Direct Measurement of Sweetpotato Surface Area and Volume Using a Low-cost 3D Scanner for Identification of Shape Features Related to Processing Product Recovery

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Abstract. The growing demand for sweetpotato French fry and other processed products has increased the need for producing storage roots of desired shape profile (i.e., blocky and less tapered). Length-width ratio (LW) is the current de facto standard for characterizing sweetpotato shape. Although LW is sensitive and descriptive of some types of shape variability, this index may be inadequate to measure taper and other subtle shape variations. Prior work has shown that surface area (SA) and volume (VOL) are important shape descriptors but current direct measurement methods are tedious, inconsistent, and often destructive. A low-cost three-dimensional (3D) scanner was used to acquire digital 3D models of 210 U.S. No. 1 grade sweetpotato storage roots. The 3D models were imported into Meshmixer, a free software for cleaning and processing 3D files. Processing steps included gap filling and rendering the models water-tight to facilitate VOL measurements. The software includes a tool that enables automatic measurements of length (L), width (W), SA, and VOL. LW and SA-VOL ratio (SAVOL) were subsequently calculated. Separately, a digital caliper was used for manual measurements of L and W. The shrink-wrap method was used to measure SA, and water displacement was used to measure VOL. 3D scanner-based and manual L measurements showed high correlation, whereas VOL was lowest. Principal component analysis (PCA) of 3D scanner-based measurements showed that the first two principal components (PCs) accounted for 96.2% of the total shape variation in the data set, named Ib3D. The first PC accounted for 62.15% of the total variance, and captured variation in storage root shape through changes in VOL, SA, SAVOL, and W. The second PC accounted for 34.4% of the variance, and the main factors were LW and L. Most storage root samples that were classified as processing types were located in the fourth quadrant. The methods described in this work to nondestructively acquire 3D models of sweetpotato also can be adopted for analyzing shape in other horticultural produce like fruits, vegetables, tubers, and other storage roots that meet the specifications for 3D scanning. The data support the hypothesis that knowledge of variables that determine storage root L and W can lead to the development of methods and approaches for enhanced processing product recovery and size assortment for fresh market.

Knowledge of intrinsic and environmental variables that control sweetpotato shape is of fundamental and applied importance. Prior work in sweetpotato and other horticultural produce traditionally characterized the shape of objects by direct measurements of L and maximum diameter (W) and using the LW as an index of shape (Lowe and Wilson, 1974; Wang, et al., 2016). LW is the current de facto standard for characterizing sweetpotato shape. Although LW is sensitive and descriptive of some types of shape variability, this index may be inadequate to describe small variations and limits the full exploitation of shape analysis (Snee and Andrews, 1971). There are other important

features like SA and VOL that describe sweetpotato shape (Wright et al., 1986). In general, knowledge of SA and VOL can be applied in the design of machinery, in predicting amounts of surface applied chemicals, and in quantification of bruise, abrasion, and insect damage (Wang and Nguang, 2007; Wright et al., 1986). SA and SAVOL are also useful for calculating rate of post-harvest loss in horticultural produce (Furness et al., 2002; Lownds et al., 1993; Moreda et al., 2012). Wright et al. (1986) described an indirect method for estimating sweetpotato storage root VOL and SA that involved capturing images of samples, extraction of features, and inputting these data

into predictive equations. LaBonte and Wright (1993) described the procedure for using a shrink-wrap method to measure sweetpotato SA. Currently, the shrink-wrap and water displacement methods are the accepted standards for measuring SA and VOL, respectively, in sweetpotato as well as other horticultural produce (Furness et al., 2002; Wang and Nguang, 2007). Such methods are very tedious, slow, and prone to measurement errors (Wang and Nguang, 2007).

The growing demand for sweetpotato French fry (Sato et al., 2018) and other processed products has increased the need for producing storage roots of desired shape and consistency. In the processing industry, especially in French fry processing, uniform, nontapered storage roots are desirable to reduce nonuniform slices (Hoque and Saha, 2017). This requires the development of rapid and accurate methods to measure shape attributes. Such tools will lead to the development and testing of methods and approaches for manipulating shape in sweetpotato. Three-dimensional (3D) scanners are now being tested or routinely used in medical, industrial and other applications (Aikins, et al., 2019; Ravanelli et al., 2017; Rosicky et al., 2016). Reported advantages of 3D scanner-based measurements include high accuracy and precision, rapid acquisition, noninvasiveness, and the ability to rotate and view the 3D scan from all angles; the main disadvantage is the high cost and requirement for increased processing capacity of computers (Knoops et al., 2017). Rosicky et al. (2016) classified currently available 3D scanners as low-end (less than \$1000), high-end (less than \$25,000), and specialty high-end (more than \$25,000). The objective of this study was to assess the feasibility of using the low-cost Structure 3D scanner (\$499; Occipital Inc., San Francisco, CA) to measure L, W, SA, and VOL in sweetpotato. A secondary objective was to generate preliminary information on sweetpotato shape features related to the desired shape profile for processing, in particular French fry processing.

Materials and Methods

Study site and field preparation. Storage root samples were obtained from two field trials conducted in 2018 in a well-drained research field at the Sweet Potato Research Station, Chase, LA (lat. 32°6' N, long. 91°42' W). The soil taxonomic class of the experimental site is fine-silty, mixed, active, thermic Typic Glossaqualfs. Previous measurements of bulk densities at the 7 cm and 30 cm depth for this soil series were 1.1 g·cm⁻³ and 1.5 g·cm⁻³, respectively. The following are properties of the soil that was used for the study: 16% sand, 72% silt, 12% clay, 1.8% organic matter, 5.3 meq/100 g cation exchange capacity, and pH 6.2. Research plots were prepared by disk cultivating fields followed by application of 853 mL·ha⁻¹ Belay (clothianidin) and 4.45 L·ha⁻¹ Lorsban (chlorpyrifos). A second

disk operation was performed and then rows were formed on 1-m centers. Experimental plots were 1.5 m long (micro plots; in-row spacing = 30 cm).

Plant materials and experimental design. Field experiments were planted on 4 and 23 May 2018. Slips were obtained from virus-tested generation 1 (G1) seed stock. All planting materials were manually set within 1 d of cutting. All plants were watered in to 75% of field capacity within 12 h of planting. Previous studies have determined that for the soil series used in the studies, field capacity is achieved at 32% volumetric water content (VWC) ($\pm 3\%$) (Villordon et al., 2010). Soil moisture was monitored at two depths (5 and 15 cm) by vertically installing soil moisture sensors (Model 5TE; Decagon Devices Inc., Pullman, WA) linked to automated data loggers (EM50; Decagon Devices Inc.). Prior work has shown that direct measurement of soil moisture at these depths provides guidance in optimizing soil moisture and irrigation timing across stages of development and varying environmental conditions (Villordon et al., 2010). Water was applied through subsurface drip irrigation. Subsequent supplemental irrigation was applied when soil moisture approached 15% VWC at the 15-cm depth. The following herbicides were used: Command 3ME (clomazone, 3.114 L·ha⁻¹) was applied immediately after transplant and metolachlor (1.06 kg·ha⁻¹ a.i.) was applied at 10 to 15 d after planting.

Experimental treatments. To generate as much variation in storage root shape as possible, prior work on sweetpotato shape was used as guidance in developing the experimental treatments. Miller and Kimbrough (1936) previously documented planting date effects on storage root shape. Recent evidence supports the hypothesis that phosphorus (P) helps to determine storage root length and varieties respond differently to phospho-

rus availability (Villordon et al., 2018). Based on these findings, three cultivars were used in this study: ‘Bayou Belle’, ‘Bellevue’, and ‘Orleans’. The experimental design was split plot with P rate as the main plot and cultivar as subplot. The experimental treatments consisted of two rates of P₂O₅ applied as triple super phosphate (0N–46P–0K): fertilized control (101 kg·ha⁻¹ P₂O₅) and P omission (no supplemental P₂O₅). Nitrogen (50 kg·ha⁻¹) was applied as urea (45N–0P–0K), and potassium (224 kg·ha⁻¹) was applied as potassium chloride (0N–0P–60K). The fertilizer materials were applied pre-plant by opening rows with a plow, applying the fertilizer by hand, and incorporating when the rows are reformed with a hipper. The pots were harvested on 16 Aug. 2018. A mechanical harvester with a one-row chain digger was used. Storage roots traveled 170 cm on the chain and then dropped 60 cm to the soil surface. The storage roots were then graded and U.S. No. 1 grade roots were carefully placed in plastic bins. The size for U.S. No. 1 grade storage roots were from 50.8 to 88.9 mm in diameter and from 76.2 to 228.6 mm in length (U.S. Department of Agriculture, 2005). The storage roots were cured for 5 d at 29 °C and 85% relative humidity and then transferred to long-term storage at 15 °C and 85% relative humidity until 3D scanning was conducted. After 8 months of long-term storage, U.S. No. 1 grade storage roots (n = 210) that met the following criteria were selected for 3D scanning: no evidence of rotting, free from insect injury, and no visible mechanical damage that altered L, W, SA, and VOL measurements. To ensure representation from each planting date, P level, and cultivar, we used a stratified sampling approach wherein 15 to 20 storage roots were randomly sampled from each treatment combination (planting date $\times$ P level $\times$ cultivar).

3D image acquisition. The major components of the 3D image acquisition system are depicted in Fig. 1. The Structure 3D scanner (Occipital Inc.) is attached to an iPad Air 2 (Apple Inc., Cupertino, CA). This scanner is a structured light range camera and consists of an infrared laser projector and a frequency-matched infrared camera (Ravanelli et al., 2017). The first emits infrared dots on the surface of the object, and the latter generates data that capture 3D geometry (shape and dimensions in metric units) (Ravanelli et al., 2017). Color information is provided by the iPad’s built-in camera. It has a scanning range of 0.4 to 3.5 m with depth precision of 0.5 mm at 0.4 m, and 30 mm at 3 m (Occipital, 2014). In our work, scanning distance was kept within the 1-m range (depth precision ≈ 1.25 mm). Li et al. (2020) reported increased measurement errors with increasing distance from the object. The scanning (Structure Scanner; Occipital Inc.) and calibration (Structure Sensor Calibrator; Occipital Inc.) apps are free of charge and downloaded separately. The calibration procedure helps to ensure accuracy of depth measurement and alignment of point cloud

Fig. 1. Diagram of the three-dimensional (3D) scanning system. The sample (S) is suspended from an overhead attachment by thin, insulated wires (TW, diameter = 1.75 mm). The operator moves the Structure 3D scanner (3DS) within 1 m of either direction to capture the 3D model data. It is also necessary to move the 3DS up and down to capture information from the proximal and distal sections of the sample. The reference surface (RS) is necessary to assist in tracking.

data (Li et al., 2020). To confirm baseline estimates of precision, we scanned reference spherical objects of known diameter, calculated the SA and VOL, and compared the calculated and scanned measurements. Preliminary scanning sessions indicated that suspending the sample from an overhead position permitted the acquisition of the entire object. An insulated wire (diameter = 1.7 mm) minimized interference with the integrity of the periderm and was not routinely captured by the scanning process. It also made possible the nondestructive scanning of the sample. Each individual imaging session as described in Fig. 1 lasted for 3 to 5 minutes. For certain samples, especially for some tapered or ridged storage roots, the scanning session was repeated if the scanned 3D model possessed gaps that distorted the shape and affected the shape measurements. The operator slowly moves around the object, following a 360° path. It is also necessary to move the sensor up and down to capture the entire proximal and distal sections of samples. We also tested alternative methods of staging the sample, including mounting on a glass cylinder, tripods, and rods of various diameters. Most of these methods precluded the scanning of the proximal and distal sections of the sample, especially blocky-shaped specimens. Complete scans were possible with samples mounted on rods, but this involved piercing the sample, and interfering with measurements.

3D image processing and feature measurements. The image processing aspect of this study comprised three steps: 1) removal of artifacts, 2) gap filling and water tightness, and 3) dimensional calibration. All of these steps were performed using Meshmixer (v 3.5.474; Autodesk Inc., San Rafael, CA). Image processing was performed using Meshmixer’s “edit” feature. Minor gaps or holes in the 3D

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Fig. 2. Two-dimensional (2D) images of three-dimensional (3D) models taken from three different viewpoints of samples representing the shape profiles used to classify storage roots. Top and middle views of images are 3D models that were imported into Microsoft 3D Viewer (V 7.1; Microsoft Corp, Redmond, WA) and exported as 2D image files. Bottom row: images of 3D models shown enclosed in a bounding box defined by its X, Y, and Z maximum coordinates. These images are screenshots of 3D models in “units/dimensions” submenu of Meshmixer (v 3.5.474; Autodesk Inc., San Rafael, CA). FRESH = fresh market; TAPER = tapered storage root; FRY = blocky, fry-type.

Table 1. Spearman rank coefficients and corresponding *P* values for comparisons between three-dimensional (3D) scanner-based and manual measurements of sweetpotato shape features.²

Shape feature	<i>r_s</i>	<i>P</i> value
Length	0.98	<2.2 × 10 ⁻¹⁶
Width	0.93	<2.2 × 10 ⁻¹⁶
Surface area	0.93	<2.2 × 10 ⁻¹⁶
Volume	0.90	<2.2 × 10 ⁻¹⁶

²3D models were acquired using a Structure 3D scanner. Processing of 3D models and 3D-based measurements were performed in Meshmixer (v 3.5.474; Autodesk Inc., San Rafael, CA). Manual measurements for length and width were acquired using a digital caliper. Manual measurements for surface area and volume were acquired using shrink-wrap and water displacement methods, respectively. Description of experimental procedures is found in “Materials and Methods.”

model can typically be repaired during the image processing step. However, if gap repairs interfere with measurements, then the sample has to be rescanned. 3D models were

imported into Meshmixer in the .OBJ format. Image artifacts included portions of the reference surface (Fig. 1) and other artifacts not related to the sample. 3D models acquired from the Structure 3D scanner have a scale factor of 1 meter per unit (Salisi et al., 2019). The 3D samples were rescaled using the “analysis” menu, using the “units/dimensions” submenu. The “units/dimensions” submenu also displays the object in a bounding box, which shows the L and two measurements of W (Fig. 2). The “stability” submenu provided estimates of SA and VOL. L-W and SA-VOL ratios were subsequently calculated.

Manual measurements. A digital caliper was used to measure L and W at the widest point (Lowe and Wilson, 1974). Three measurements were conducted for W and the largest value was retained. A volumetric edema gauge (Baseline; Fabrication Enterprises, Inc., White Plains, NY) was used for manual measurements. The main component of this gauge is a custom-made chamber with a spout that channeled the displaced water to

a container for measurement to the nearest 100 mL. Following the water displacement measurements, the SA of each sample was measured following the procedure described by LaBonte and Wright (1993). Briefly, each sample was shrink-wrapped and applied with hot air using a handheld blow dryer. On cooling, the shrink-wrapped sample was spray painted with black paint. The plastic wrap was then removed and mounted on paper. Each paper was then scanned (Epson V700 scanner; Epson America Inc., Long Beach, CA) and the area estimated by image analysis using ImageJ (v. 1.50i; National Institutes of Health, Bethesda, MD; Schneider et al., 2012).

Statistical analysis and data set availability. Unless otherwise noted, all analyses were performed with R Studio (v. 1.2.1335, R Studio Inc., Boston, MA) using R version 3.6 (R Development Core Team, 2019). One hundred fifty samples were randomly selected for validation of 3D scanner-based measurements for L, W, SA, and VOL. Correlation analysis was performed to compare the 3D scanner-based and manual measurements. Bootstrapped confidence region for correlation estimates was calculated using the function “scatboot” [confidence = 0.90, number of iterations (nreps) = 1000] (Rogers, 2011). PCA was performed on the complete data set (n = 210) using factominer (Husson et al., 2019) and factextra (Kassambara and Mundt, 2017). All samples were classified as “fresh market” (FRESH), “tapered” (TAPER), or “French fry-type” or “blocky” (FRY) based on specifications provided by industry (M. McHargue, personal communication). Representative samples for the shape classes are shown in Fig. 2. Bootstrapped confidence intervals for eigenvalues were calculated using Tanagra (v. 1.4; Rakotomalala, 2005).

This data set, called Ib3D, is available on GitHub at <https://github.com/ipomoea2000/sweetpotato-2.0/raw/master/Ib3Dv1.csv>. The raw 3D models of samples are available as a compressed file (size = 64 MB) from <http://bit.ly/2v3rmyl>.

Results and Discussion

Comparison of 3D scanner and manual measurements. The correlation coefficient and *P* value for each comparison of 3D scanner and manual measurement is shown in Table 1. Highest *r_s* value (0.98) was observed for L, and the lowest was observed for VOL (0.90). Bootstrapped 90% confidence region for each comparison is shown in Fig. 3. In our internal calibration measurements of reference spherical objects with known dimensions, the 3D scanner-based measurements for W, SA, and VOL were within 1.6% (SD = 1.71), 2.8% (SD = 2.39), and 6.6% (SD = 0.25), respectively, of actual W, and calculated SA and VOL values (data not shown). These calibration ranges are consistent with our experimental results and within published accuracy ranges given the scanning distance for the Structure 3D

Fig. 3. Bootstrapped 90% confidence regions for correlations between manual and three-dimensional (3D) scanner-based measurements of sweetpotato storage root shape attributes length (A), width (B), surface area (C), and volume (D). The function “scatboot” (number of iterations = 1000) was used in calculating the bootstrapped confidence intervals (Rogers, 2011).

scanner (Johnson and Symons, 2019; Occipital, 2014). Knoop et al. (2017) noted that the Structure 3D scanner is less effective in defining high curvature areas when used in craniomaxillofacial imaging in a clinical setting. After accounting for accuracy specifications of the 3D sensor, the relatively low r_s values between the 3D scanner-based and manual measurements of W, SA, and VOL can be attributed to errors associated with manual-based measurements of these features. He et al. (2017) documented errors associated with manual W measurements of irregularly shaped strawberry samples, resulting in nonmaximal distances or non-orthogonal axes. In our work, one operator measured W using a digital caliper on three separate occasions, producing nonidentical measurements for predominantly irregularly shaped samples (data not shown). Prior work (Hulsey et al., 1971; Marcellis, 1992; Radovich and Kleinhenz, 2004) described that water displacement method used in measuring fruit and vegetable VOL was time-consuming and prone to errors. Hulsey et al. (1971) documented that tomato shape affected water displacement estimates of VOL. In sweetpotato, washed storage roots are prone to soft rot (Brash et al., 2009), rendering water displacement method as a destructive sampling technique. Furness et al. (2002) described that the use of shrink-wrap

method to measure SA of vegetables with irregular shape or rough and uneven areas produced inconsistent results. In our work, applying the shrink-wrap to sweetpotato samples with tapered ends was difficult and, in most cases, removal of the plastic wrap involved slicing through the plastic wrap, resulting in damage to the samples, precluding other measurements like using water displacement for VOL determination. Hence, the water displacement measurements needed to be performed before the shrink-wrap measurements. The Structure 3D scanner captured L, W, SA, and VOL measurements with one data capture session, with the potential for nondestructive sampling.

To date, there are several 3D scanners that are commercially available, with varying measurement accuracies and precision. The Structure 3D scanner, along with similar low-cost structured light-based 3D scanners, were first introduced for the consumer gaming industry where accuracy of measurements is not important (Li et al., 2020). However, the Structure 3D scanner is being tested for possible use in industrial, medical, and other settings (Aikins et al., 2019; Conkle et al., 2018; Kalantari and Nechifor, 2016; Knoop et al., 2017). Conkle et al. (2018) noted that 3D imaging is now new for anthropometry, but the Structure 3D scanner shows promise as a substitute for manual measurements,

although further research and development is needed to improve the quality of anthropometric data. After comparing the Structure 3D sensor with high-end 3D scanners, Knoop et al. (2017) concluded that it shows fair agreement with systems more than 10-fold its cost and shows potential for clinical use. Aikins et al. (2019) used the Structure 3D scanner to measure soil surface and furrow profiles and concluded that the accuracy was similar to the relatively more expensive laser and LIDAR-based solutions. Johnson and Symons (2019) observed volume measurement errors and recommended additional studies, but concluded that the Structure 3D scanner is a low-cost alternative for measuring equine limb swelling as a result of exercise and mechanical stress. Technological improvements will likely lead to increased resolution, reducing potential measurement errors (He et al., 2017). A new version of the Structure 3D sensor has already been released with increased accuracy and tracking capabilities; the model used in the current study is no longer available (Occipital, 2019). It is possible that the methods and procedures optimized for the current version of the Structure 3D scanner may need to be revised. For example, the optimum scanning distance as described in Fig. 1 may have to be recalibrated due to the revised accuracy specifications.

Identification of features related to shape using 3D scanner-based measurements. There was considerable variation for the shape features (Fig. 4). In general, the storage roots suitable for French fry processing (FRY) types had lower values for L, LW, and SAVOL compared with samples classified as FRESH and TAPER shape classes. FRY types had relatively higher W and VOL values compared with the FRESH and TAPER. PCA revealed the relationships among the 3D shape attributes and how these features accounted for variability in the shape classes. Samples classified as FRY were generally clustered in the fourth quadrant (Fig. 5). There were a few overlaps with the FRESH and TAPER shapes, and most of these overlaps were in the third quadrant. The first two PCs accounted for 96% of the total variability. PC1 (62.1%) captured variation in storage root shape through changes in VOL, SA, and W, whereas PC2 (32.4%) captured variation through changes in L and LW (Fig. 5). This demonstrates the benefits of incorporating other features in addition to LW in measuring shape variability in sweetpotato. The scree plot shows that eigenvalues leveled off after the second component, indicating very little contribution by the other components to total variability (Fig. 6A). Bootstrapped 90% confidence intervals provide evidence of the stability of the results (Fig. 6B). Taken together, the available data (Figs. 4 and 5) indicated that maximum W, minimum L, and lowest possible SA and VOL were related to FRY shape profile. Increased SAVOL and LW ratios were associated with FRESH and TAPER shape profiles. The data support the hypothesis that

Fig. 4. Box plots of three-dimensional (3D) scanner-based storage root features of three shape classes in the Ib3D data set. (A) L = length, (B) W = width, (C) SA = surface area, (D) VOL = volume, (E) LW = length-width ratio, (F) SAVOL = surface area-volume ratio. Bold horizontal lines indicate median values. Boxes represent the interquartile range (IQR, or middle 50%) of values for each feature. Upper box plot whiskers represent the last data point within the range of 75% quantile + 1.5 IQR, lower box plot whiskers represent the last data point within the range of 25% quantile - 1.5 IQR. Dots represent outliers (values smaller or larger than the median $\pm$ 1.5 times the interquartile range). P values were calculated using paired t tests (ns = not significant, $*P \geq 0.05$, $**P \geq 0.001$, $***P \geq 0.0001$, $****P \geq 0.00001$).

knowledge of variables that determine storage root L and W can lead to the development of methods and approaches for manipulating storage root shape for specific uses.

There are significant knowledge gaps in our understanding of how intrinsic and environmental variables interact to control root L among plants in general (Ryser, 2006). This lack of information even in model systems hampers progress in understanding the genetic and environmental cues of storage root shape in general, and L in particular, in sweetpotato. There has been some prior work on these aspects but very few follow-up studies. The possible effect of planting date on sweetpotato storage root L (Miller and Kimbrough, 1936) has been cited earlier. This effect is likely associated with temperature, but there has been no follow-up work in this regard. Zhao et al. (1995) provided evidence that the application of high levels of phosphorus increased storage root L. This is consistent with recent findings that low phosphorus generally reduced sweetpotato storage root L under greenhouse conditions, but the effect was cultivar-specific (Villordon et al., 2018). Sulaiman et al. (2004) reviewed the evidence and concluded that storage root L might be decided early in the growth stage, $\approx$ 8 to 16 weeks, depending on variety and environmental conditions, but storage root W increased throughout the season. In terms of

storage root W, it is generally accepted that cambium activity is responsible for increase in diameter and there has been some progress in this regard (Robbins et al., 1929; Wang et al., 2018). Sulaiman et al. (2004) reported that high calcium availability reduced storage root W but the effect varied with cultivar. Considering available evidence, understanding the biological and environmental variables that limit the downward growth of developing storage roots is key to understanding storage root shape variability in sweetpotato.

PCA has been used to analyze measurements of shape features in target organs of specialty crops like apple (*Malus domestica*) (Paulus and Schrevels, 1999), cranberry (*Vaccinium macrocarpon*) (Diaz-Garcia et al., 2018), radish (*Raphanus sativus*) (Iwata et al., 2004), walnut (*Juglans regia*) (Ercisli et al., 2012), and gardenia (*Primula sieboldii*) (Yoshioka et al., 2004). Although PCA in its standard form is widely used and an adaptive descriptive data analysis tool (Jolliffe and Cadima, 2016), it has often been viewed as a “black box” approach that obscures the relationship between the input data and the output projection onto eigenspace (Jeong et al., 2009). Iezzoni and Pritts (1991) discussed the applications of PCA in horticultural research and concluded that the biological meaning and significance of the

results will depend on the specific set of characters that are measured, diversity of the entries, strength of the underlying relationships among variables, and the judgment of the researcher. Once the results are properly contextualized, the findings can be used to develop novel hypotheses, simplify large data sets, or to understand the response of complex traits to imposed treatments (Iezzoni and Pritts, 1991).

Conclusion

The accuracy and consistency of the Structure 3D scanner-based measurements of sweetpotato shape features is comparable with currently accepted manual measurement methods with added benefits of increased throughput and nondestructive sampling. The methods described in this work also can be adopted for analyzing shape in other horticultural produce, like fruits, vegetables, tubers, and other storage roots that meet device-specific specifications for 3D scanning. There are other relatively expensive 3D scanners that are already available that possess increased accuracy and tracking capabilities, especially for relatively smaller horticultural produce that do not meet the scanning specifications of low-cost 3D scanners. Technological improvements will lead to

increased accuracy and accessibility of 3D scanners for horticultural research. Using the 3D scanner-acquired data, we have provided evidence that incorporation of shape features like SA and VOL overcomes perceived limitations of LW in measuring taper and other subtle shape variation in

sweetpotato. The data support the hypothesis that understanding the intrinsic and environmental variables that determine L and W in sweetpotato will lead to the development of varieties, methods, and approaches for enhanced processing product recovery and size assortment for fresh market.

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Fig. 5. Plots of principal components PC1 (Dim1) and PC2 (Dim2) and factor loadings from principal component analysis (PCA) of three-dimensional scanner-acquired shape features of sweetpotato storage roots. L = length; W = width or diameter at the widest point; SA = surface area; VOL = volume; LW = length-width ratio; SAVOL = surface area-volume ratio; FRESH = fresh market; FRY = blocky or French fry type; TAPER = tapered.

Fig. 6. Scree plot for non-bootstrapped (A) and bootstrapped (B) eigenvalues of principal component analysis of three-dimensional (3D) scanner-acquired shape features of sweetpotato storage roots. Bootstrap analysis ($n = 1000$) was performed in Tanagra (v. 1.4; Rakotomalala, 2005).

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