Foot measurements from 3-dimensional scans: A comparison and evaluation of different methods

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Abstract

An approach to automatic foot measurement using 3D scanned data is proposed in this paper. The proposed approach was evaluated through comparisons of simulated measurements (SM) of eleven male and nine female participants with manual measurements and with the output of a commercially available automated foot measuring system (CP). The registration procedure for the measurements and unambiguous definitions for each measurement were first established. Eighteen dimensions of each foot were calculated from the scanned data that comprised point clouds and selected landmarks. Two operators manually measured each participant's foot twice. These manual measurements (MM) showed high inter- and intra-operator reliability ($ICC > 0.84$). Ten of the eighteen dimensions obtained from the three measurement methods, SM, CP, and MM, were subjected to an ANOVA and eight of the measurements showed significant differences among the three methods. After establishing a linear correction to adjust for systematic errors, there were no significant differences between the SM and MM methods for 17 of the 18 foot dimensions; and the single exception was the heel width dimension. The differences among the three methods, correction procedures and their significance are discussed.

Relevance to industry: Measuring feet to obtain the relevant dimensions that characterize feet can be quite tedious and the measurement may be dependent on the

measurer. Automatic measurement with scanned data on the other hand, can give replicable information even though the measurements depend on the intricacies of the scanning system and the computational algorithms adopted. The proposed definitions and algorithms provide a means to automate foot measurements for customized footwear.

Keywords: Foot measurement, simulated measurement, anthropometry, measurement error, foot scan, body measurement, measurement reliability.

1. Introduction

Lengths, widths, heights and girths of feet should match with those of shoes in order for footwear to be comfortable (Clarks, 1976; White, 1982; Pivečka and Laure, 1995; Venkatappaiah, 1997). There are many studies on foot anthropometry that describe different techniques to measure critical dimensions on feet (Freedman et al., 1946; Rossi, 1983; Hawes and Sovak, 1994; Kouchi, 2003; Bunch, 1988; Liu et al., 1999). In terms of technology development, there has been an exponential growth in laser scanner technologies with various applications in recent years (Blais et al., 2000; Gärtner et al., 1999; Houle et al., 1997; Wehr, 1999) that claim accuracy within 1 mm. The basic principle of scanning technology is triangulation in order to generate the surface coordinates that make the shape. The captured information is then processed and curve-fitting techniques are used to obtain the surface coordinates, sometimes after processing for known errors in the system (Carocci et al., 1997). The accuracy of the scanner itself can vary depending on the object that is scanned and the method used for scanning. In general, a human foot can be modeled using several “slices” of scanned data obtained along the length of the foot (Luximon and Goonetilleke, 2004). As a result, it is now possible to obtain surface information to make customized products such as shoes (Viavor, 2005). Even though foot scanners capture shape information, it is difficult to include all the shape information in a shoe last design. Footwear

manufacturers still resort to matching linear and girth dimensions to achieve the right fit. Consequently, measurements play an important role in footwear manufacturing. With non-uniform surfaces, such as feet, the scanner manufacturer's specifications of accuracy may not be suitable for the measurements that are required to make footwear. In addition, body sway during scanning can affect image fidelity and thereby affect the captured information and the accuracy (Corner and Hu, 1997). Thus the objectives of this study were:

1. to obtain inter-operator and intra-operator reliability in manual foot measurements (MM) and
2. to compare MM with measurements obtained from the scanner software (commercial program, CP), and measurements calculated from the algorithms we developed (simulated measurements, SM).

2. Methodology

2.1. Participants

Twenty students (11 males and 9 females) from the Hong Kong University of Science and Technology were recruited for this experiment. None of them had any visible foot abnormalities or foot illnesses. It is possible that there are differences unique to gender. In order to eliminate any such effect, both males and females were participants. The

descriptive statistics of the participants are given in Table 1.

[Insert Table 1 Here]

2.2. Equipment

The YETI™ I foot scanner (Vorum Research Corporation, 2000) was used to obtain the 3D shape of the foot. The scanner system has been designed to collect surface data on a number of slices along the length of the foot. Four lasers shine a line of light on the surface. Eight cameras then capture images of the reflected laser light at each section along the surface. The camera images are then used to determine the 3D coordinates of the points at each section.

2.3. Experimental Design

A “repeated measures” design (Montgomery, 2001) was used with the dependent variables being measurements obtained on the right-foot of each participant. The independent variable was the method of measurement at three levels, MM, SM, and CP.

2.4 Experimental Procedure

2.4.1. Manual foot measurements

The methods used were in accordance with the guidelines set forth by the committee on research practice at the Hong Kong University of Science and Technology. The participants' feet were disinfected and dried prior to measuring. Two operators measured 18 dimensions (Figure 1, Table 2) on each person's right foot twice (2 operators x 2 trials) using set squares, a measuring tape and calipers. There were four MM readings for each subject's right foot. The order of measurement between operators 1 and 2 was random. Each participant was asked to stand on a platform with equal weight on each foot (Figure 2). The posterior point of the heel (pternion) touched the measuring device plate. The foot was then rotated around pternion so that the distance between the location at landmark-1 (Figure 3) and the centerline (or X-axis) of the transparency (Figure 2) was 38.1 mm (1.5 inches). The alignment thus obtained matches with that of a Brannock device (Brannock, 2005), which has been a tool used for measuring feet in the US for a number of years. Researchers have adopted differing definitions for the foot axis (X-axis). The most common of these is the line joining the pternion and the tip of the second toe (Kouchi, 2003). An axis determined this way is sensitive to deformation of the second toe, such as feet with bunions. Thus, lengths and widths of feet with bunions and those without bunions will be significantly different with a pternion-to-second toe tip axis measurement even though the feet are similar,

except in the toe region. The Brannock axis, which is 38.1 mm (1.5 inches) from the medial side of the first metatarsal bone, was used as the x-axis to eliminate any such “noisy” variation.

[Insert Figures 1, 2, 3 & Table 2 about here]

2.4.2. Foot landmarking and scanning

After obtaining the measurements manually (MM) four times, the participant’s right foot was laser scanned in order to obtain the corresponding SM and CP measurements. Prior to the scanning, ten anatomical landmarks were identified and marked on the right foot. Five of those landmarks were on the top of metatarsal-phalangeal joints (MPJ), one each at the side of the first and fifth MPJ, one each on the medial and lateral malleolus, and one at the arch point (Figure 3). Then, the participant’s right foot was aligned and scanned on the foot scanner with half-body-weight on each foot. After the scanning, the scanned points and the ten landmarks were stored as a point cloud. Since the scanned sections were set to be 1 mm apart and each section had 360 points, the total number of points was dependent on the foot length.

2.4.3. Simulated foot measurements

The foot scan data were thereafter processed using the YETI Shape Builder software version 4.1.0.95 (CP) and also using our program (SM) developed using C++ (Section 3). Out of the 18 foot dimensions (Table 2), only ten (foot length, arch length, heel-to-medial malleolus, heel-to-lateral malleolus, foot width, medial malleolus height, lateral malleolus height, ball girth, instep girth and short heel girth) were available in the commercial software system. Those ten measurements are henceforth referred to as the “common measurements” and the other eight measurements (heel-to-fifth toe length, heel width, bimalleolar width, mid-foot width, height at 50% of the foot length, long heel girth, ankle girth and waist girth) are referred to as “other measurements”.

3. Algorithms

3.1. Foot Registration

Registration was used to minimize variations due to misalignment. The same alignment as in the manual measurement was adopted to transform each foot scan prior to measurement as follows:

- 1) All scanned points no more than 25 mm above the platform were first selected.
- 2) These points were then projected on to the XY plane (Figure 4). For every scanned section, the two points on the boundary of the XY projection (points with minimum

Y coordinate and maximum Y coordinate) were then found.

- 3) A second degree polynomial $x = a * y^2 + b * y + c$ was fitted for the points on the boundary of XY projection and within 25 mm from the heel point along the X-axis in order to generate the heel curve (Figure 4).
- 4) The pternion (x_P, y_P) was determined from $x_P = \frac{(4 * a * c - b^2)}{(4 * a)}$ and $y_P = \frac{-b}{(2 * a)}$.
- 5) The distance, d_{P-M1} , between the pternion point and landmark-1 (x_{M1}, y_{M1}) in the XY plane was calculated from $d_{P-M1} = \sqrt{(x_P - x_{M1})^2 + (y_P - y_{M1})^2}$.
- 6) The distance, d_{M1} , between landmark-1 and the line parallel to the X-axis running through the pternion was calculated from $d_{M1} = |y_P - y_{M1}|$.
- 7) The foot was rotated around the pternion and parallel with the XY plane through an angle $\theta = \sin^{-1}(d_{M1} / d_{P-M1}) - \sin^{-1}(38.1 / d_{P-M1})$, to make the distance from landmark-1 to the line parallel with X axis and across the pternion equal 38.1 mm in order to maintain the same alignment as the Brannock device (Brannock, 2005).

[Insert figure 4 about here]

Figure 4 shows the point cloud data before and after the alignment procedure.

3.2. Determination of Dimensions

3.2.1. Length

Foot length is calculated as the distance between the minimum X value (mean of five minimum points) and the maximum X value (mean of five maximum points) along the X-axis:

$$L_{FL} = |x_{\min} - x_{\max}|.$$

Arch length is calculated as the distance between the point with the minimum X value (mean of five minimum points) and landmark-1 (Figure 3) along the X-axis:

$$L_{AL} = |x_{\min} - x_{M1}|.$$

The heel to medial malleolus length is calculated as the distance between the point with the minimum X value (mean of five minimum points) and landmark-8 (Figure 3) along the X-axis:

$$L_{HMM} = |x_{\min} - x_{M8}|.$$

The heel to lateral malleolus length is calculated as the distance between the point with the minimum X value (mean of five minimum points) and landmark-9 (Figure 3) along the X-axis:

$$L_{HLM} = |x_{\min} - x_{M9}|.$$

The heel to fifth toe length is calculated as the distance between the point with minimum X value (mean of five minimum points) and the fifth toe along the X-axis:

$$L_{HT5} = |x_{\min} - x_{T5}|.$$

The location of the fifth toe was determined using the inflection point characteristic.

The shape of the boundary points projected on to the XY plane on the lateral side of the forefoot vary smoothly until the inflexion point at the tip of the fifth toe (Figure 5). The algorithm for locating the fifth toe is as follows:

- 1) Project the point cloud onto the XY plane; for every scanned section, find two points on the boundary of the XY projection (the point with the minimum Y value and the point with the maximum Y value).
- 2) Consider the lateral boundary points ahead of landmark-7¹ (along the X-axis) (Figure 3) and on the lateral side of landmark-5 (along the Y-axis). i.e., the lateral boundary points of the region bounded by two straight lines as shown in Figure 5(a).
- 3) Take the point with the minimum X value as the first boundary point, which is on the lateral side of the ith section, and then find the next four boundary points.
- 4) Fit a straight line, $y=ax + b$ for these five points using the least squares method, and

¹ Landmark-5 may be more suited to eliminate any possibility of error due to curvatures near the fifth toe.

take a as the starting gradient.

- 5) Take the boundary point of the $(i+1)^{\text{th}}$ section as the first boundary point; update i as $i=i+1$; then find the next four boundary points; and then fit a straight line, $(y = a * x + b)$, for these five points using the least squares method.
- 6) Repeat Step 5 until the difference between the updated gradient value (a) and the starting gradient value is greater than 0.5.
- 7) Repeat Step 5 until the updated gradient value (a) is less than the gradient value of the previous iteration, and take the boundary point of the i^{th} section as the tip of the fifth toe, as shown in the right of Figure 5.

[Insert figure 5 about here]

3.2.2. Width

Foot width is calculated as the distance between the point with the minimum Y value and the point with the maximum Y value along the Y-axis of the fore-foot (the area in which all points are ahead of landmark-7 (along the X-axis)). The mean of five points were used to determine both the minimum and maximum values in order to minimize the effects of “noise” in the scanned points:

$$W_{FW} = |y_{f_min} - y_{f_max}|.$$

Heel width is calculated as the distance between the point with the minimum Y value (mean of five minimum points) and the point with the maximum Y value (mean of five maximum points) along the Y-axis in the rear-foot region, i.e. points within 40 mm from pternion along X-axis and no more than 20 mm above the platform:

$$W_{HW} = |y_{h_min} - y_{h_max}|.$$

Bimalleolar width is calculated as the distance between landmark-8 and landmark-9 along the Y-axis:

$$W_{BW} = |y_{M8} - y_{M9}|.$$

Mid-foot width is calculated as the distance along the Y-axis between the minimum Y value (mean of five minimum points) and the maximum Y value (mean of five maximum points) at the foot center; i.e., points within a slab of half-thickness of 0.6 mm on either side of 50% of the foot length along the X-axis:

$$W_{MF} = |y_{m_min} - y_{m_max}|.$$

3.2.3. Height

Medial malleolus height is calculated as the distance along the Z-axis from the platform (mean of five maximum Z points) to landmark-8 (the positive Z-axis is pointing downwards, and hence the scanner platform has the maximum Z value, see Figure 3):

$$H_{MM} = |z_{\max} - z_{M8}|.$$

Lateral malleolus height is calculated as the distance along the Z-axis between the platform (mean of five maximum Z points) and landmark-9:

$$H_{LM} = |z_{\max} - z_{M9}|.$$

The height at 50% of the foot length is calculated as the distance along the Z-axis from the platform (mean of five maximum Z points) to the minimum Z value (mean of five minimum points) at 50% of the foot length: i.e., points within a slab of ± 0.6 mm distance from 50% of the foot length along X-axis:

$$H_{MF} = |z_{\max} - z_{m_min}|.$$

3.2.4. Girth

Traditionally, custom footwear manufacturers use a tape measure to determine girth. However, the tape does not have contact with the full foot due to the uneven contours on the foot. When the tape is stretched around the foot, there are apertures between the tape

and the skin surface. In order to simulate such a measurement, convex hulls were used. In computational geometry, a convex hull of a set of points is defined as the smallest convex set containing the points. Berg et al. (1997) described a 2D convex hull like when an elastic rubber band is put around a series of nails. When the rubber band is let go, it will then snap around the nails, minimizing its length, making a convex hull. To determine the girth, the intersection points between the tape plane and the point cloud are first determined and transformed to be parallel with one plane of the 3D coordinate system. Then, a 2D convex hull is constructed and the girth is calculated as the sum of the distances between two neighboring points on the convex hull.

[Insert figure 6 about here]

As illustrated in Figure 6(a), three control points locate the tape plane, and T1 are the intersection points between the tape plane and the point cloud in the XY, XZ and YZ planes respectively. The intersection points (T1) are then rotated around one control point to be parallel with the XY plane (from T1 to T2), then rotated around the control point to be parallel with the XZ plane (from T2 to T3), and then rotated around the control point to be parallel with the YZ plane (from T3 to T4). Thus the intersection points are transformed to be parallel with the XY plane and only the X and Y

coordinates are considered when the 2D convex hull method is used for girth calculations. The points in Figure 6(b) are an example of the transformed intersection points (i.e., T4), and the corresponding convex hull generated for tape measurement simulation. Girth measurements on the foot are shown in Figure 7.

[Insert figure 7 about here]

The ball girth is calculated from the intersection points between the point cloud and the tape plane determined by landmark-1, landmark-2 and landmark-7.

The instep girth is calculated from the intersection points between the point cloud and the tape plane determined by the three control points, P1, P2 and P3.

The long heel girth is calculated from the intersection points between the point cloud and the tape plane perpendicular to the XZ plane and located by two control points, P3 and P4.

The short heel girth is calculated from the intersection points between the point cloud and the tape plane perpendicular to the XZ plane and located by two control points, P5 and P6.

The ankle girth is calculated from the intersection points between the point cloud and the tape plane parallel to the XY plane and located by one control point, P6.

The waist girth is calculated from the intersection points between the point cloud and the tape plane parallel to the YZ plane and located by the midpoint of landmark-1 and one control point, P1.

The control points, P1 to P6 are identified as follows:

- 1) Control point P1 is the arch point, i.e. landmark-10 (Figure 3).
- 2) Project the points no more than 20 mm above the platform to XY plane and find points on the lateral boundary of the XY projection (the point with maximum Y value) of every scanned section.
- 3) Calculate the distance between P1 and every boundary point on the lateral side from 25% to 45% of the foot length, and take the boundary point with the minimum distance as control point P2, as shown in the upper left of Figure 8.
- 4) Project the point cloud to the XZ plane, and for every scanned section, find the highest point on the boundary of the XZ projection (the point with the minimum Z value).
- 5) Calculate the girth from P1, P2 and every point on boundary of the XZ projection within 40% to 55% of the foot length, and take the boundary point with the minimum girth as control point P3, as shown in the upper right of Figure 8.
- 6) Calculate the girth perpendicular to the XZ plane and located by P3 and the lowest points on the boundary of the XZ projection (point with the maximum Z value of

every section) from 0% to 3.5% of the foot length, and take the boundary point with the maximum girth as control point P4, as shown in the lower left of Figure 8.

- 7) Find the first (along the X-axis) lowest point on the boundary of the XZ projection and another boundary point that just touches the platform, and take the midpoint of these two as control point P5.
- 8) Calculate the girth perpendicular to the XZ plane and located by P5 and all the highest points on the boundary of the XZ projection (within the region from 50% of the foot length to the front of the leg), and take the boundary point with the minimum girth as control point P6, as shown in the lower right of Figure 8.

[Insert figure 8 about here]

4. Results

4.1. Inter-operator and intra-operator reliabilities

The inter-operator and intra-operator reliabilities for all manual foot measurements were calculated using intraclass correlation coefficients (ICC), type (2,1) (Shrout and Fleiss, 1979; Webster et al., 2005). The inter-operator reliability, ICC(2, 1) for all 18 manual

measurements was within the range of 0.920 to 1.000 and the intra-operator reliability, ICC(2, 1) for operator 1 was within the range of 0.841 to 0.998 and for operator 2 within the range of 0.943 to 0.998 (Table 3).

[Insert Table 3 Here]

4.2. Measurement Comparisons

Our pre-experimental data analysis revealed significant differences between SM and MM for most foot dimensions, even though the variations in the differences were relatively small (standard deviations were generally within 1mm except in the girth measurements). To investigate the potential presence of any systematic errors between SM and MM, the 20 participants were randomly grouped into a ten-participant “training data set” and a ten-participant “test data set”. The two data sets were used for two purposes:

- (1) to quantify the systematic errors between SM and MM using the training data set and to use the quantified systematic errors to adjust SM and validate the results with the test data set and
- (2) to compare the three measurement methods, CP, SM and MM.

Homogeneity of variance was checked using the Bartlett test (Bartlett, 1937). There were no significant differences among the different methods in both the training and test data sets at the $p = 0.05$ level.

The training data set was subjected to a linear regression ($SM = a*MM + b$) followed by ($SM=MM+b$) in order to find any systematic errors between SM and MM. The SM results extracted from the test data set were adjusted based on calculated linear regression models. Descriptive statistics of all 18 measurements obtained from the three methods (MM, SM and CP) for the training and test data sets are given in tables 4 and 5. A two-way (Measurement Method * Participant) analysis of variance (ANOVA) with post-hoc Student Newman-Keuls (SNK) tests and a paired t-test were conducted to compare the measurement methods. The following statistical model was used (Montgomery, 2001) for testing the ten common measurements:

$$Y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij} \quad i=1,...,3 \quad \text{and} \quad j=1,...,10$$

where Y_{ij} is the magnitude of each foot measurement of the j^{th} subject from the i^{th} measuring method; τ_i is the effect of the i^{th} measuring method and assumed to be a fixed factor; β_j is the effect associated of the j^{th} subject and a random factor; ε_{ij} is the random error. The test static for the measuring method ($df=2$) was $F = MS_{\text{measuring method}}/MS_{\text{error}}$ with MS_{error} having 18 degrees of freedom. The SAS statistical package was used for all the statistical analyses and all statistical significance levels were set at 0.05.

[Insert Table 4 & Table 5 Here]

4.2.1 Comparisons within the training data set

Since the reliability of MM was relatively high, SM and CP were compared with MM.

The mean of MM ($\overline{MM}$) taken by operator 1 and operator 2 was used for further analysis.

The three measurement methods were significantly different ($p < 0.05$) in eight of the ten “common measurements” with the exception of medial malleolus height ($P = 0.4418$) and lateral malleolus height ($P = 0.4607$) (Table 6). The *post-hoc* SNK tests (Table 6) showed that there were no significant differences between $\overline{MM}$ and SM in five dimensions (foot length, arch length, heel-to-medial malleolus, medial malleolus height and lateral malleolus height). Four dimensions, medial malleolus height, lateral malleolus height, instep girth and short heel girth were not significantly different between $\overline{MM}$ and CP (Table 6). The descriptive statistics of the measuring methods SM, CP and $\overline{MM}$ are summarized in Table 7. As a whole, the training data set results indicated that for all length dimensions, SM was significantly closer to $\overline{MM}$ than was CP, and, on the other hand, for the instep girth and short heel girth dimensions, CP was significantly closer to

$\overline{MM}$ than SM.

[Insert Table 6 & Table 7 Here]

The paired t-test was used to compare the SM and MM for the eight “other measurements” (Table 8). SM and $\overline{MM}$ were significantly different ($p < 0.05$) for five of the eight “other measurements” with the exceptions being the heel to fifth toe length ($p = 0.8328$), the long heel girth ($p = 0.9135$) and the waist girth ($p = 0.1723$).

[Insert Table 8 Here]

4.2.2. Linear regression model

Comparisons between SM and $\overline{MM}$ in the training data set revealed significant differences in ten of the 18 foot dimensions (heel-to-lateral malleolus, foot width, heel width, bimalleolar width, mid-foot width, height at 50% of the foot length, ball girth, instep girth, short heel girth and ankle girth). Similarly, the comparison between CP and $\overline{MM}$ showed significant differences in six of the ten foot dimensions (Table 6). These results indicate that SM and CP are not exactly the same as MM. Hence, a linear regression was used to adjust the discrepancies between SM and MM. The 10 foot

dimensions that were significantly different between SM and MM were subjected to a linear regression of the form $SM = a * \overline{MM} + b$ (Table 9). The hypothesis that $a=1$ was checked and it was found that $a=1$ for all the regression equations at $p = 0.05$. Hence, the regression was re-run in the form of $SM = \overline{MM} + b$ (Table 10 and Figure 9). All linear regression equations had relatively high R^2 values (≥ 0.9032), which suggested that the intercept (or systematic error) could be used to adjust SM in order to generate the manual measurement.

[Insert Tables 9, 10 & Figure 9 Here]

4.2.3. Measurement method comparison of the test data set

The test data set was used to compare SM, CP and MM. The SM measurements of heel-to-lateral malleolus, foot width, heel width, bimalleolar width, mid-foot width, height at 50% of the foot length, ball girth, instep girth, short heel girth and ankle girth were adjusted using the $SM = \overline{MM} + b$ linear regression models (Table 10).

ANOVA and post-hoc SNK tests (Table 11) showed that there were no significant differences between the adjusted SM and $\overline{MM}$ in the ten common foot dimensions. Additionally, the paired t-test (Table 12) showed that there were no significant

differences between adjusted SM and $\overline{MM}$ in 17 of the 18 dimensions, with the only exception being heel width ($P=0.0123$). Figure 10 shows the heel width differences between the adjusted SM and $\overline{MM}$ for each participant. The maximum of the absolute difference is less than 2mm. The descriptive statistics of the differences between the adjusted SM and $\overline{MM}$ for 18 foot measurements are summarized in Table 12. After adjusting SM with the regression equations given in Table 10, the differences with $\overline{MM}$ were within 3mm for all the lengths except the heel to fifth toe, within 2mm for all widths and within 3.5mm for all heights. The ball girth, short heel girth and waist girth measurements showed higher precision (within 5mm) in the adjusted SM.

[Insert Table 11, Table 12 & Figure 10 Here]

5. Discussion

In this study, foot measurements obtained from three methods were compared. These included manual measurements (MM) using simple measuring devices, commercial software generated measures (CP) and the simulated measurements (SM) obtained from our coded algorithms. The manual measuring sessions consisted of four repetitions (2 operators x 2 trials). The two operators demonstrated measurement reliability (Table 3)

higher than that established by Liu et al (1999), both within and between operators even though very basic measuring instruments like rulers, tapes and setsquares were used (Table 2). It is hypothesized that good control of the alignment procedures and unambiguous definitions are key ingredients in high measurement reliability.

Even though triangulation errors due to the quality of a laser beam can affect measurement accuracy, they have been reported to be on the order of micrometers (Collier and Nurre, 1999). However, the geometry of a laser system can result in errors on the order of millimeters. Thus, differences in CP and SM compared with MM may be attributed to such an effect. Since the same laser scans were used to obtain both the CP and SM measurements, differences between the two are likely due to other reasons. The ANOVA on the training data set (Table 6) showed that the three methods, CP, MM and SM were different in eight of the ten common measurements. The only exceptions were the medial and lateral malleolus heights, primarily because these two heights were measured or calculated from the anatomical landmarks on the malleolus. This result clearly shows that knowing the exact locations can provide the same measurement no matter which measurement method is used. The *post-hoc* SNK tests showed significant differences among the three methods. CP had no significant differences with MM on the instep girth and short heel girth dimensions while the SM measurements of these two dimensions were different from the MM dimensions. The

SM dimensions were programmed to be identical to those of MM, even though the locations at which the measurements were taken could have been different, as shown below, but the same cannot be said about the CP dimensions. The exact definitions in CP are unknown and hence differences between SM (or MM) and CP are not surprising. Different organizations and researchers use their own sets of standards of measurements that differ from each other. For example, foot length has been measured in many ways. Freedman et al (1946) defined foot length as the length from the heel to the longest toe tip along rectilinear ordinates. Others such as Baba (1975) defined foot length as the distance from the most posteriorly projecting point on the heel (pternion) to the tip of the most anteriorly projecting toe (acropodion, usually the tip of the big or second toe). Pheasant (1988) measured foot length parallel to the long axis of the foot, from the back of the heel to the tip of the longest toe. Physical measurements are highly dependent by the way they are defined and measured. This dilemma highlights the necessity of developing a set of acceptable and meaningful definitions for the measurement of the foot that would be useful to all manufacturers of footwear.

Since the dimension definitions used in CP are unknown, it is worthwhile to focus primarily on the differences between MM and SM in order to gain an understanding of the underlying differences between scanned data and tape- or ruler-based data. The ANOVA and paired t-test results for the training data set showed no differences

between MM and SM for foot length, arch length, heel-to-medial malleolus, heel to fifth toe, medial malleolus height, lateral malleolus height, long heel girth and waist girth (Table 6 and Table 8), The similar medial malleolus and lateral malleolus heights has already being discussed. The lack of any difference between the other measures between SM and MM is primarily attributed to the precise identification of the identical end-points of the measurement. The only exception is the long heel girth where variations between SM and MM were very large ($SD=7.03\text{mm}$, $Max=10.78\text{mm}$, $Min=-7.99\text{mm}$, see table 8), primarily due to inconsistent locations between SM and MM. A more detailed analysis of dimension locations on one of the participants illustrates this effect. Figure 11 shows the dimension locations for SM (point P3) using the algorithm and MM (point P3') when using a tape. The differing locations resulted in a (SM-MM) difference of 10.78 mm for this particular participant.

[Insert Figure 11 Here]

The measurements that were significantly different between SM and MM in the training data set (Table 6 and Table 8) were height at 50% of the foot length, ball girth, instep girth, short heel girth, ankle girth, foot width, heel width, bimalleolar width, mid foot width and heel-to-lateral malleolus distance. The differences in the height at 50% of the foot length can be attributed to two main reasons: skin deformation and a locational

issue. The manual measurement is almost always lower than SM (Table 8). A post-experiment check on ten plaster castings showed that the mean difference between SM and the manual measurement on the castings was only 1.17 mm, whereas the difference in the experiment reported here was 2.00 mm for the training data set when the measurements were on real feet. Thus, the difference of $(2-1.17) = 0.83$ mm may be attributed to skin deformation as the castings were made of rigid Plaster of Paris. The second potential reason for the difference relates to a locational issue. At exactly 50% of the foot length, there may not be any point data as the laser scan slices are separated by a 1 mm thickness. To ensure that there are points for the height calculation, the algorithm considered the point with the maximum height in the region of $[50\% \text{ of the foot length}-0.6, 50\% \text{ of the foot length}+0.6]$ (see Section 3.2.3 Height). Since the scan slices are 1 mm apart, using a total thickness of 1.2 mm will guarantee that at least one slice is included in the height calculation. This operation will always result in a SM that is larger as the region encompasses points that are 0.6 mm on either side of the middle of the foot. Tables 7 and 8 show that SM is smaller than MM in ball girth, instep girth, short heel girth, and ankle girth. Two potential reasons for the differences are the use of the convex hull for determining girths and the approximation of using point-to-point linear distances to determine girth. Since a distance of 1 mm separated the scanned sections, it was necessary to consider a slab when determining girths even with the use of landmarks or control points as the number of points on any inclined

plane can otherwise be very small. The slab thickness can influence the girth measurement. Figure 12 illustrates two cases where the slab thickness was 1.2 mm and 7.2 mm. As can be seen from Figure 13, the girth increases monotonically with increasing region thickness due to an increase in the size of the convex hull. In addition, the sum of the Euclidean distances between neighboring points on the 2D convex hull was used to determine the SM girths and such a calculation will not account for the curvatures present in a girth measurement even though a higher number of points can approximate the curvature. The only possible way to get a higher number of points is to increase the thickness of the section, which can cause other artifacts as explained above. Hence, it may be appropriate to investigate the effects of using differing fitting methods such as B-Splines, NURBS, Bezier or Catmull curves (Mortenson, 1939; Su and Liu, 1989) in the modeling. In addition, computational integration along a curve rather than the sum of piecewise linear distances may allow a higher accuracy in the girth computation (Priestley, 1997). Additionally, other approaches that can be used include the generation of a closed convex surface (Hagen and Roller, 1991) followed by the determination of a geodesic distance (Kimmel and Sethian, 1998) between the chosen points.

[Insert Figures 12 and 13 Here]

It is clear that there are differences between SM and MM in ten of the dimensions. To understand if these errors are systematic, a linear regression was performed to convert the SM measurements to MM. Table 10 shows that the regression of the form $SM = \overline{MM} + b$ (constant) can achieve $R^2 > 0.9$ for the 10 dimensions that were found to be significantly different. The form of the equation with a constant is an indication that the difference is primarily the result of a systematic bias induced from either the manual measurements or the algorithms. To unify and check the influence of the systematic error, the SM(Adjusted) was calculated as (SM-b) on the test data set. The ANOVA on the test data set (Table 11) indicated differences among MM, CP and SM(Adjusted) for seven of the ten dimensions with the exceptions of the medial and lateral malleolus height and the instep girth dimensions. The post-hoc SNK tests (Table 11) and the paired t-tests (Table 12) showed no difference between MM and SM(Adjusted) except for heel width. The difference in heel width can be traced to a point construction issue in the scanner software. In the rearfoot region, the scanner captures the lower leg as well. In order to generate a smooth shape for each slice, the software seems to use a construction center. If the captured height is large (like in the rearfoot region), the radius of the construction line will tend to be large and vice versa. This effect is clearly seen when we changed the height of the scan in the rearfoot region and obtained point cloud data for participant number 5 and as shown in Figure 14. The inset of Figure 14 shows how the point data moves inward at the maximum width

location as the scanned height increases. The variation in width with the change in height is shown for two participants in Figure 15. For participant number 5, the heel width reduced from 61.43 mm to 59.60 mm when the scanning height was changed from 25 mm to 150 mm. The scan height that was used for SM was 130 mm and it is clear from Figure 15 that it is not optimal. However, the cause for the difference between SM and MM was only found after the fact and prior to that it seemed reasonable to use the highest height that the scanner could possibly scan in order to generate the point cloud. Lowering the scan height can have adverse effects on the SM measurement of malleolus heights, bimalleolar width, short heel girth and ankle girth and hence a compromise is needed. Thus, if heel width is not a critical measure, it may be appropriate to increase the scanning height in the rearfoot region to generate accurate measures for these four dimensions. Another alternative method is to use differing scanning heights for different dimensions. A low height (e.g. 25mm) can be used for the measurement of heel width whereas all other measurements can be obtained with a higher scanning height such as 130 mm. Such a procedure, however, may be unique to each type of scanner.

[Insert Figures 14 and 15 Here]

6. Conclusions

In general, this study highlights important differences in manual foot measurements and 3D scanned measurements. For both cases, it is of utmost importance to have good definitions and registration procedures so that the measurements can be reproducible and repeatable. The differences between the commercial software measures and those that we generated may be primarily attributed to differences in definitions and the alignment procedures. The registration process can make a significant difference in measurements of linear as well as girth dimensions. Because manual measurements may take a longer time compared with scanning, there is a possibility of shape changes due to the participant fatigue (Goonetilleke, 1999; Winkel and Jørgensen, 1986). In addition, the skill level of the measurer and the instruments used can influence the measurements, even though having well-defined measurement procedures can minimize this effect as seen in our experimental results. Similarly, the scanned data may not be free of errors. The presence of dust particles on the scanner bed or its side walls or high levels of ambient light can cause the divergence of the laser beam and thereby affect the noise introduced and the accuracy of the scanned points data (Blais et al., 2000; Bornaz et al., 2005). In addition, transformations of data into a single global coordinate system, data stitching and the creation of a computer model can result in inaccuracies as well. Thus, it is essential that the measurement algorithms be robust in order to be insensitive to any noise in the point cloud data. Using the mean of many points (such as the mean

of five points as in this study) rather than just one point can prevent or minimize the effect of noisy data. In addition, locating some of the critical points that have to be measured is not as easy when using algorithms in comparison with locating the point manually as palpation is not possible. The lack of a difference in the malleolus heights among the three methods is proof that the problem can be minimized, if not eliminated, by placing landmarks after manual location or palpation. It is also important to understand the point cloud construction methodology in the scanned data, as it can affect some measurements such as heel width. Overall, choosing the method to use for taking measurements on feet will depend on many different factors. It is important to note that any measurement is dependent on the registration, dimension definition, and algorithm used. The ultimate method selection should be based on cost, accuracy, and precision of the method or algorithms and the allowable tolerances for each measurement.

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Table 1. Descriptive statistics of participants (N=20)

Characteristics	Mean	Maximum	Minimum	Standard deviation
Age (years)	21.25	23	19	1.16
Height (cm)	166.0	178.0	155.3	7.44
Body Weight (kg)	58.26	94.25	41.80	13.36

Table 2. Foot dimension definitions. Numbers correspond to those shown in Figure 1.

Lengths	[1] Foot length: The distance along the brannock axis (X-direction) from pternion to the tip of the longest toe.
	[2] Arch length: The distance along the brannock axis from pternion to the most medially prominent point on the 1 st metatarsal head.
	[3] Heel to medial malleolus: Length from pternion to the most medially protruding point of the Medial Malleolus measured along the brannock axis. (Modified from Kouchi, 2003)
	[4] Heel to lateral malleolus: Length from pternion to the most laterally protruding point of the Lateral Malleolus measured along the brannock axis. (Modified from Kouchi, 2003)
	[5] Heel to 5th toe: The distance along the brannock axis from pternion to the anterior 5th toe tip.
Widths	[6] Foot width: Maximum horizontal breadth (Y-direction), across the foot perpendicular to the brannock axis in the region in front of the most laterally prominent point on the 5 th metatarsal head
	[7] Heel width: Breadth of the heel 40 mm forward of the pternion (Modified from last measurements given in Pivečka and Laure, 1995).
	[8] Bimalleolar width: Distance between the most medially protruding point on the medial malleolus and the most laterally protruding point on the lateral malleolus measured along a line perpendicular to the brannock axis (Kouchi, 2003).
	[9] Mid-foot width: Maximum horizontal breadth, across the foot perpendicular to the brannock axis at 50% of foot length from the pternion.
Heights	[10] Medial malleolus height: Vertical (Z-direction) distance from the floor to the most prominent point on the medial malleolus
	[11] Lateral malleolus height: Vertical (Z-direction) distance from the floor to the most prominent point on the lateral malleolus
	[12] Height at 50% foot length: Maximum height of the vertical cross-section at 50% of foot length from the pternion. (Kouchi, 2003)
Girths	[13] Ball girth: Circumference of foot, measured with a tape touching the medial margin of the head of the 1 st metatarsal bone, top of the 1 st metatarsal bone and the lateral margin of the head of the 5 th metatarsal bone

[14] Instep girth: Smallest girth over middle cuneiform prominence (Clarks, 1976)

[15] Long heel girth: The girth from instep point around back heel point. (Chen, 1993; Clarks, 1976)

[16] Short heel girth: Minimum girth around back heel point and dorsal foot surface (Chen, 1993)

[17] Ankle girth: Horizontal girth at the foot and leg intersection

[18] Waist girth: Circumference at the approximate center of the metatarsal, measured in a vertical plane, perpendicular to the brannock axis.

Table 3. Inter-operator and intra-operator reliabilities: intraclass correlation coefficients (ICCs)

Foot Measurements	Inter-operator	Intra-operator reliability ^c	
	reliability ^b	ICC(2, 1)	
	ICC(2, 1) ^a	Operator 1	Operator 2
Lengths			
Foot length	1.000	0.998	0.997
Arch length	0.994	0.994	0.986
Heel to medial malleolus	0.978	0.976	0.966
Heel to lateral malleolus	0.920	0.841	0.943
Heel to 5 th toe	0.999	0.995	0.998
Widths			
Foot width	0.988	0.992	0.978
Heel width	0.992	0.975	0.992
Bimalleolar width	0.978	0.989	0.988
Mid-foot width	0.978	0.992	0.986
Heights			
Medial malleolus height	0.981	0.986	0.974
Lateral malleolus height	0.992	0.986	0.996
Height at 50% foot length	0.997	0.994	0.994
Girths			
Ball girth	0.995	0.991	0.991
Instep girth	0.995	0.990	0.992
Long heel girth	0.989	0.993	0.994
Short heel girth	0.980	0.932	0.995
Ankle girth	0.991	0.993	0.988
Waist girth	0.992	0.996	0.994

^a ICC (2, 1) was used in our study, since all foot measurements were measured by the same operators, and they were assumed to be a random subset of all possible operators (Shrout and Fleiss, 1979);

^b Inter-operator reliability was calculated from the mean of the two trials of operator 1 and operator 2;

^c Intra-operator reliability was calculated for each operator respectively and used two trials data for each operator.

Table 4. Descriptive statistics of all 18 measurements obtained from the three methods, MM, SM and CP for the Training data set (N=10). All measurements in mm

Foot Measurement	Mean			Max			Min			Std. dev.		
	MM	SM	CP	MM	SM	CP	MM	SM	CP	MM	SM	CP
Foot length	250.6	250.2	249.3	274	273	271	231	231	230	12.7	13.1	13.3
Arch length	183.3	183.5	181.1	198	197	195	164	164	162	9.7	9.7	9.7
Heel to medial malleolus	61.4	61.7	59.3	71	73	70	51	53	51	5.8	6.3	5.8
Heel to lateral malleolus	53.0	52.3	54.0	60	60	62	43	43	45	4.9	4.9	5.3
Foot width	97.2	96.2	95.8	106	105	107	87	87	88	6.1	5.8	6.0
Medial malleolus height	76.6	76.9	77.0	87	87	87	69	70	69	4.7	4.9	4.9
Lateral malleolus height	65.7	65.2	65.4	75	74	74	54	55	55	6.2	5.6	5.7
Ball girth	239.5	235.1	235.9	263	255	256	219	219	220	13.2	12.4	12.8
Instep girth	247.5	242.8	245.2	277	263	272	222	215	221	15.0	15.7	16.3
Short heel girth	314.5	311.3	313.6	350	346	348	289	290	294	17.4	17.3	17.6
Heel to 5 th toe	202.6	202.7	***	222	222	***	191	192	***	9.6	9.4	***
Heel width	65.4	63.9	***	75	73	***	59	58	***	4.2	4.1	***
Bimalleolar width	68.5	67.4	***	78	75	***	61	60	***	4.7	4.6	***
Mid-foot width	91.6	90.2	***	104	101	***	80	80	***	6.7	6.4	***
Height at 50% foot length	60.6	62.6	***	70	72	***	51	53	***	4.8	4.9	***
Long heel girth	336.4	336.2	***	371	378	***	311	304	***	17.4	20.7	***
Ankle girth	248.7	242.6	***	275	262	***	229	226	***	13.5	12.3	***
Waist girth	239.1	238.0	***	260	259	***	216	215	***	14.0	14.0	***

*** Not available in CP

Table 5. Descriptive statistics of all 18 measurements obtained from the three methods, MM, SM and CP for the Test data set (N=10). All measurements in mm

Foot Measurement	Mean			Max			Min			Std. dev.		
	MM	SM	CP	MM	SM	CP	MM	SM	CP	MM	SM	CP
Foot length	246.7	246.2	245.1	271	269	268	226	226	226	12.3	12.6	12.5
Arch length	179.3	179.3	176.7	197	196	195	164	164	163	9.5	9.4	9.3
Heel to medial malleolus	59.3	60.0	57.5	69	70	68	47	49	48	6.3	6.9	6.5
Heel to lateral malleolus	51.0	51.0	52.8	61	59	61	39	41	44	5.8	5.4	5.5
Foot width	96.4	95.3	94.9	108	107	108	84	82	82	7.4	7.9	8.8
Medial malleolus height	73.2	73.6	73.6	81	80	81	63	65	65	5.4	5.3	5.8
Lateral malleolus height	61.8	61.2	61.2	75	75	75	52	51	51	6.7	7.1	7.5
Ball girth	236.3	232.1	232.2	269	261	262	207	203	204	18.8	19.0	19.7
Instep girth	239.1	233.1	235.5	273	275	274	209	202	209	18.9	19.8	21.8
Short heel girth	307.5	305.3	307.1	337	338	338	279	279	281	19.2	19.7	19.9
Heel to 5 th toe	199.7	198.9	***	212	214	***	179	179	***	10.5	11.3	***
Heel width	63.5	61.5	***	72	70	***	57	55	***	4.0	4.1	***
Bimalleolar width	67.1	65.6	***	78	75	***	61	60	***	5.3	5.7	***
Mid-foot width	88.5	86.7	***	105	103	***	73	72	***	9.5	9.5	***
Height at 50% foot length	58.6	60.5	***	67	67	***	49	52	***	5.6	5.5	***
Long heel girth	327.3	326.2	***	356	357	***	302	288	***	17.8	22.3	***
Ankle girth	245.1	239.8	***	275	276	***	216	215	***	17.3	19.5	***
Waist girth	231.4	230.3	***	270	271	***	203	201	***	20.9	22.6	***

*** Not available in CP

Table 6. ANOVA and post-hoc Student-Newman-Keuls (SNK) tests for comparing three measurement methods ($\overline{MM}$, SM, CP) on 10 common measurements of training data set

Common foot measurements	Measurement method effect (P-value)	†SNK grouping of measurement method		
Foot length	<0.0001*	$\overline{MM}$	250.6	A
		SM	250.2	A
		CP	249.3	B
Arch length	<0.0001*	$\overline{MM}$	183.3	A
		SM	183.5	A
		CP	181.1	B
Heel to medial malleolus	<0.0001*	$\overline{MM}$	61.4	A
		SM	61.7	A
		CP	59.3	B
Heel to lateral malleolus	<0.0001*	$\overline{MM}$	53.0	A
		SM	52.3	B
		CP	54.0	C
Foot width	0.0252*	$\overline{MM}$	97.2	A
		SM	96.2	B
		CP	95.8	B
Medial malleolus height	0.4418	$\overline{MM}$	76.6	A
		SM	76.9	A
		CP	77.0	A
Lateral malleolus height	0.4607	$\overline{MM}$	65.7	A
		SM	65.2	A
		CP	65.4	A
Ball girth	<0.0001*	$\overline{MM}$	239.5	A
		SM	235.1	B
		CP	235.9	B
Instep girth	0.0263*	$\overline{MM}$	247.5	A
		SM	242.8	B
		CP	245.2	A B
Short heel girth	<0.0001*	$\overline{MM}$	314.5	A
		SM	311.3	B
		CP	313.6	A

† Means with the same letter (at right side of each cell) are not significantly different;

* P<0.05.

Table 7. Differences between computerized measurement (SM, CP) and manual measurement ($\overline{MM}$) of the 10 common measurements in training data set

Common foot measurements	Differences	Mean	Maximum	Minimum	Std. dev.
Foot length	SM- $\overline{MM}$	-0.32	0.52	-1.09	0.63
	CP- $\overline{MM}$	-1.30	0.25	-2.55	0.84
Arch length	SM- $\overline{MM}$	0.23	1.88	-2.21	1.20
	CP- $\overline{MM}$	-2.15	0.70	-5.30	1.80
Heel to medial malleolus	SM- $\overline{MM}$	0.24	3.67	-1.68	1.59
	CP- $\overline{MM}$	-2.09	1.05	-4.60	1.66
Heel to lateral malleolus	SM- $\overline{MM}$	-0.72	0.86	-3.64	1.20
	CP- $\overline{MM}$	0.95	2.80	-1.55	1.23
Foot width	SM- $\overline{MM}$	-0.92	0.56	-3.41	1.21
	CP- $\overline{MM}$	-1.31	1.85	-3.20	1.60
Malleolus height (Medial)	SM- $\overline{MM}$	0.24	1.68	-1.50	0.90
	CP- $\overline{MM}$	0.35	1.60	-0.60	0.74
Malleolus height (Lateral)	SM- $\overline{MM}$	-0.50	1.16	-2.85	1.27
	CP- $\overline{MM}$	-0.24	1.90	-2.75	1.49
Ball girth	SM- $\overline{MM}$	-4.39	-1.69	-8.21	1.96
	CP- $\overline{MM}$	-3.59	-1.10	-6.50	1.72
Instep girth	SM- $\overline{MM}$	-4.70	3.08	-12.34	5.02
	CP- $\overline{MM}$	-2.29	3.65	-7.95	3.17
Short heel girth	SM- $\overline{MM}$	-3.15	-0.20	-7.51	2.16
	CP- $\overline{MM}$	-0.84	1.35	-4.55	1.87

Table 8. Paired t-test results of differences ($SM - \overline{MM}$) of the 8 other measurements in training data set.

Foot measurements	Mean	Max	Min	Std. dev.	P Value (H0: Mean=0)
Heel to 5 th toe	0.12	1.81	-3.92	1.71	0.8328
Heel width	-0.92	0.56	-3.41	1.21	<0.0001 [*]
Bimalleolar width	-1.08	-0.04	-2.15	0.66	0.0006 [*]
Mid-foot width	-1.37	-0.46	-2.30	0.64	<0.0001 [*]
Height at 50% foot length	2.00	3.09	1.28	0.53	<0.0001 [*]
Long heel girth	-0.22	10.78	-7.99	7.03	0.9227
Ankle girth	-6.09	-3.61	-10.59	2.52	<0.0001 [*]
Waist girth	-1.09	2.93	-4.32	2.32	0.1723

^{*} P<0.05

Table 9. Linear regression $SM = a * \overline{MM} + b$ and the hypothesis test of $a=1$ for measurements that had significant differences between SM and $\overline{MM}$ in the training data set. (All measurements in mm)

Foot measurements	Linear regression equation ($SM = a * \overline{MM} + b$)	R^2	p Value ($H_0: a=1$)
Lengths			
Heel to lateral malleolus	$SM = 1.0094 * \overline{MM} - 1.222$	0.9428	0.9195
Widths			
Foot width	$SM = 0.9333 * \overline{MM} + 5.5601$	0.9643	0.3231
Heel width	$SM = 0.9823 * \overline{MM} - 0.3071$	0.991	0.6095
Bimalleolar width	$SM = 0.9642 * \overline{MM} + 1.3662$	0.9815	0.4645
Mid-foot width	$SM = 0.9480 * \overline{MM} + 3.3884$	0.9934	0.0918
Heights			
Height at 50% foot length	$SM = 1.0082 * \overline{MM} + 1.507$	0.9888	0.8400
Girths			
Ball girth	$SM = 0.9205 * \overline{MM} + 14.653$	0.9835	0.0955
Instep girth	$SM = 0.9875 * \overline{MM} - 1.6$	0.9034	0.9155
Short heel girth	$SM = 0.9876 * \overline{MM} + 0.7566$	0.9853	0.7789
Ankle girth	$SM = 0.8929 * \overline{MM} + 20.559$	0.9741	0.0710

Table 10. Linear regression $SM = \overline{MM} + b$ for those measurements that had significant differences between SM, $\overline{MM}$ of training data set. (All measurements in mm)

Foot measurements	Linear regression equation ($SM = \overline{MM} + b$)	R^2
Lengths		
Heel to lateral malleolus	$SM = \overline{MM} - 0.720$	0.9427
Widths		
Foot width	$SM = \overline{MM} - 0.94$	0.9594
Heel width	$SM = \overline{MM} - 1.465$	0.9906
Bimalleolar width	$SM = \overline{MM} - 1.095$	0.9802
Mid-foot width	$SM = \overline{MM} - 1.400$	0.9904
Heights		
Height at 50% foot length	$SM = \overline{MM} + 2.005$	0.9887
Girths		
Ball girth	$SM = \overline{MM} - 4.450$	0.9762
Instep girth	$SM = \overline{MM} - 4.700$	0.9032
Short heel girth	$SM = \overline{MM} - 3.150$	0.9852
Ankle girth	$SM = \overline{MM} - 6.160$	0.9600

Table 11. ANOVA and post-hoc Student-Newman-Keuls (SNK) tests for comparing the three measurement methods ($\overline{MM}$, adjusted SM[‡], CP) on 10 common measurements of test data set

Common foot measurements	Measurement method effect (P-value)	[†] SNK grouping Of measurement method		
Foot length	0.0001 [*]	$\overline{MM}$	246.7	A
		SM	246.2	A
		CP	245.1	B
Arch length	<0.0001 [*]	$\overline{MM}$	179.3	A
		SM	179.4	A
		CP	176.7	B
Heel to medial malleolus	<0.0001 [*]	$\overline{MM}$	59.3	A
		SM	60.0	A
		CP	57.5	B
Heel to lateral malleolus	0.0002 [*]	$\overline{MM}$	51.0	A
		Adjusted SM	51.7	A
		CP	52.8	B
Foot width	0.0078 [*]	$\overline{MM}$	96.4	A
		Adjusted SM	96.2	A
		CP	94.9	B
Medial malleolus height	0.2356	$\overline{MM}$	73.2	A
		SM	73.6	A
		CP	73.6	A
Lateral malleolus height	0.4110	$\overline{MM}$	61.8	A
		SM	61.2	A
		CP	61.2	A
Ball girth	<0.0001 [*]	$\overline{MM}$	236.3	A
		Adjusted SM	236.6	A
		CP	232.2	B
Instep girth	0.1513	$\overline{MM}$	239.1	A
		Adjusted SM	237.9	A
		CP	235.5	A
Short heel girth	0.0340 [*]	$\overline{MM}$	307.5	A B
		Adjusted SM	308.4	A
		CP	307.1	B

[‡] Original SM data was adjusted on heel to lateral malleolus, foot width, ball girth, instep girth and short heel girth;

[†] Means with the same letter are not significantly different;

^{*} P<0.05.

Table 12. Paired t-test results of difference (adjusted SM[‡]- $\overline{MM}$) on all 18 foot measurements of test data set

Foot measurements	Mean	Maximum	Minimum	Std. dev.	P Value (H0: Mean=0)
Lengths					
Foot length	-0.44	0.92	-1.38	0.74	0.0922
Arch length	0.11	2.38	-0.77	0.87	0.7100
Heel to medial malleolus	0.69	2.61	-1.31	1.16	0.0950
Heel to lateral malleolus	0.73	2.69	-1.54	1.27	0.1042
Heel to 5 th toe	-0.84	1.84	-5.12	2.42	0.3034
Widths					
Foot width	-0.19	1.10	-1.36	0.94	0.5332
Heel width	-0.51	0.13	-1.65	0.52	0.0123*
Bimalleolar width	-0.37	0.55	-1.67	0.70	0.1329
Mid-foot width	-0.38	0.34	-1.37	0.58	0.0678
Heights					
Medial malleolus height	0.42	2.58	-0.94	0.99	0.2142
Lateral malleolus height	-0.57	1.02	-3.32	1.31	0.1996
Height at 50% foot length	-0.12	0.38	-1.04	0.48	0.4418
Girths					
Ball girth	0.27	1.31	-0.93	0.76	0.2860
Instep girth	-1.13	7.78	-13.99	6.79	0.6107
Long heel girth	-1.20	11.43	-18.71	9.98	0.7125
Short heel girth	0.97	3.49	-1.67	1.85	0.1327
Ankle girth	0.85	7.73	-3.19	3.27	0.4350
Waist girth	-1.07	2.49	-4.07	2.06	0.1338

[‡] Only measurements showing significant differences (listed in table 10) between original SM and MM were adjusted;

*P<0.05.