Reliability study

For the assessment in the national variety trials in SE, the correlations between 2019 and 2020, 2020 and 2021, and 2019 and 2021 were: $r\ (9) = 0.8566$, $p =$ 3.12 e-3; $r\ (18) = 0.9449$, $p =$ 3.62 e-9; and $r\ (7) = 0.7448$, $p =$ 5.48 e-2. For 2020 and 2021, the shared sample consisted of 18 varieties, and the varieties occupying the highest three and lowest four rank positions were identical (Figure 6). The correlation value between 2019 and 2021 is based on a shared sample of only seven varieties and has a p-value greater than 0.05. Handheld Pressure values were generally greatest in 2020, and least in 2019.

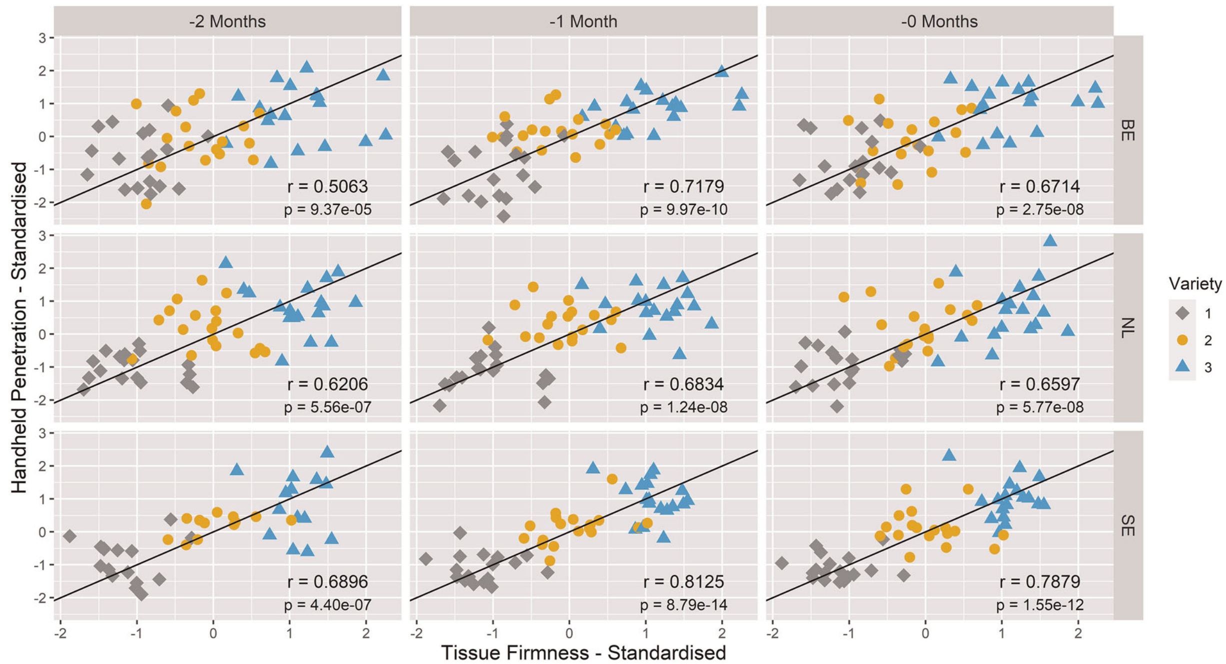

Figure 4. Comparison of Handheld Pressure and Tissue Firmness of roots of three sugar beet varieties, by country and field sampling occasion, 2019. Plot level standardised values. Pearson's *r* correlation and associated *p*-values shown. 1:1 line shown. $N = 10$ per plot and occasion (Handheld Pressure), 15 per plot (Tissue Firmness). BE = Belgium, NL = the Netherlands, SE = Sweden.

Table 4. Power analysis for handheld pressure in sugar beet field trials in Sweden (SE) 2019 and 2020.

Source	Fixed value		SE 2019		SE variety 2019		SE variety 2020	
s.d.			0.2836		0.1389		0.1826	
Design			Survey		Block (10 obs. per plot, 4 reps)		Block (5 obs. per plot, 4 reps)	
	Mean diff.	*n*	Mean diff.	*n*	Mean diff.	*n*	Mean diff.	*n*
SE variety 2020 min.	**0.01**			8452.9		2029.1		3505.4
SE variety 2020 mean	**0.04**			530.1		128.6		220.9
Marker	**0.10**			86.5		22.3		37.0
Marker	**0.30**			11.5		4.6		6.1
Marker	**0.60**			4.6		2.9		3.3
SE variety 2020 max.	**0.97**			3.2		2.4		2.6
SE variety		**4**	0.71		0.35		0.46	
Marker		**30**	0.17		0.09		0.11	

$\alpha = 0.05$, Power = 0.90. Standard deviations shown in table. Mean diff. = Mean difference in handheld pressure (MPa). *n* = sample size. Fixed values in bold. Values below the horizontal line are for the analysis of fixed sample size. 'SE Variety' indicates Swedish national variety trials. 'Marker' indicates a round fixed value taken from within the range of SE variety 2020.

Discussion

Average textural properties and comparison of measurement procedures

The values obtained for Handheld Pressure reflect the laboratory measures. The ranking of varieties was stable over sampling occasion and trial site (Figure 2), and over the three years of the reliability study (Figure 6). This also reflects the findings in the laboratory for sugar beet roots in Kleuker and Hoffmann (2021). This suggests that the handheld penetrometer is an acceptable method for assessing the textural properties of sugar beet roots. The absolute magnitude of the variety mean Handheld Pressure values was similar to Puncture Resistance (Figure 2), but the range in values was most similar to Tissue Firmness (Table 3). The similarity in range of the Handheld Pressure values to Tissue Firmness, coupled with the high correlation coefficients for these two measures in all countries at all occasions (Figures 3 and 4), suggests the handheld penetrometer is able to capture data of high value; Kleuker and Hoffmann (2020) found that tissue strength is an indicator of rates of damage during harvest and transport of sugar beets, and of subsequent post-harvest storage loss. Statistically, the stronger associations between Handheld Pressure and Tissue Firmness can be contributed to

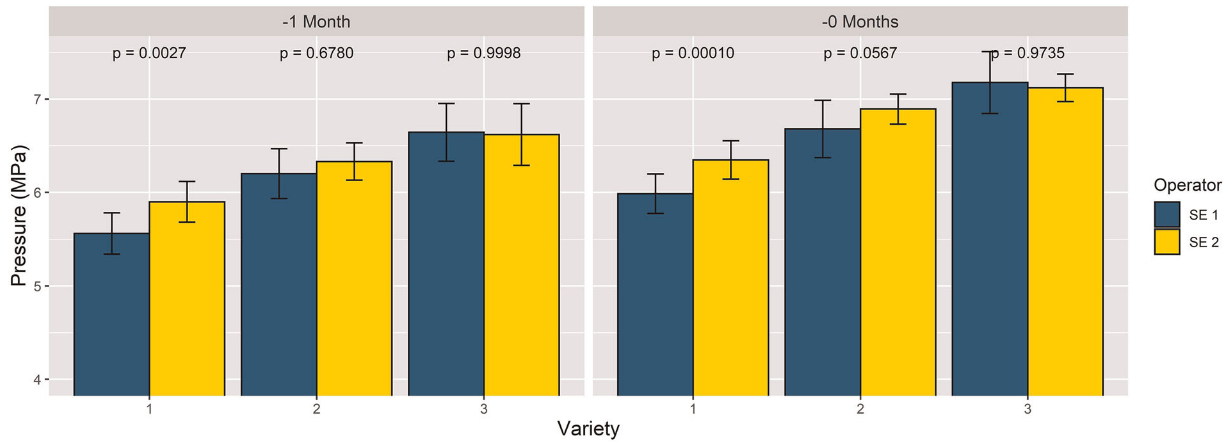

Figure 5. Comparison of mean Handheld Pressure of roots of three sugar beet varieties for two operators in Sweden (SE) during occasions −1 Month and −0 Months. 2019. Numbers over clustered bars indicate p-values from post-hoc Tukey test for operator comparison for each variety × occasion. Vertical bars indicate standard deviation. $N = 18$ per variety and occasion.

the greater between variety variation of the Tissue Firmness values in comparison to Puncture Resistance – (Figure 2, Table 3). This is reflected on the scatter plots as a distribution that more clearly clusters by variety while also forming around the 1:1 line (Figures 3 and 4). It has to also be kept in mind that the varieties were chosen with regard to creating differences in mechanical properties, and as evidenced in the reliability study, small mean differences are unlikely to be found as significant.

The similarity of the magnitude of Handheld Pressure to Puncture Resistance reflects the similarity in the mechanics of the measurements. The handheld penetrometer records the maximum force over the sample range of 0–5 mm, and Kleuker and Hoffmann (2019) show that the maximum force over the 0–5 mm sampling range in a sugar beet root is typically the force required to rupture the periderm; that is, the Puncture Resistance (Table 3). The greater range of values measured for Handheld Pressure than for Puncture Resistance despite the similarity in the parameters, then becomes noteworthy. This is possibly a result of operator control in the application of the handheld penetrometer. This would be similar in mechanism to the issue of application speed as discussed by Abbott (1999) in which the greater viscous behaviour of the softer material leads to a lesser loading rate and a lesser measured resistance. This difference may alternatively originate from the selection of the sampling point on the sugar beet root with the handheld penetrometer. Smaller beets may have been sampled higher on the root, as the available root surface above the soil becomes limited. Kleuker and Hoffmann (2019) found variations in Puncture Resistance along the length of the root and the higher concentration of vascular tissue over parenchyma tissue suggests the crown

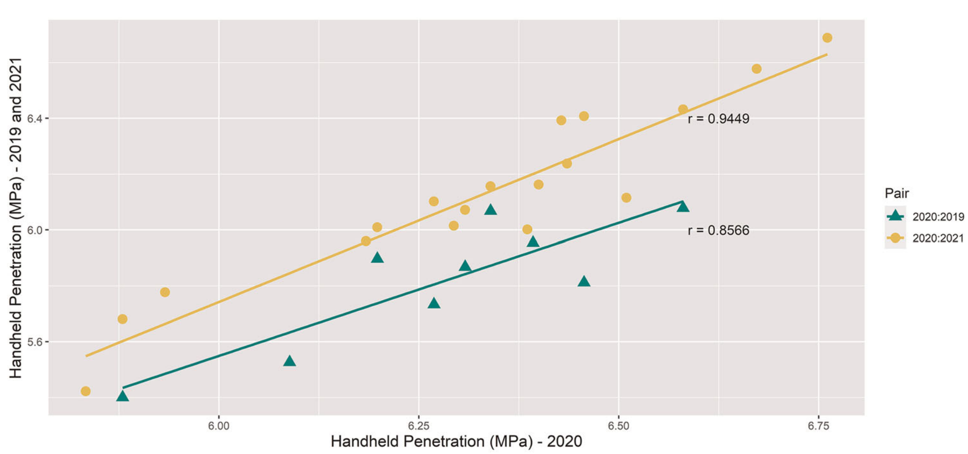

Figure 6. Comparison of handheld pressure (MPa) of sugar beet roots from Swedish national variety trials 2019, 2020 and 2021. Correlation coefficients shown.

region of the beet should be stronger (Gemtos 1999). Observation in the field suggested that at any one point in time, there was an inverse relationship between sugar beet root strength and the size for the three varieties used in this research. This could mean that stronger beets may have been sampled at a point of typically stronger cell tissue, which would accentuate any differences in tissue strength. For this to hold, however, it must be assumed that the general increase in Handheld Pressure occurring over the season and at the same time as a general increase in root size, is a result of a general increase in tissue strength. Given sugar beet is a biennial plant that neither undergoes senescence or ripens prior to harvest in commercial systems (Elliott and Weston 1993; Scott and Jaggard 1993), changes in Handheld Pressure over time will not capture maturity as it may in other crops. In a situation with sugar beet roots of different sizes, being able to reliably select a uniform sampling point is paramount.

The generally larger standard deviations for Handheld Pressure in comparison to the two laboratory measures (Figure 2) can also be attributed to the ability of the operator to control the handheld penetrometer. Even if the sampling point and speed and angle of insertion were relatively easy to control, it is simply not possible for a human operator to match the consistency of speed of application achieved by the mechanical drive motor of the laboratory analyser. The need for a reasonable sample size was highlighted in the large increase in the average standard deviation that accompanied the large decrease in within plot sample size from 2019 to 2020 in the reliability study (Table 4).

Timing of data collection

The results in general do not indicate a preferred sampling occasion. The ranking of Handheld Pressure values was consistent over the three occasions (Figure 2), each of the three trial sites had the largest range in Handheld Pressure during a different sampling occasion (Table 3), and the pattern of correlations between the field and laboratory measures were similarly variable (Figures 3 and 4). A similar conclusion could be drawn from Nause et al. (2021), who recently showed that the ranking of textural properties of different sugar beet varieties was stable over the period August to November. However, given the issues with variable resistance at different points along the length of the root, the issues with accessing the sampling points in SE in occasion −2 Months, and the slightly higher standard deviations in the first sampling occasion, sampling in the last month prior to harvest appears preferable.

The general increase in Handheld Pressure with sampling occasion (Figure 2) suggests that comparisons of absolute strength are only valid when sampling occurs within a single period. This should be coupled with the conclusions of Kleuker and Hoffmann (2021), who show that such comparisons are only valid within a single growing environment. The decrease in mean Handheld Pressure in NL between occasions −1 Month and −0 Months also highlights this point. The reason for this decrease is not known but likely reflects beet physical properties that differ with varying environment conditions between sampling occasions, such as beet cell turgor.

Sample size

The power analysis (Table 4) demonstrates that rapid sampling with a handheld penetrometer to rank varietal strength is feasible, but also that the sampling size is highly dependent on the expected standard deviation of measurements. With the survey design, 86.5 samples were needed to find a mean difference of 0.10 MPa significant (Figure 5). This is a similar sample size to the 90 employed per variety and location in Kleuker and Hoffmann (2021). Being able to identify mean differences of 0.10 MPa as significant would increase the number of significant groups in the reliability study for 2020 from seven to 14. The reliability study, however, used a block design. The 37.0 and 22.3 observations the power analysis showed where needed to find a mean difference of 0.10 MPa significant with the standard deviations from the block designs, is an unrealistic number of plots for most experiments. For large trials, like the national variety trials of Sweden with six sites and four replicates per site (24 plots in total), it could be achieved. Kleuker and Hoffmann (2022) state that the inclusion of measures of tissue strength in variety trials could be of benefit to industry through the provision of information around the underlying storage potential of varieties. The power analysis suggests the handheld penetrometer would be able to achieve this with sufficient accuracy.

Comparison of operators

The results from the second operator in SE further support the proposition that the handheld penetrometer is a viable tool for assessing the textural properties of sugar beet roots. The rank of the varieties remained constant, and the differences remained significant (Figure 5). The absolute values varied only marginally, and the reduction of within variety variation – from an average standard deviation of 0.2836 for operator SE-1 to a standard deviation of 0.1711 for operator SE-2 – suggests it is possible to find smaller between variety difference for a survey design with a given sample size than the original power analysis suggested. However, given this comparison only covers two operators in two time periods, it is difficult to draw conclusive generalisations on what between operator variation can be expected.

Following Li et al. (2016), a possible explanation for the operator differences is in the measurement speed applied. In this case, operator SE-2 applied a higher speed and the between operators differences disappear for samples with higher resistance. Following Gemtos (1999) and Kleuker and Hoffmann (2019) selection of sampling point is an alternative explanation. In this case, operator SE-1 may have selected points relative to the soil surface instead of relative to the crown, resulting in the selection of points that were lower and weaker for the larger roots of Variety 1. Whatever the reason for these differences, it highlights the need to standardise method and operator training.

Choice of penetrometer

The inherit repeatability of the laboratory penetrometer method commends it as the preferred choice of method in analysing textural properties when a more controlled testing environment is desired. The laboratory method also has the advantage of supplying multiple metrics and more detailed and automated data – it remains the benchmark method. Given the reliability of the handheld penetrometer method, as tested here, its application can be recommended in large-scale experiments, as an economic additional test in ongoing experiments, or in circumstances in which the financial demands of the laboratory equipment is too great. The handheld equipment has much lower costs in terms of capital, but also in avoiding the need to expand trials to provide material for laboratory testing, to divert this material from the field, and in a quicker sampling rate. Examples of its potential use include examinations of the strength of sugar beet varieties on national lists, surveys of intra-national or inter-farm variation in sugar beet root strength, or surveys of variation in sugar beet root strength near to harvest time or during storage. It should be kept in mind that comparisons of the absolute strength of sugar beet roots is only valid under constant growing conditions, and the results from any penetrometer cannot be used to draw direct conclusions about harvest damage or post-harvest losses, but can be used in an indicative manner. While the focus of this work has been on varieties, using the handheld penetrometer within a variety but across agronomic conditions or treatments would also be viable, as long as sufficiently large differences in Handheld Pressure are expected. Standard procedure and operator training is essential.

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Data availability statement

Data and script from this project can be found here: https://github.com/Nordic-Beet-Research/COBRI-Handheld_penetrometer.

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References

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

Blanpied GD, Bramlage WJ, Dewey DH, LaBella RL, Massey LM, Mattus GE, Stiles WC, Watada AE. 1978. A standardized method for collecting apple pressure test data. New York's Food Life Sci Bull. 74: 3–8.

Bosemark NO. 1993. Genetics and breeding. In: D. A. Cooke, R. K. Scott, editor. The sugar beet crop. Science into practice. London: Chapman & Hall; p. 67–119.

DeJong JM, Prange RK, Harrison PA, McRae KB. 2000. Comparison of a new apple firmness penetrometer with three standard instruments. Postharvest Biol Technol. *19*:201–209. doi:10.1016/S0925-5214(00)00097-1.

Elliott MC, Weston GD. 1993. Biology and physiology of the sugar-beet plant. In: D. A. Cooke, R. K. Scott, editor. The sugar beet crop. London: Chapman & Hall; p. 37–66.

Feng J, McGlone A, Tanner D, White A, Olsson S, Petley M, Woolf I. 2011. Effect of penetration speed on flesh firmness measured on stored kiwifruit. Postharvest Biol Technol. *61*:29–34. doi:10.1016/j.postharvbio.2011.01.014.

Gemtos TA. 1999. Sugar beet root properties in relation to harvesting damage. Agric Eng Int J. *22*:4. https://cigrjournal.org/index.php/Ejounral/article/view/1038.

Gorzelany J, Puchalski C. 2000. Mechanical properties of sugar beet roots during harvest and storage. Int Agrophys. *14*:173–179. http://www.old.international-agrophysics.org/pl/zeszyty.html?stan=lista.

Harker FP, Maindonald JH, Jackson PJ. 1996. Penetrometer measurement of apple and kiwifruit firmness: operator and instrument differences. J Am Soc Horticult Sci. 151:927–936.

Hoffmann CM, Kleuker G, Wauters A, English W, Leijdekkers M. 2022. Root texture and storage losses of sugar beet varieties as affected by N application and irrigation. Sugar Ind. 146:34–41. doi:10.36961/si28254.

Huijbregts T, Legrand G, Hoffmann C, Olsson R, Olsson Å. 2013. Long-term storage of sugar beet in North-West Europe. COBRI (Report No. 1 – 2013).

Jantra C, Slaughter DC, Roach J, Pathaveerat S. 2018. Development of a handheld precision penetrometer system for fruit firmness measurement. Postharvest Biol Technol. 144:1–8. doi:10.1016/j.postharvbio.2018.05.009.

Kenter C, Hoffmann CM, Märländer B. 2006. Sugarbeet as raw material – advanced storage management to gain good processing quality. Zuckerindustr Sugar Ind. 131:706–720.

Kleuker G, Hoffmann CM. 2019. Method development for the determination of textural properties of sugar beet roots. Zuckerindustr Sugar Ind. 144:392–400. doi:10.36961/si23306.

Kleuker G, Hoffmann CM. 2020. Influence of tissue strength on root damage and storage losses of sugar beet [Influence of root strength on damage and storage losses of sugar beet]. Zuckerindustr Sugar Ind. 145:435–443. doi:10.36961/si24556.

Kleuker G, Hoffmann CM. 2021. Tissue strength of sugar beet roots – genotypic variation and environmental impact. Crop Sci. doi:10.1002/csc2.20523.

Kleuker G, Hoffmann CM. 2022. Causes of different tissue strength, changes during storage and effect on the storability of sugar beet genotypes. Postharvest Biol Technol. 183:111744. doi:10.1016/j.postharvbio.2021.111744.

Lehman-Salada L. 1996. Instrument and operator effects on apple firmness readings. Horticult Sci. 31:994–997. doi:10.21273/HORTSCI.31.6.994.

Li H, Pidakala P, Billing D, Burdon J. 2016. Kiwifruit firmness: measurement by penetrometer and non-destructive devices. Postharvest Biol Technol. 120:127–137. doi:10.1016/j.postharvbio.2016.06.007.

Magness JR, Taylor GR. 1925. An improved type of pressure tester for the determination of fruit maturity. Department Circular, Issue. U. S. D. o. Agriculture. https://archive.org/details/improvedtypeofpr350magn/page/n1/mode/2up.

Murneek AE. 1921. A new test for maturity of the pear: pear harvesting and storage investigations (third report). Station Bulletin, Issue. O. A. College. https://babel.hathitrust.org/cgi/pt?id=uiug.30112019815874&view=1up&seq=5.

Nause N, Tossens A, Tschoep H, Hoffmann CM. 2021. High stability of genotypic differences in puncture resistance of sugar beet (*Beta vulgaris*) roots under various growing conditions. Plant Breed. In press. doi:10.1111/pbr.12988

Nedomová Š, Kumbár V, Pytel R, Buchar J. 2017. Mechanical properties of sugar beet root during storage. Int Agrophys. 31:507–513. doi:10.1515/intag-2016-0081.

R Core Team. 2021. R: a language and environment for statistical computing. https://www.R-project.org/.

RStudio Team. 2021. RStudio: integrated development environment for R. http://www.rstudio.com/.

Schäfer J, Hale J, Hoffmann CM, Bunzel M. 2020. Mechanical properties and compositional characteristics of beet (*Beta vulgaris* L.) varieties and their response to nitrogen application. Eur Food Res Technol. *246*:2135–2146. doi:10.1007/s00217-020-03562-4.

Scott RK, Jaggard KW. 1993. Crop physiology and agronomy. In: D. A. Cooke, R. K. Scott, editor. The sugar beet crop. London: Chapman & Hall; p. 179–237.