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USE OF 3D SCANNER AND PHOTOGRAMMETRY METHOD FOR SCANNING FOOT DEFORMITIES: CAD DATA ANALYSIS OF MORPHOLOGY AND SHAPE OF GEOMETRY

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ABSTRACT

Orthotic footwear requires a comfortable design to solve biomechanical foot issues such as walking, standing or running of the patients. In this case, the accurate geometrical data are needed by applying a 3D scanner. However, geometrical deviations of the final product may be often found in the manufacturing process related to the system or changing the CAD data format. The purpose of this research was to investigate the effect of the data transfer process on the geometry and morphology of the foot scanning results. Firstly, variations in data format from the patient's foot were obtained using 3D scanning with Handyscan 700 scanner, Einscan Pro 2X Plus, ScanPod 3D and photogrammetry method with a Canon EOS 500D camera. The second step involved the data transfer to the CAD modeller using Solidworks software. The results showed that the geometry and morphology of the scans from each scanner were indifferent and the variation of CAD data formats did not affect the geometry and morphology. In CAD software, the very large CAD data format is IGES, the result of a Handyscan 700 scanner with a file size of 38,864 KB. The smallest data format is the STL on the ScanPod 3D scan results of 671 KB.

Keywords: 3D scanner, photogrammetry, foot scan, CAD data format.

INTRODUCTION

Measurements of foot dimension play a significant role in providing accurate data for conformity evaluation and clinical applications (Hawes and Sovak, 1994; Wang, 2010; Witana et al., 2004). Moreover, these accuracy data corresponding to sizes of footwear is required to be incompatible with a person's foot characteristics, in order to avoid the risk associated with lower extremity musculoskeletal problems including deformity and foot pain (Menz and Morris, 2005). Accordingly, designing of footwear using dimensional information and foot size data points would improve shoe compatibility (Au and Goonetilleke, 2007; Menz and Morris, 2005). In this case, quantitative descriptions of 3D-foot geometry are essential for a number of different purposes such as designs of ergonomic footwear, foot orthotics insoles, and for research and clinical assessment of foot abnormalities, such as those related to rheumatoid arthritis (Chen *et al.*, 2003; Luximon and Goonetilleke, 2004; Payne, 2007; De Mits *et al.*, 2009). Thus, various measurement methods have been applied to collect data on foot characteristics such as foot shape, dimensions, and plantar contours. The most familiar methods may include direct measurements by using digital calipers, 3D scanning, and indirect footprint measurements and analysis.

Recently, 3D scanning methods have a significant contribution to the improvement of designing customized products, namely devices and kit designed for individuals using accurate anthropometric measurements (Istook and Hwang, 2001; Zhao *et al.*, 2008). The 3D scanning techniques have an important role to produce digital representations of parts of human anatomy and provide the possibility to conduct modification of the dimension for a wide range of products before being manufactured. Therefore the 3D scanning data have more complete information about body contours, and subsequently, it can be used to gain insights into alterations in anthropometric measurements connected with dynamic motion. Additionally, 3D foot scanning provides advantages with a large number of foot participants that can be scanned briefly, whilst their measurements are robust and efficient (Telfer and Woodburn, 2010).

At present, the use of 3D scanners for providing relevant geometrical data is very common to shoe designers. Specifically, 3D scanning data can be used for the analysis of the differences in male and female feet showing that the male has feet longer and wider than those of females (Luo *et al.*, 2009). These measuring results are also in agreement with data published in previous literature data when measurements were performed manually (Wunderlich and Cavanagh, 2011). Chen *et al* (2003) employed a 3D scanner to assess the angle of the forefoot versus in individuals with flexible flatfoot, showed that a "fast and accurate" measurement technique was obtained. Pfeiffer *et al.* (2006) used 3D scanning to examine the flatfoot prevalence in a group of 835 children. In this work, age, gender, and weight were the key factors influencing on flat foot development. Also, a study conducted by Krauss *et al.*, (2011) utilised the resulting data from the 3D scanning process to categorize feet into various types: voluminous, flat pointed and slender. Similarly, a study by the same group conducted foot scans of 2867 children and verified the results of their feet belonging to three-foot types (Mauch *et al.*, 2009).

In particular, the 3D scanning data can be used for making orthotics insole of patients with diabetes (Anggoro *et al*., 2018). In this way, the 3D scanning data are converted into a CAD model which is acquired as a 3-dimensional point cloud data for the making of insoles and shoe soles. But the application of a 3D scanner in providing the accurate geometric model is apparently very challenging. For making orthotic shoes for diabetic patients, the shape and size of the CAD model come indifference of the final product obtained with a CNC machining. The different sizes and shapes in point cloud or mesh data may be related to the data acquisition of scan processing, such as smoothing, whilst CNC machining of the product relies only on those data, yielding manufacturing products with tolerances or unfit size of the shoe (Anggoro *et al*., 2017; 2018).

Further deviations in size caused by the manufacturing process may be found generally due to the transfer of CAD data from one system to another leading to change in the CAD data format. Switching from one to another system and changing CAD data format may change in the type of geometry and increase or decrease in file size. These changes make certainly influence a product entering the manufacturing process. Here a good product data management is required to solve the problem of 3D scanners and CAD data that move from one system to another. Accordingly, this topic has become a great concern of research recently; therefore many computational methods have been developed to make portions of the geometry of a product with significant features. However, only limited components within a restricted geometric domain (such as polyhedral components) can be solved. The purpose of this study was to use a scanner to acquire foot modelling that can produce a precise and accurate morphology (shape) and CAD geometry in accordance with the foot shape. In addition to using a scanner, a photogrammetric method was also implemented to take 3-dimensional modelling of human feet. CAD data exchange by varying CAD format data was also done to find a fit CAD data format.

METHODOLOGY

In this study, two stages of research, namely the stage of taking a data scan and the stage of processing data in CAD software were performed. Here a 3D foot scanners (Handyscan 700, Einscan Pro 2X Plus, ScanPod 3D, and DSLR Cameras on the Photogrammetry Method) were used to collect the foot dimensions. Since photogrammetry is suitable for 3D reconstruction of anatomical parts, as long as these can hold still during the whole image acquisition process, photogrammetry could be used to scan patient foot. Correspondingly, a comfortable position for the patient must be found to ensure that the part remains in the same position throughout the process. In this way, their right feet of the participants were firstly washed and the dried with tissue paper before taking measurements. Subsequently, the number of meshes and the size of the scan files were taken to be analyzed and smoothed before transferring to CAD software. The scanning data on each of the four scanners were stored in five types of data format variations, namely IGES (.igs/.iges), STEP (.stp/.step), ACIS (.sat), Parasolid (.x_t), and Stereolithography (.stl). These data including morphology, the geometry of the feet and file size were processed in CAD software.

Morphological Generation in CAD Software

The foot scanning data on each scanner can be retrieved in a different way, whilst the morphological processing of the scanning results can do in the same way. The position of taking the geometry of the foot for each scanner was selected by placing the foot in a straight line held by the pad. The scan resulting from each scanner were allowed to generate 2D or 3D digital models of a surface to reduce the risk in changes of the geometry of the scanned foot. The scanning results were processed first using Auto Desk Meshmixer, before moving the scan results to the CAD software (Solidworks 2017). In this software, the model was changed in the form of solid and the mesh data were refined (smoothing) by reducing the mesh density by 75 with a solid type "Accurate". Illustration of taking the foot shape scan data from each scanner and the photogrammetric method is shown in Figure-1.

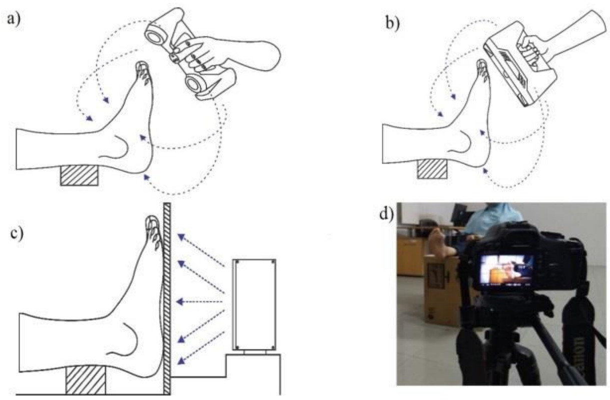

Figure-1. Illustration of foot shape morphology taking with a scanner (a) Handyscan 700, (b) EinScan Pro 2X Plus, (c) ScanPod 3D, and Photogrammetry method with (d) Canon 500D DSLR Camera.

Geometrical Measurements in CAD Software

Geometrical measurement in CAD software was performed by measuring from one point (vertex) to another point (vertex). Subsequently, the center point was determined for measuring geometry required in the Solidworks 2017 software. In this study, the center point according to the instructions of I-Ware Laboratory (2017) was determined from the midpoint between the tibial metatarsal and fibular metatarsal and the foot axis with the extreme heel point to the head of the second metatarsal bone or the extreme heel point. The measurement point for the analysis of the geometry of the scan results with the Handyscan 700 scanner is presented in Figure-2, showing that there are points A1 to A7 and the midpoint/center point (CP).

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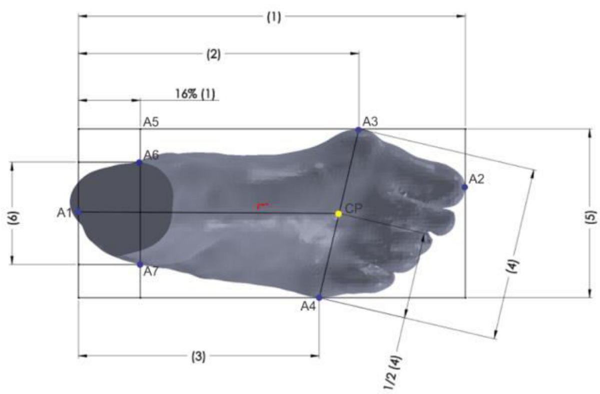

Figure-2. Point and dimensional measurements of foot scanning results with a Handyscan 700 scanner.

The results of the scan with the Handyscan 700 scanner included measurements of foot length (1), tibial instep length (2), fibular instep length (3) and diagonal feet (4), while foot width is a measurement from point A3 to A4 parallel to the vertical axis. The measurement of heel width was carried out from 16% foot length (1), or from points A1 to A5. After determining 16% of foot length (1), the width of the heel was determined by measuring from points A6 to A7. These measurement steps were also applied to the same to other types of scanners.

CAD Data Transfer Process

There are two steps to exchange CAD data, namely change in the variation of format types and transferring CAD data to Solidworks 2017 again. These two stages are focused on knowing the file size and data format capability when opened back to the original software (interoperability). Analysis of the effect of changes in CAD data format on file size and interoperability was done by indirect translation. The first step involved changing, varying, or saving CAD (Solidworks Part) data formats, respectively to IGES (.igs), STEP (.stp), ACIS (.sat), Parasolid (.x_t), and Stereolithography (.stl). Then all types of CAD data formats were reopened to Solidworks 2017 software.

RESULTS AND DISCUSSIONS

Morphological Analysis

The results of scanning from each scan tool with the data format .stl is shown in Figure-3. It can be seen that the results of scanning with the Handyscan 700 scanner have the sharpness and accuracy in taking the object of the respondent's right foot very well. In this type of scanner, transferring data from .stl into Solidworks 2017 software in the form of surfaces results in 86, 244 faces. The data is processed and simplified in the AutoDesk Meshmixer software into a solid form by reducing the mesh density to 75, so that the number of mesh is reduced to 21,058 faces. The scanned data will be varied again in the form of .stl file which produces a mesh of 19,636 faces. The foot morphology results made with the Handyscan 700 scanner have the same foot shape as the respondent's foot shape. But the results of the scans of the middle finger to the little finger on the foot merge into one form. Scans using this scanner have detailed shapes on the instep of the foot and sole of the foot.

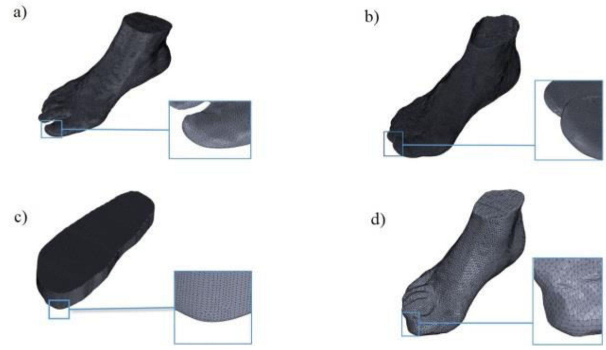

Figure-3. Scan resulting from the scanner (a) Handyscan 700, (b) EinScan Pro 2X Plus, (c) ScanPod 3D, and (d) Photogrammetric method.

Similar to the Handyscan 700, the scanning results with the Einscan Pro 2X Plus scanner also have excellent sharpness and accuracy. In this type of scan, transferring data from .stl into Solidworks 2017 software in the form of surfaces produces with 160,545 faces were divided into small parts (mesh). Data were then processed and simplified into solid parts with a mesh density of 75, so the number of meshes became 19,496 faces. The scanned data were altered again in the form of STL resulting in a net of 17,574 fonts. The foot morphology results made by the Einscan Pro 2X Plus scanner have a foot shape similar to the foot shape of the respondent. The resulting data using this scanner included on the entire toe together and having detailed shapes on the instep of the foot, sole of the foot, heel and the shape of the toes.

The next scanning process used a ScanPod 3D type scanner with good scanning results. In this type of scan, transferring data from .stl into Solidworks 2017 software in the form of surface results having 27,734 faces. The data were finally processed and simplified in the AutoDesk Meshmixer software into a solid form by reducing the mesh density to 75 so that the number of mesh reduced to 15,211 faces. The scanned data were also modified again in the form of STL yielding the mesh of 13,730 faces. Here the foot morphology results made by the ScanPod3D scanner provided only form the soles of the respondents' feet. In this scanning results, the fingers and instep could be not formed in detail.

Further scanning results with the Photogrammetry method provided the sharpness and accuracy of the final object quite well. In this type of scan, transferring data from .stl into Solidworks 2017 software in the form of surfaces produced 118,431 faces which were divided into small parts (mesh). When data were processed and simplified into solid parts with a mesh density of 75, the number of meshes reduced to 20,592 faces. The scanned data were altered again in the form of .stl resulting in the mesh of 18,790 faces. Significantly,

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the morphological results of the feet using the photogrammetric method were quite similar to those of the respondent's feet. In this scan result, the toes were joined together, but the heel of the foot was not formed properly for heel curvature.

Geometrical Analysis Results in CAD Software

The results of the foot geometrical scan using the Handyscan 700 scanner are shown in Figure-4. The comparison of the measurement results of the Handyscan 700 of each CAD data format in the 2017 solid work software provided indifferent geometry. This is because each of the five data may cause insignificant different sizes. For instance, measuring foot length (1) was obtained to be 215.57 mm, tibial instep length (2) was 156.33 mm, fibular instep length (3) was obtained 134.19 mm, instep diagonal width (4) was 96.93 mm, the horizontal width (5) is 94.37 mm, and the heel width (6) was 57.18 mm.

Likewise, the geometrical scanning results using the Einscan Pro 2x Plus scanner have the indifferent measurement results as shown in Figure-5. Apparently, the results of the EinScan Pro2XPlus scans were measured in Solidworks 2017 software providing the indifference in geometries for each of the five data format variations. Here the obtained measuring foot length (1) was 215.95 mm, tibial instep length (2) was 159.98 mm, fibular instep length (3) obtained 135.19 mm, instep diagonal width (4) was 97.43 mm, the horizontal width (5) is 94.35 mm, and heel width (6) is 57.44 mm, respectively.

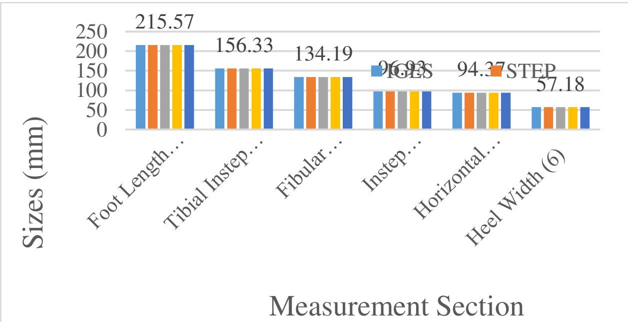

Figure-4. Comparison results of the Handyscsan 700 measurements.

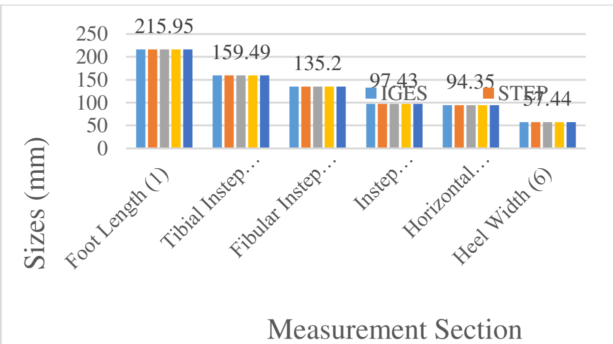

Figure-5. Comparison results of the Einscan Pro 2X Plus measurements for each CAD data format in Solidworks 2017 software.

Further results of the scanning foot geometry using the ScanPod 3D scanner are presented in Figure 6. Obviously, scanning results by the ScanPod 3D were then measured in Solidworks 2017 software, yielded no different geometries for each of the five data format variations. Here the obtained measuring foot length (1) was 215.37 mm, including tibial instep length (2) of 139.55 mm, fibular instep length (3) of 143.10 mm, instep diagonal width (4) of 84.98 mm, the horizontal width (5) of 84.90 mm, and the heel width (6) was 57.15 mm.

The results of the foot geometry scanned using the photogrammetric method have also the measurement results (Figure-7). The results of the photogrammetric method measured in the 2017 Solidworks software have no different geometries for each of the five data format variations, on which the obtained measuring foot length (1) was 215.86 mm, followed by tibial instep length (2) of 155.52 mm, fibular instep length (3) of 134.36 mm, instep diagonal width (4) of 97.37 mm, the horizontal width (5) of 95.05 mm, and the heel width (6) of 57.04 mm.

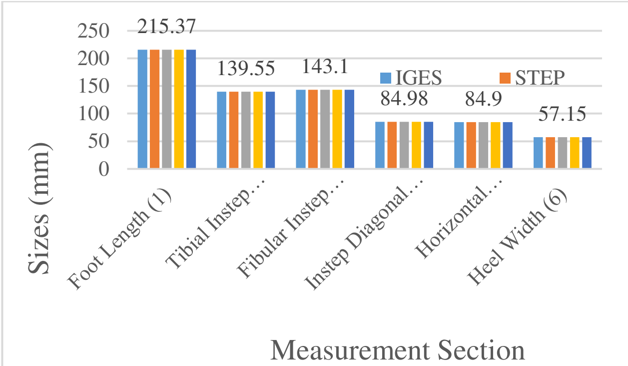

Figure-6. Comparison results of the ScanPod 3D measurements for each CAD data format in Solidworks 2017 software.

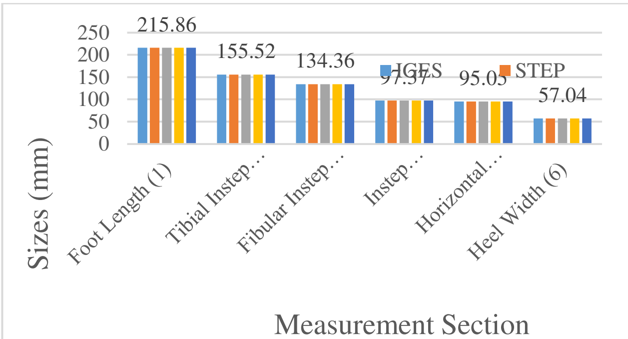

Figure-7. Comparison results of the photogrammetric measurements for each CAD data format in Solidworks 2017 software.

Analysis of Data Transfer in CAD Software

Data transfer analysis in this study included the geometry imported into Solidworks 2017, the size of files produced by each data format, and file capabilities when reopened in Solidworks 2017 software. From the results of data transfer, it can be seen that the five data formats can

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be opened back in Solidworks 2017 software for all scanning processes. The comparison of CAD data file sizes for each scan type is shown in Figure-8.

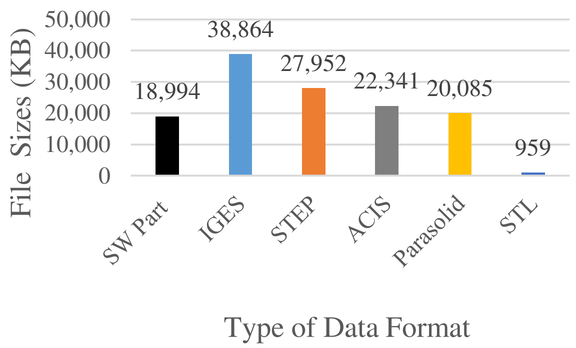

Figure-8. Comparison of CAD data file sizes for each CAD data format in Solidworks 2017 software from the results of the scan process with Handyscan 700.

It can be seen that in the scanning process using Handyscan 700, the largest file size is IGES (.iges) with a file size of 38,864 KB, while the smallest file size is STL (.stl) with a file size of 959 KB. In the process of scanning with Einscan Pro 2X Plus (Figure 9), the largest file size is IGES (.iges) with a file size of 34,739 KB, while the smallest file size is STL (.stl) with a file size of 859 KB. As for the scan process with ScanPod 3D (Figure 10) the smallest file size is owned by CAD data with data format that is STL (.stl) with a file size of 671 KB and the largest with IGES data format (.iges) with a file size of 25,858 KB. Furthermore, the results of the photogrammetric scan method (Figure 11) produced a CAD data format with the smallest file size of 918 KB in the STL data format (.stl) and the largest in the IGES data format (.iges) with a file size of 37,094 KB.

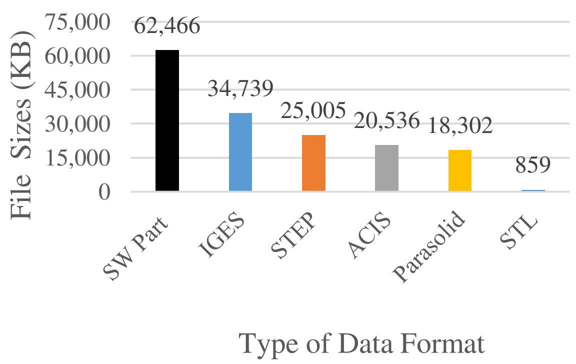

Figure-9. Comparison of CAD data file sizes for each CAD data format in Solidworks 2017 software from the results of the scan process with EinScan Pro 2X Plus.

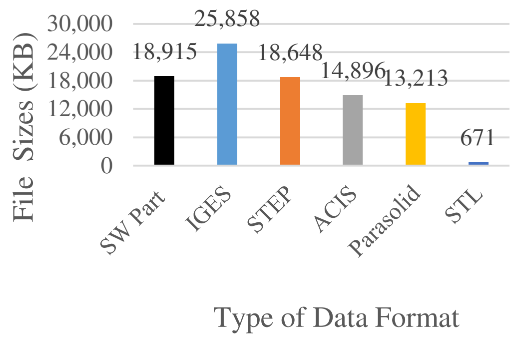

Figure-10. Comparison of CAD data file sizes for each CAD data format in Solidworks 2017 software from the results of the scan process with ScanPod 3D.

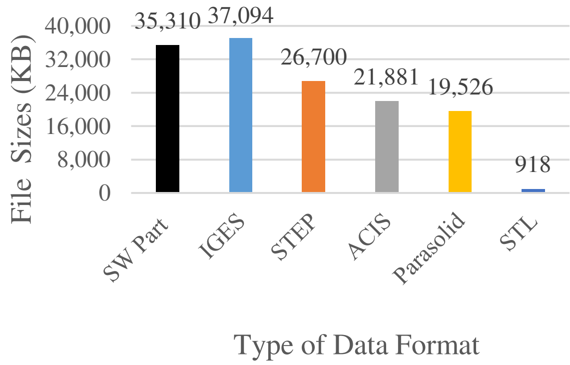

Figure-11. Comparison of CAD data file sizes for each CAD data format in Solidworks 2017 software from the results of the scan process with photogrammetric method.

Further, this work has demonstrated that the making customized shoes have complicated in nature and flexibility with other manufacturing sectors, while the medical industry has been developing and changing in an efficient way with the new digital technological era. It can be confirmed through the literature review that the shift to advanced technology could relate to the need for fast and efficient manufacturing products. Moreover, digital technology have made possibly manufacturing customized shoes on a fast and accurate basis which has transformed from the traditional shoemaking approach. Driven by patient demand, the fast delivery phenomena and the improved final product have become a great concern to do intensive research for reducing the production time (Anggoro *et al.*, 2017; 2018).

Traditionally, the customized shoe product development route is labor and time-intensive often resulting in an inaccurate size of final shoe product for each style. The use of advanced technology to decrease the shoe development time would have a significant impact on the delivery time to market (Mauch *et al.*, 2009). Here CAD has been suggested to be the accepted norm which can change from 2D to 3D foot wear design (Telfer and Woodburn, 2010). However, modeling customized shoes appeared to be hampered by two factors, the accurate computer representation of the foot structure, and the realistic simulation of the shoe model. Correspondingly, a significant innovation in computational power and hardware performance technology promoted the progression of 3D CAD systems which are specifically aimed at the customized shoe industry. Even 3D CAD systems from the 3D to the 2D concept has been investigated and developed, the commercial companies are favorable with the 2D to the 3D approach of the current product development process (Witana et al., 2004).

Furthermore, 3D scanning technology has contributed to the theory and a better understanding of factors regarding foot structure measurement and categorization (Wang, 2010). Their reliability, precision, and speed continue to optimize activities relating to acquisition and digitization of foot measurement data, and virtual shoe simulation. However, the precise generation of shoe models derived from 3D foot scanning only forms a part of the process inadequately assessing fit within the virtual foot environment. It was evident that there are still significant challenges in obtaining the data points of foot size and shape. Therefore there is still further work to be undertaken in the precise modeling of the foot shape and size for the customized shoe production (Istook and Hwang, 2001).

CONCLUSIONS

An accurate foot measurement method with 3D scans was carried out in this study. This method facilitated the analysis of customer's foot size and can be used as basic data for making custom shoes. Several finding of the study can be concluded as follows:

a) Morphological measurement results indicated that almost scanner provided morphological results similar to the respondent's right foot, while the results of the ScanPod 3D scanner can only retrieve data on the surface of the sole of the foot. The use of the photogrammetric method for scanning the foot object provided the imperfect resulting heel part.

b) The scanned CAD data have varying format as IGES (.igs / .iges), ACIS (.sat), STEP (.stp / .step), Parasolid (.x_t), and Stereolithography (.stl). The five CAD data formats have been altered, but there are no morphological and geometric differences from the scan results for each scanner and photogrammetric method. The largest CAD data file size is the type of IGES data format (.iges), and the smallest CAD data file size is Stereolithography (.stl) for each scanner and photogrammetric method.

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