

Fast, Portable and Low-Cost 3D Foot Digitizers: Validity and Reliability of Measurements

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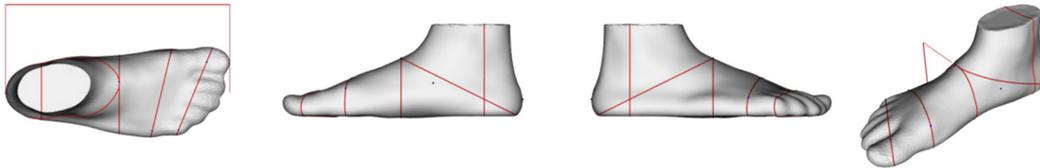


Fig. 1. Examples of digital measurements elicited from a 3D reconstructed foot model using a phone app

Abstract

This paper presents partial results of a larger validation study of two innovative products based on Data-driven 3D Reconstruction (D3DR) technology: a smartphone app, Avatar3D, and a portable booth, DomeScan. This study quantifies the reliability (Standard Error of Measurement, SEM, Intra-class Correlation Coefficient, ICC) of the automatic foot measurements elicited by these solutions and compares it to traditional anthropometry and to a commercial laser foot scanner. Moreover, it assesses the compatibility (systematic bias) of measurements among these techniques. The results show that, for the six measurements assessed, D3DR is as reliable as high resolution 3D scanners and more reliable than manual measurements made by an expert. Due to its lower cost, speed and portability they could be more suitable for retail and home environments than actual 3D scanners.

Keywords: foot scanner, low-cost, data-driven, 3D reconstruction, anthropometry, foot morphology, foot measurements, PCA, accuracy, reliability, SEM, ICC, validity, digital measuring, smartphone app.

1 Introduction

Human body shape and dimensions are useful for ergonomic product design [1,2,3]. Foot dimensions are required for footwear and foot orthotic design [4,5] as well as for the clinical assessment of foot conditions [6,7,8,9]. High accuracy and reliability are indispensable for these purposes.

Historically, the standard method for measuring feet for product design has been traditional anthropometry [10,11,12,13,14,15]. This technique requires a trained measurer and specialized metrology instruments such as calipers for linear measurements (heights, lengths and widths) and digital measuring tape for girths. Its accuracy depends on the skills of the measurer and usually there are systematic biases between measurers [16,17]. In clinical environments, radiographic techniques have been commonly used due to their accuracy in taking linear measurements, however it requires more time and resources and the patients are exposed to ionizing radiation [18].

The release of the first commercial 3D foot scanning solutions in the nineties revolutionized the methods for foot measuring [19,20,21]. Foot scanners can acquire the surface of the foot in 3D accurately and enable to measure it digitally [22]. They facilitated the use of the actual foot shapes, and not just measurements, in digital product design [23,24,25]. Since then, different technologies have been developed to gather the actual 3D shape of feet including laser, structured light, stereophotogrammetry [26] and, more recently, depth sensors [27]. Despite their accuracy, they are too bulky and expensive to be used at retail shops or at home.

More recently, and thanks to the databases created using 3D foot scanners, new foot digitizers based on lower-cost methods such as data-driven 3D reconstructions (D3DR) from a few measurements or 2D images had been developed to estimate the 3D shape of faces [28], feet [29,30,31,32,33,34,35] or bodies [36,37,38,39]. This technology has much lower hardware requirements than actual 3D scanners, which makes it potentially suitable for being deployed in low-cost simple devices for retail shops or even implemented into a smartphone app, making it possible to and have a foot scanner in your pocket.

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In 2015, IBV released two 3D low-cost foot digitizing systems based on D3DR, which have been evolved since then [40]: a smartphone app, Avatar3D^{*} (Fig. 2), and a booth, DomeScan[†] (Fig. 3).



Fig. 2. Avatar3D app

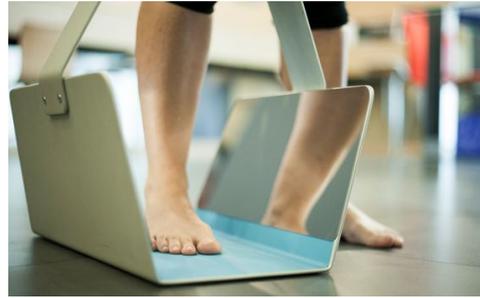


Fig. 3. DomeScan

Avatar3D is a smartphone app that acquires three images (medial, top and lateral, Fig. 4a) of each foot with the rear camera of the smartphone and an A4 or US letter sheet as camera calibration element (Fig. 4a). Images are processed (Fig. 4b) at a remote service that sends back the 3D foot models (Fig. 4c) and a set of measurements in less than 1 minute (Fig. 1). It is conceived to be used at home. A free version of Avatar3D for Android is available on Google Play.

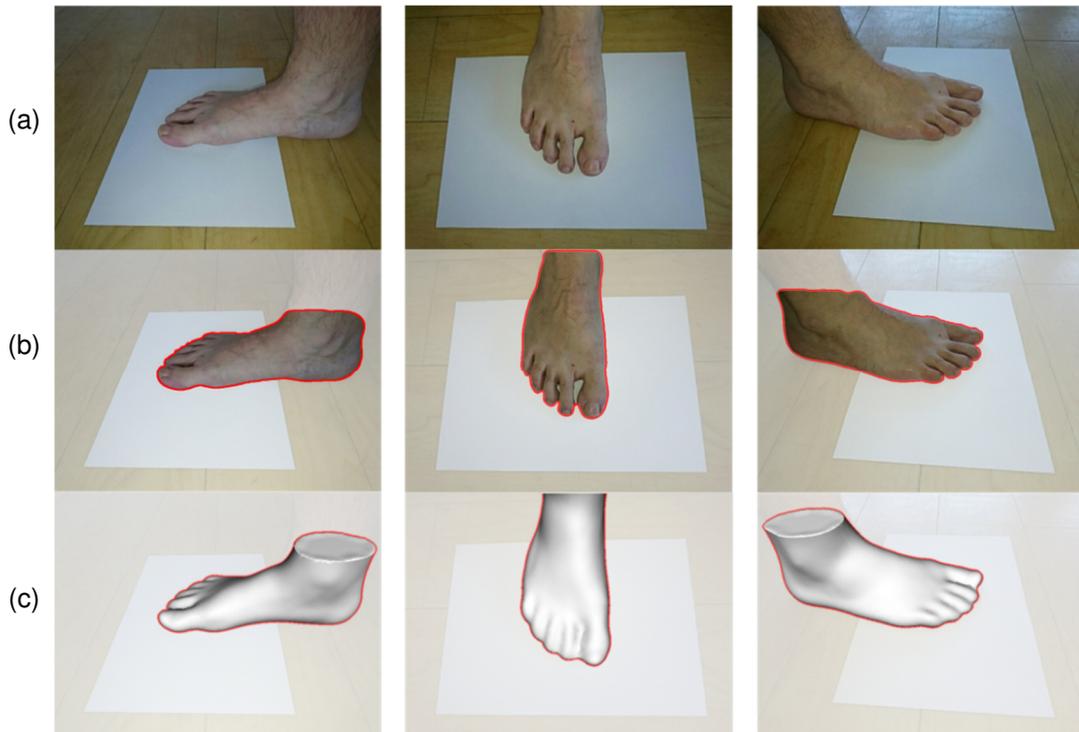


Fig. 4. (a) three foot images (medial, top and lateral) acquired with Avatar3D app, (b) Segmented foot outlines, and (c) 3D foot matching the three segmented outlines.

DomeScan is a small lightweight booth (35x45x45 cm) that consists of an aluminum frame in U shape with a non-reflecting vinyl bottom surface and two mirrors on the sides equipped with a Raspberry Pi, camera, Bluetooth communication and illumination system mounted on a bridge over the frame (Fig. 3). DomeScan just needs a single picture that contains the top, medial and lateral images reflected in the mirrors, which makes it the fastest foot scanner in the market. It scans and measures two feet in less than 1 minute. A Windows application running in a PC with Bluetooth connection is used to manage the hardware and the data gathered. DomeScan is conceived for retail shops, labs or scanning points.

^{*}; Avatar3D: <https://www.youtube.com/watch?v=OVnj6n1-FSI>

[†] DomeScan/IBV: <https://www.youtube.com/watch?v=SfP8FHgQ77M>

The **D3DR process** used consists of five steps (Fig. 6): Image Acquisition, Image Segmentation, Camera Calibration, 3D Reconstruction and Digital Measuring. The technology implementation of the first three steps is slightly different for each system because of the differences in hardware (e.g. smartphone vs booth). Foot measuring algorithms are common for both systems. Both use the same space of human foot shape, which was synthesized by applying Principal Components Analysis (PCA) to a database of more than 700 adult foot scans [41] registered to a common parameterization to achieve point-to-point correspondence across feet [42,34,43]. This PCA-based foot shape space yields a data-driven method to generate arbitrary foot based on 40 parameters (i.e. the first principal components, Fig. 5).

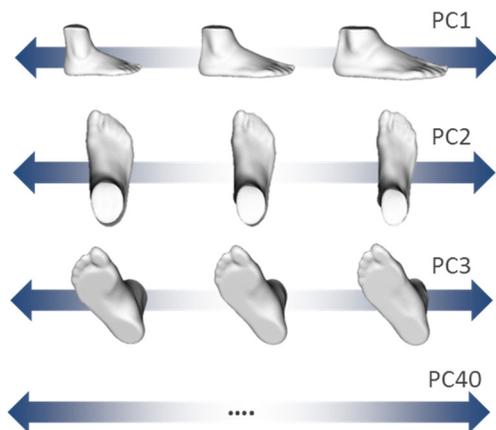


Fig. 5. First 4 Principal Components (PC) of the Foot Shape Space describing different foot shape variations

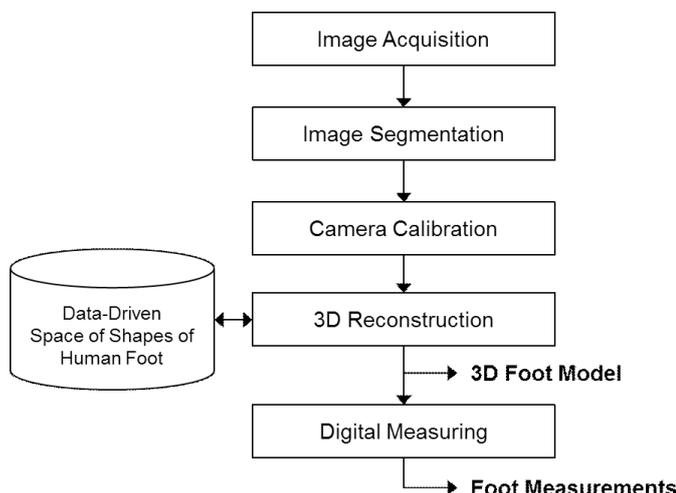


Fig. 6. Data-driven 3D Reconstruction (D3DR) steps

2 Objectives

The three objectives of this paper are: (1) to investigate the reliability of measurements extracted from 3D foot models acquired using two implementations of D3DR technology (i.e. a smartphone app, Avatar3D, and a portable booth, DomeScan); (2) to compare them to the established methods, namely traditional anthropometry and actual 3D foot scanning; and (3) to investigate its validity compared to 3D foot scanning and traditional anthropometry, both used in product design and clinical practice [44,45,46,47,48].

Based on results, this paper discusses the potential of the technologies assessed and their suitability for different product design applications such as personalization and size selection of footwear and orthotics. This paper focuses only on measurement reliability of healthy foot. The data gathered will also be used in further analyses to quantify the accuracy of D3DR compared to Laser 3D scans, and quantify and compare the reliability of both technologies when scanning human feet.

3 Materials and methods

Equipment: Our study aimed to measure bare feet with four techniques: manual measurements using traditional anthropometry, laser 3D scanner, DomeScan, and Avatar3D. Traditional anthropometry measurements were taken by a highly skilled measurer using a scale, a caliper and a measuring tape, with respective precisions of 1, 0.1 and 1 millimeters (Fig. 7). 3D foot scans were taken with Infoot* (Fig. 8a). Avatar3D prototype app was installed on a Sony Xperia Z (Fig. 8c) and used by a single measurer during the study.

Foot measurements: 22 measurements used in product design and in clinical assessment were considered in our study, from which 6 were selected to be included in this paper due to their relevance. They were Foot Length (FL), Toes Girth (TG), Ball Girth (BG), Ball Width (BW), Instep Girth (IG) and Instep Height (IH). All digital feet gathered digitally in 3D (i.e. with Infoot, DomeScan and Avatar3D) where measured with the same digital measuring algorithms developed by IBV. In contrast to body

* INFOOT Scanner, http://www.iwl.jp/main/infoot_std.htm

measurements, foot measurements are not standardized. Only FL, BG and BW are considered in ISO 8995 [49], ASTM D5219 [50], ISO 7259 [51], and those definitions are ambiguous and open to different interpretations. Definitions used for the four techniques were those used by the Human Shape Lab of IBV. They comply with standards and are compatible with accepted definitions found in bibliography [52,53,54,55,56].



Fig. 7. Traditional anthropometric methods; scale, caliper and measuring tape



Fig. 8. Digital acquisition of 3D feet, from left to right: Infoot, DomeScan, Avatar3D app.

Design of experiment: 16 healthy adult volunteers (8 females and 8 males) aged 24 to 63 y.o. participated in our study. According to optimal sample size estimation for concurrent designs [57,58], a minimum of 8 subjects is required to assess interrater reliability among 4 instruments with an expected ICC of 0.95 and an acceptable ICC of 0.80. For intrarater reliability, the minimum number of repetitions with 8 subjects is 3 for expected and acceptable ICCs of 0.99 and 0.95. Significance and power of the sample size estimations were fixed at 95% and 80%, respectively. Volunteers were selected to cover the size range between sizes EUR35 (US5w) to EUR47 (US13m). At each measuring session, they were measured three times with each technique in a randomized order while standing comfortably on both feet (half weight bearing, HWB). A total of 192 observations were gathered (16 subjects x 4 instruments x 3 repetitions).

Analytical procedures: Reliability was assessed using Standard Error of Measurement (SEM), which provides the magnitude of the random error in measurement units, and Intraclass Correlation Coefficient (ICC), which provides its relative reliability. Validity was assessed by studying the systematic errors of the two new methods (DomeScan and Avatar3D) with respect to the established ones (Infoot 3D scanner and traditional anthropometry), whose validity has been addressed in literature [17,44,45,46]. SEM, ICC and systematic errors were calculated according to Elasziv et al. [57] using the function `lmer` from R package `lmerTest` for model calculation and significance analysis.

4 Results

Reliability: SEM and ICC of the six measurements for each of the four techniques assessed are presented in Table 1 and Table 2. Results show that the four techniques performed similarly. ICCs of measurements from the three digital techniques (Infoot, DomeScan and Avatar3D) were beyond 0.980 and ICCs of traditional anthropometry are beyond 0.970. SEM of linear measurements (FL, BW, IH) from all techniques were below 1mm. SEM of measurements from the three digital techniques are below 2mm except for TG. SEM of measurements from traditional anthropometry values are below 2mm except for TG and BG.

Validity: Systematic errors in mm between DomeScan and Avatar3D, and traditional anthropometry and Infoot are presented in Table 3. Results show that the only significant differences between DomeScan and Avatar3D with Infoot are respectively in BW and FL but are just of 1mm. Significant biases appear between the three digital measuring techniques and the traditional methods, differences in TG and BG are the most significant in value, respectively 4.7-6.1mm and 2.3-3.3mm.

Table 1. SEM values in mm of the present study for Traditional Anthropometry, Infoot, DomeScan and Avatar3D compared to literature references for Traditional Anthropometry and 3D Foot Digitizers and to Allowable Observer Error (AOE) established by ANSUR study.

	Trad. Ant.	Infoot	DomeScan	Avatar3D	Trad. Ant. [16,44,59,60]	3D Scanner [46]	AOE [60]
FL	0.9	0.8	0.6	0.7	0.5-2.4	0.8-1.0	3
TG	3.3	3.0	2.3	1.8	-	-	-
BG	2.1	1.6	1.2	1.0	1.8-2.1	1.1	4
BW	0.8	0.8	0.6	0.6	1.0-1.8	0.7	2
IG	1.1	0.6	1.3	1.2	-	0.6	-
IH	1.0	0.8	0.7	0.8	0.5-1.8	0.5-0.6	-

Table 2. ICC values of the present study for Traditional Anthropometry, Infoot, DomeScan and Avatar3D compared to literature references for Traditional Anthropometry and 3D Foot Digitizers

	Trad. Ant.	Infoot	DomeScan	Avatar3D	Trad. Ant. [5,16, 45,61,62,63,64]	3D Scanner [46,61]
FL	.998	.999	.999	.999	.968-.998	.997-.998
TG	.977	.981	.988	.993	-	-
BG	.991	.994	.997	.998	.991	.995-.996
BW	.990	.992	.995	.996	.871-.992	.950-.991
IG	.997	.999	.996	.997	.990-.992	0.999
IH	.977	.985	.988	.985	.897-.994	.970-.990

Table 3. Systematic errors in mm between DomeScan and Avatar3D and traditional anthropometry and Infoot

	Avatar3D - Infoot	DomeScan - Infoot	Trad.Ant. - Infoot	Trad.Ant. - DomeScan	Trad.Ant. - Avatar3D
FL	1.0*	-0.2	-0.5*	-0.3	-1.5*
TG	0.2	-1.2	-5.9*	-4.7*	-6.1*
BG	-0.1	-1.0	2.3*	3.3*	2.5*
BW	0.1	-1.0*	-1.2*	-0.2	-1.4*
IG	0.3	-0.7	-1.1*	-0.4	-1.3*
IH	-0.3	0.3	-2.0*	-2.2*	-1.7*

* Significant difference (p<0.05)

5 Discussion

This paper assessed the **reliability** of four foot measuring techniques and compared them. SEM and ICC obtained for Infoot and traditional anthropometry measurements are consistent with prior literature [5,16,44,46,59,60,61,62,63,64], cf. Table 1 and Table 2. ICC values for the four techniques and the six measurements showed excellent reliability (beyond 0.95). SEM values for all techniques are within the allowable intra-observer error established by ANSUR [60]. Avatar3D and DomeScan are as reliable as Infoot for FL, BW and IH and slightly more reliable than Infoot for TG and BG. Infoot is more reliable for IG. TG is the least reliable of all measurements possibly because toe area is the most articulated part of the foot and toes can adopt slightly different poses at each repetition [65]; moreover, uncertainty in the location of the small joints (toes) may also have an influence [66]. These errors correspond to within-rater (intra-observer) variability; namely, a single scanner unit in the case of DomeScan and Infoot and a single measurer in the case of Avatar3D app and traditional anthropometry. It has to be noted that in traditional anthropometry, inter-observer errors are greater than intra-observer ones [17,45,66,67].

This paper also assessed the **validity** of two innovative products based on Data-driven 3D Reconstruction (D3DR) technology: a smartphone app, Avatar3D, and a portable booth, DomeScan. Measurements elicited from 3D feet acquired with D3DR technologies were compared to those of Infoot scanner and traditional anthropometry. Systematic error of measurements from D3DR technologies compared to Infoot is small (1mm or less) and not significant. Both DomeScan and

Avatar3D measurements can be considered compatible with Infoot measurements according to ISO 20685 [68], which establishes a threshold of 2mm for foot dimensions [17].

Systematic errors found between the three digital techniques and the traditional anthropometry are consistent with prior literature [5,45,46]. Traditional anthropometry compared to digital techniques underestimated all measurements except BG. In our study, these systematic differences could be due to the pressure exerted over the soft tissue during manual measuring (touching vs. non-touching measurement), to slight differences in the measuring posture/weight-bearing with traditional methods and to systematic differences between the palpated landmarks of traditional anthropometry and the geometrically searched landmarks [47,69]. These systematic biases have been reported to be adjustable by linear correction, if required [45,46].

The accuracy and reliability of the digital techniques seem adequate for both product design (footwear and orthotics) and clinical assessment. The main advantage of D3DR implementations compared to actual 3D scanners is its efficiency, which results in lower costs and fastest processing because they do not require high-end cameras, projectors and computing resources. Avatar3D app and DomeScan are, respectively, the most portable and the fastest 3D foot scanning solutions available.

The validation of the full list of measurements and of the 3D models obtained by D3DR techniques, not investigated in this study, is however necessary. Moreover, in order to fully assess adequacy of these techniques (along with other 3D scanning solutions) for such uses, it would also be necessary to quantify the effects of different factors affecting significantly bare foot measurements methods such as posture/weight-bearing (fixed effect), foot swelling along the day (fixed effect) and the uncertainty related of measuring the same person on different days (random effect).

6 Conclusions

The results show that, for the six measurements assessed in healthy adults, D3DR is as reliable as high resolution 3D scanners and slightly more reliable than manual measurements made by one expert. Due to its lower cost, speed and portability they have the potential to be more suitable than actual 3D scanners in certain contexts. Avatar3D app can be massively distributed and comfortably used at home for online size recommendations or for made-to-measure (MtM) orders of footwear, insoles and orthotics and even at general medical practitioner offices. DomeScan can be used at points with high measuring traffic such as retail shops.

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