Foot Landmark Detection with Structure

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Abstract

Characterization and measurement of foot shape is an important tool in the design and customization of shoes and orthotics. Advances in 3D scanning technology provide the opportunity to automate and improve the accuracy and objectivity of these assessments, as well as support a streamlined manufacturing process by moving easily from 3D model to 3D printer. The Structure SDK provides robust and accurate 3D mesh reconstruction using iPhone TrueDepth, LiDAR, or Structure Sensor devices. In addition, Structure apps provide markerless foot anthropometrics analysis to identify landmarks and metrics on the mesh, including length, width, girth, anterior transverse, lateral and medial arch lengths, and arch height of the foot. To evaluate the accuracy and reliability of our automated foot shape analysis, we first established ground truth measurements for a realistic model foot, then acquired repeated Structure 3DFootScan app scans and metrics for the model. The process was repeated for each of 6 Apple TrueDepth devices (iPhones and iPads) and all three generations of the Structure Sensor. The resulting measurements were analyzed with respect to the reference data to quantify the performance of the system.

Keywords: foot anthropometrics, anatomic landmarks, metatarsals, orthotics

1. Introduction

Characterization and measurement of foot shape is an important tool in the design and customization of shoes and orthotics and is key to customer comfort and satisfaction for these products. A variety of approaches and metrics have been used in this characterization process due to the complexity and deformability of the anatomy [1]. Typical shape analysis is based on a visual inspection by an expert clinician, but the results can be subjective. Specific measurements such as length, width, and circumference can be acquired using tapes and calipers. Advances in 3D scanning technology provide the opportunity to automate and improve the accuracy and objectivity of these assessments [2].

The Structure SDK provides robust and accurate 3D mesh reconstruction using iPhone TrueDepth, LiDAR, or Structure Sensor devices [3] [4]. In addition, the foot anthropometric feature, made available in the Structure SDK as early as in version 3.5 provides markerless foot anthropometrics analysis to identify landmarks on the mesh and calculate relevant metrics including length, width, girth, distances between the heel and first and fifth metatarsals [5] [6] and arch height of the foot. These foot anthropometric tools operate on valid foot mesh structures from any source. Figure 1 shows an example of extracted landmarks and measured parameters superimposed on the 3D foot mesh.

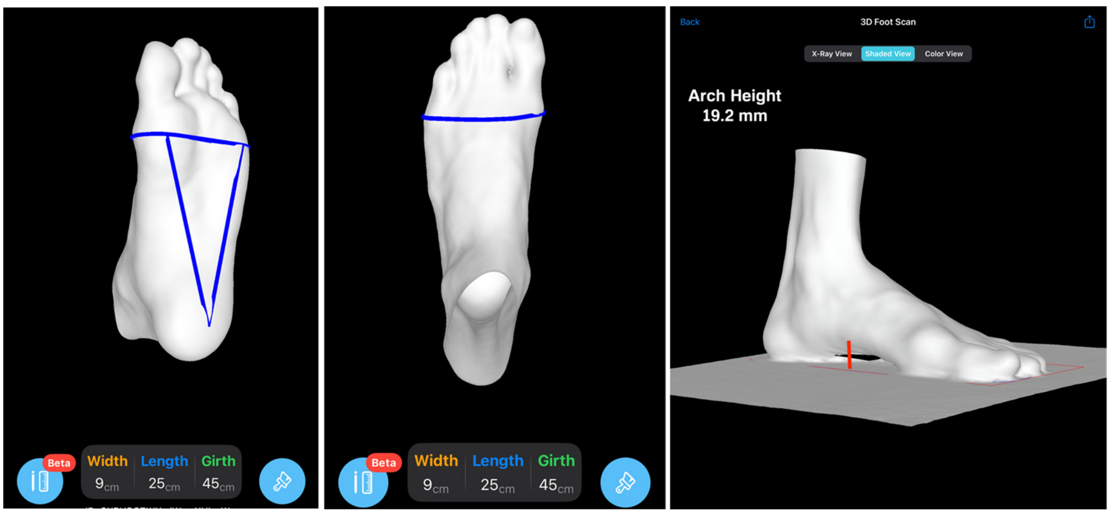

Figure 1 Foot Anthropometrics results: transverse and longitudinal arch measurements (left), metatarsal girth (center), arch height (right).

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In this paper we evaluate the accuracy and reliability of Structure's foot anthropometric measurement tools. As a reference object on which to base reference metrics and comparisons, we used the female silicone foot model (TDHLW) pictured in Figure 2. We acquired reliable ground truth metric values via repeated manual measurements for the reference foot model following standard methods and definitions. A set of 3D meshes were acquired through repeated scans of this physical foot model using Structure Sensor and Apple TrueDepth devices. Metrics for each mesh were calculated using foot anthropometric tools from the Structure SDK. Accuracy for extracted foot anthropometric measurements was evaluated with respect to ground truth measurements from the foot model reference.

Figure 2 Realistic foot model used for reference

The choice of a single foot model, no matter how realistic, presents a significant study limitation. However, it comes with the benefit of allowing accurate ground-truth measurements and multiple scans using a wide range of devices over the span of multiple days without incurring the anatomic changes one would expect from feet of actual human subjects. As will be shown in Section 4, the value of this specific study design is derived from its ability to draw conclusions when using a diversity of devices, at the cost of a diversity of anatomic features.

Overall, our study demonstrates that the Structure foot anthropometric tools are robust and accurate, but accuracy strongly depends on the coupled requirement of an accurate input foot mesh representation. This fact is demonstrated by first showing strong anthropometric accuracy using a synthetic foot mesh. Then, experimental results are analyzed for data from multiple depth sensors, thus demonstrating that the Structure Sensor 3 provides the most reliable mesh models, while some models from Apple TrueDepth sensors can struggle to meet the same quality of 3D reconstruction and measurements [7].

This paper is organized as follows: Section 2 describes the Methods used to characterize the ground truth, capture the 3D reconstruction and perform the measurements. Section 3 presents the experimental results, which are discussed in Section 4. Section 5 concludes the paper.

2. Methods

In this study we aim to determine of the repeatability of foot anthropometric measurements using the Structure SDK, as well as evaluate measurement accuracy with respect to the best estimate of the "ground truth" for a physical foot model. The authors acknowledge that there is no such thing as "ground truth" when speaking about human body parts. Hence, the term is used to denote the best estimate, from the average of multiple measurements using the best possible methods (Table 3), as described below.

2.1. Foot Anthropometrics

Structure's foot anthropometric measurement tools operate on mesh structures constructed via 3D scanning. The foot mesh data in this study was acquired using the 3 generations of Structure's custom sensors, and Structure's scanning technology applied to a range of Apple TrueDepth sensors. The metrics estimated are described in Table 2, including foot width, foot length, metatarsal girth and arch height. We use metric definitions from *ISO 7250-1:2017 Basic human body measurements for technological design* [5] (foot width and length) and from the *IEEE SA 3D body processing industry connections--comprehensive review of foot measurements terminology in use* [6]. These metrics are defined by distinguished structural and shape features or landmarks on the foot, as illustrated in Figure 1 and Figure 3 and described in Table 1.

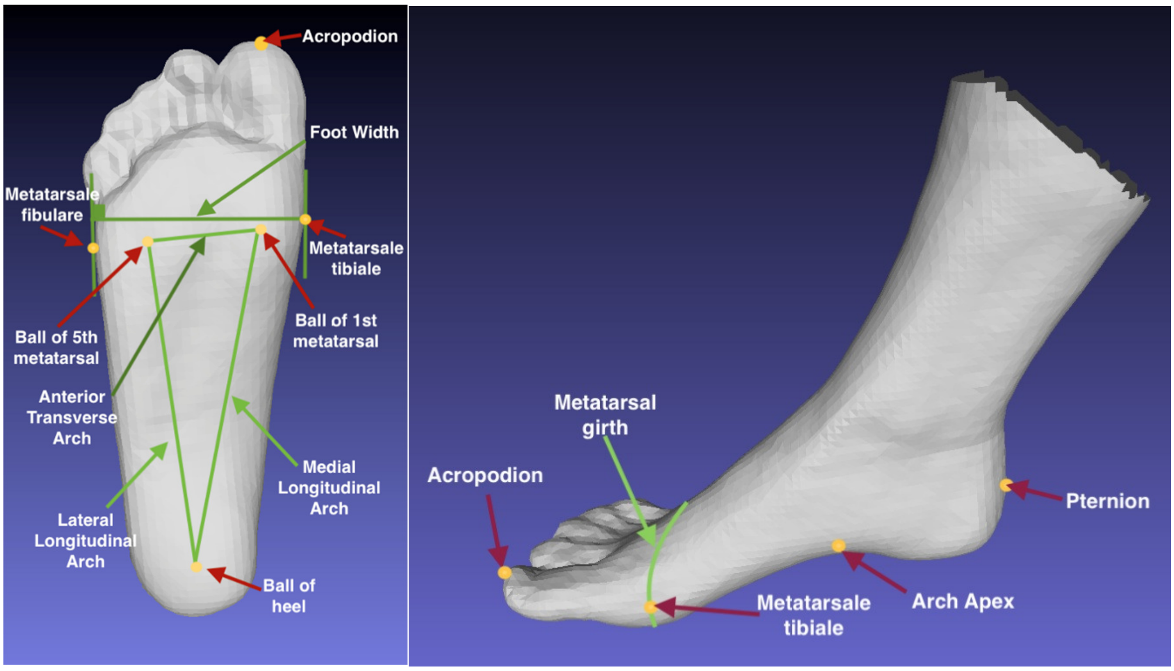

Figure 3 Sample scan illustrating foot landmarks (yellow dots) and derived metrics (green lines)

2.2. Metric Calculation

The methodology for processing 3D foot scan data employs a multi-stage approach comprising plantar surface aligned ground plane identification, model alignment, and anatomical landmark detection.

2.2.1. Ground Plane Determination

The algorithm begins by identifying the optimal ground plane that serves as the reference for all measurements. The algorithm evaluates multiple orientations to determine the configuration that best simulates the anatomical pose of a standing foot. Each candidate orientation is assessed using morphological features and stability criteria, and the orientation most representative of a standing position is selected as the ground plane reference.

2.2.2. Model Alignment and Coordinate System Definition

Once the ground plane is established, the foot model is aligned to create a standardized coordinate system. The foot outline projected onto the ground plane is extracted and analyzed to determine the primary anatomical axes. A right-handed coordinate system is then constructed with the primary foot axis (heel to toe) serving as the reference direction, enabling consistent morphological measurements across all foot scans.

2.2.3. Anatomical Landmark Localization

The aligned foot model then undergoes a series of procedures for precise localization of critical anatomical landmarks.

The heel region is identified through geometric analysis of the posterior foot contour. Arc fitting techniques are applied to locate the heel and extract its characteristic geometric properties for measurement purposes. Then the metatarsal points are located by first identifying the medial border line from the foot's contour profile. Key anatomical landmarks (Table 1) are then determined through geometric analysis of the forefoot region relative to this reference line. After alignment, the metrics from Table 2 can be calculated in a straightforward way. The Ball girth measurements are obtained by intersecting the 3D foot model with a measurement plane positioned perpendicular to the ground and oriented through the identified metatarsal landmarks. The Arch height is determined through an iterative search process that begins at the medial border midpoint. The algorithm systematically evaluates candidate points along the arch region using surface angle criteria to identify the optimal measurement location. The final arch height is calculated as the vertical distance from this identified point to the ground plane reference.

Table 1 Foot Landmarks

Landmarks			
#	**Names**	**Definitions**	**Ref**
1	Best-fitting plane to plantar surface	Plane of reference, fit to the foot plantar surface.	
2	Ball of 1st metatarsal	Portion of the sole underneath the head of the first metatarsal bone (estimated from the center point of foot mesh geometry).	[6]
3	Ball of 5th metatarsal	Portion of the sole underneath the head of the fifth metatarsal bone (estimated from the foot mesh geometry).	[6]
4	Ball of heel bone	The posterior portion of the calcaneus (heel bone). Estimated from the foot mesh geometry.	[8]
5	Pternion	maximum point of the heel curve; center of the back of the heel	[6]
6	Metatarsale tibiale (MT)	projection to the skin of the most medial point (outside swell) of the head of the first metatarsal bone	[6]
7	Metatarsale fibulare (MF)	projection to the skin of the most lateral point (outside swell) of the head of the fifth metatarsal bone.	[6]
8	Arch apex	The top point of the Medial longitudinal arch.	[9]
9	Acropodion	The end of the most prominent (longest) toe	[6]

Table 2 Extracted metrics for model foot and scans.

Metrics				
#	**Names**	**Definitions**	**Ref**	**Ground truth measurement methods**
1	Foot Width	Maximum distance between medial and lateral surfaces of the foot perpendicular to the longitudinal axis of the foot.	[5]	Distance between medial and lateral surfaces of the foot perpendicular to the longitudinal axis using the caliper.
2	Foot Length	Maximum distance from the rear of the heel to the tip of the longest (first or second) toe, measured parallel to the longitudinal axis of the foot.	[5]	Distance from the rear of the heel to the tip of the longest (first or second) toe using the caliper.
3	Metatarsal girth	Vertical circumference of the foot passing MT and MF (perimeter of ball section).	[6]	Length of a thin metal wire circumscribing the foot, passing through the MT and MF points.
4	Arch height	The vertical distance from the ground to the highest point of the arch.	[10]	Distance from floor to arch apex
5	Anterior transverse arch (from 1st to 5th metatarsal)	Arch across the width of the foot from the 1st to 5th metatarsal.	[11]	Distance from ball of 1st metatarsal to ball of 5th metatarsal.
6	Lateral longitudinal arch	Arch along the outer side of the foot, from heel to 5th metatarsal.	[11]	Distance from heel bone to ball of 5th metatarsal.
7	Medial longitudinal arch	Arch along the inner side of the foot from heel to the 1st metatarsal.	[11]	Distance from heel bone to ball of 1st metatarsal.

2.3. Determining the Ground Truth

To establish a baseline for evaluation and comparison, landmarks were established and marked on the reference foot model (Figure 2) by visual inspection, following the definitions listed in Table 1. Foot metrics were then manually measured based on the definitions from Table 2, using a gauge (foot width, length, arch apex), wire (metatarsal girth) or calipers. Each measurement was repeated 5 times. The resulting mean, standard deviation and coefficient of variance (CV%) for each metric are reported in Table 3. Table 3 makes it clear that some measurements are significantly harder to perform than others, resulting in larger CV%, such as the metatarsal girth and arch height measurements, with CV% values of 1.404 and 1.156, respectively.

Table 3 Ground truth metric values

Ground Truth metrics	Width (mm)	Length (mm)	Metatarsal Girth (mm)	Arch Height (mm)	Anterior Trans Arch Length (mm)	Lateral Arch Length (mm)	Medial Arch Length (mm)
Physical Model							
Best-estimate	68.63	214.63	178.35	21.77	48.70	115.62	128.15
Std. dev.	0.250	0.629	2.504	0.252	0.178	0.545	0.329
C.V. (%)	0.364	0.293	1.404	1.156	0.366	0.471	0.257

2.4. Experimental Datasets

2.4.1. Synthetic Foot Mesh

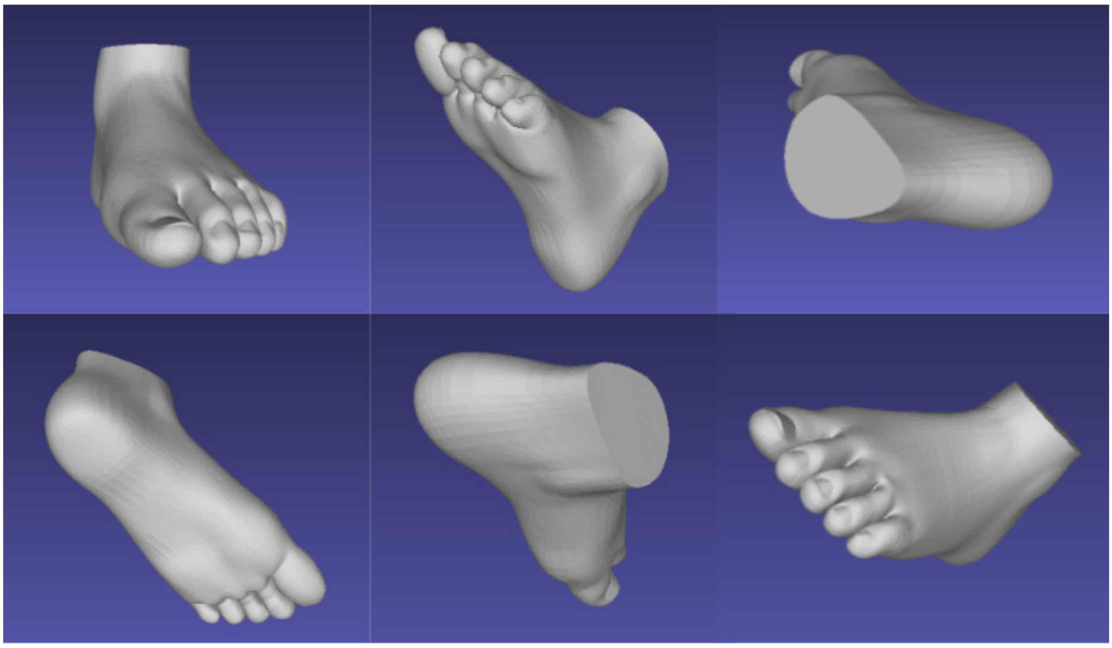

Figure 4 Synthetic foot mesh poses to challenge repeatability foot anthropometric extraction.

To establish the repeatability of our foot measurement technology we obtained a synthetic foot mesh and varied its pose in each of 6 OBJ files (Figure 4). Metrics were extracted for each mesh file and results compared to the mean for the set (Table 4) to establish the consistency of our methods.

2.4.2. Physical Reference Foot Model

Structure provides software tools and apps which enable users to create 3D mesh representations (meshes) by scanning with 3D sensor devices. These meshes can then be processed with Structure's foot anthropometric software to estimate the metrics from Table 2.

The Structure SDK was used to collect 5 scans of the foot model for each of the Structure Sensor (ST01), Structure Sensor Pro (ST02) and Structure Sensor 3 (ST03) devices and a selection of 6 TrueDepth enabled iPad and iPhone devices including iPhone 13, iPhone 14, iPhone 15 Pro Max, iPhone 16e, iPad Pro (11-inch) (3rd Gen) and iPad Pro 11-inch (M4). All collected meshes were then processed with Structure's foot anthropometric measurement tools to estimate the metrics from Table 2. These values were then analyzed with respect to the measured ground truth values (Table 3) and the results are summarized in Table 5 and Table 6.

For best results, the Structure Sensor 3 used a 7x7 aggregate window with a confidence threshold of 10, as explained in [3]. During scanning the foot model was placed on a table, with the plantar surface facing upwards. The operator would then start from the plantar surface and scan the entire foot and part of the ankle in an anticlockwise motion. This provided a stable and repeatable platform from which multiple scans could be performed. A sample scan is shown in Figure 3.

3. Results

Our goal with this study is to provide a comprehensive evaluation of Structure's foot anthropometric measurement accuracy across multiple sensing technologies and device configurations. The analysis examines performance patterns for seven key foot parameters - width, length, metatarsal girth, arch height, anterior transverse arch length, lateral arch length and medial arch length, extracted using Structure's foot anthropometric measurement tools applied to foot meshes obtained using Structure's SDK with multiple generations of Structure sensors (ST01, ST02, ST03 [3]) and seven different TrueDepth-enabled iOS devices. In addition, we use an idealized synthetic foot mesh to evaluate the repeatability of measurements under mesh transformation.

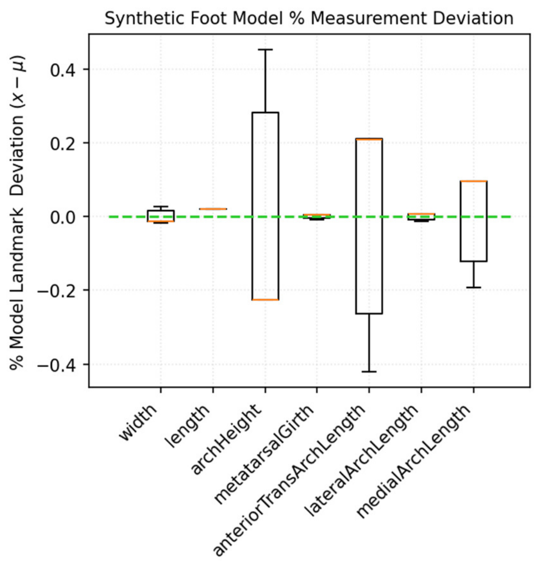

Figure 5 Percent variation in synthetic mesh foot metrics with respect to the observed mean.

3.1. Synthetic Foot Mesh

Foot anthropometric tools were used to estimate foot metrics for the 6 synthetic mesh poses illustrated in Figure 4. Figure 5 shows box-and-whisker plots illustrating the very tight distribution (<0.5%) of percent error (with respect to the mean) of metric estimates. The means, standard deviations and Coefficients of Variation (CV%) over the mesh set for each metric are provided in Table 4. Again, we see very low variability of metrics over the data set.

Table 4 Synthetic foot mesh metric performance.

Ground Truth metrics	Width (mm)	Length (mm)	Metatarsal Girth (mm)	Arch Height (mm)	Anterior Trans Arch Length (mm)	Lateral Arch Length (mm)	Medial Arch Length (mm)
Synthetic Mesh							
Best-estimate	91.529	240.703	250.973	18.919	65.932	129.898	134.212
Std. dev.	0.017	0.113	0.014	0.060	0.196	0.011	0.183
C.V. (%)	0.019	0.047	0.006	0.319	0.297	0.009	0.137

3.2. Reference Foot Model

Our extensive evaluation of foot anthropometrics over a range of depth sensors focuses on three critical aspects: metric performance characteristics, depth technology-specific effects, and parameter specific measurement challenges. The results show distinct accuracy patterns for each sensing technology, with Structure Sensors generally providing the most consistent performance: lower variability and mean value close to ground truth. TrueDepth sensors demonstrate significant variation and median values underestimating ground truth - performance that reflects hardware and software variation across iOS device models (Figure 6).

3.2.1. Structure Sensors

The three generations of Structure sensor [3] were evaluated for this study, collecting and evaluating 5 scans of the reference foot for each (see Table 5), where the of a given measurement RMSE is calculated by Equ. 1:

$$RMSE = \left[\sum_{i=1}^{N} \frac{(m_i - \bar{x})^2}{N}\right]^{\frac{1}{2}}$$

where N is the total number of measurements, m_i is an individual measurement, and $\bar{x}$ is the ground truth best estimate of that measurement. The % CV, as before, is calculated by Equ. 2:

$$\%\,CV = 100\frac{\sigma}{\bar{x}}$$

where σ is the standard deviation of the N measurements.

Table 5 Structure Sensor foot metric statistics.

Structure Sensors	Width (mm)	Length (mm)	arch Height (mm)	metatarsal Girth (mm)	anterior Trans Arch Length (mm)	lateral Arch Length (mm)	medial Arch Length (mm)
ST01							
mean	69.463	213.045	21.127	181.520	51.191	119.962	126.849
std	0.664	0.513	0.456	1.864	1.161	2.327	4.156
rmse	1.065	1.666	0.788	3.678	2.749	4.926	4.355
% CV	0.957	0.241	2.156	1.027	2.268	1.940	3.276
ST02							
mean	69.966	211.712	21.425	179.445	52.326	121.622	127.365
std	0.892	0.585	1.059	1.959	1.136	8.796	8.489
rmse	1.606	2.977	1.113	2.244	3.800	10.648	8.526
% CV	1.274	0.277	4.941	1.091	2.172	7.232	6.665
ST03							
mean	68.581	213.074	21.468	183.820	50.886	114.389	125.924
std	0.955	0.748	1.189	4.274	0.665	3.744	2.287
rmse	0.956	1.727	1.227	6.942	2.285	3.941	3.192
% CV	1.392	0.351	5.539	2.325	1.307	3.273	1.816

Structure sensors demonstrate reliable accuracy across all measurement parameters as illustrated in Figure 6. ST03 consistently delivers accurate estimates in critical measurements, including length, width, and arch height, while maintaining good performance across all other parameters. ST01 and ST02 also show strong overall accuracy but exhibit slightly weaker performance in arch height measurements compared to ST03's results. The relatively larger metatarsal girth measured using the ST03 sensor is explained by the larger number of triangles available in the meshes produced by that sensor, and the fact that we calculate girth by summing Euclidian distances between interconnected mesh points. This points to a clear potential improvement in our algorithm, using geodesic distance to calculate girth instead of Euclidian distance.

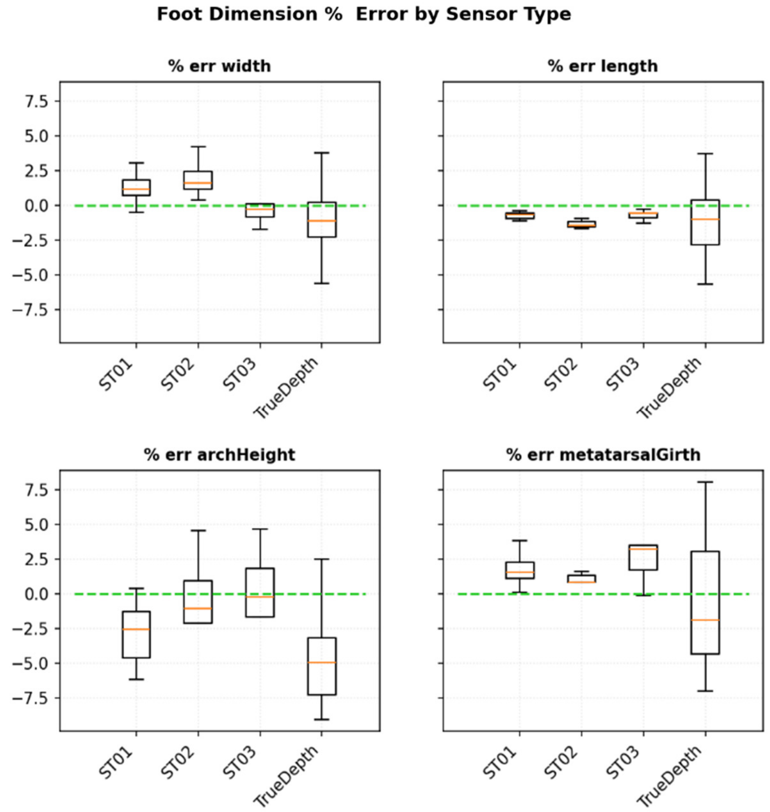

Figure 6: Percent error for Structure Sensors and cumulative performance for Structure SDK

3.2.2. TrueDepth Devices

The TrueDepth sensor category shows a large variability across all parameters (Figure 6). However, this variability is misleading, as it results from combining data from multiple device models rather than representing individual sensor model performance and device-specific depth scaling differences across TrueDepth hardware implementations.

Analysis of individual TrueDepth devices (Table 6) reveals distinct performance patterns across the six models tested. Three of the tested devices demonstrate consistently superior performance: iPhone 13, iPhone 14, and iPad Pro 11-inch (M4). These models show tight error distributions and stable accuracy across nearly all measurement parameters. In contrast, recent iPhone models and some iPad variants exhibit greater variability and reduced accuracy. This could be the result of a combination of reduced baseline distance and reduced pixel pitch of their TrueDepth sensors (see, for example [12] and [13]) – both of which contribute to increased noise - or potentially due to registration errors of the raw TrueDepth depth frames with respect to the RGB frames (see Figure 7).

The Metatarsal Girth measurement variability indicates that hardware architecture and software updates across device generations differently impact mesh reconstruction algorithms. While these variations affect volumetric calculations, they do not compromise the precision of basic dimensional measurements critical for foot sizing applications.

Table 6 iOS TrueDepth foot metric statistics

iOS TrueDepth Devices	width	length	arch Height	metatarsal Girth	anterior Trans Arch Length	lateral Arch Length	medial Arch Length
iPhone 13							
mean	68.661	212.770	19.786	176.184	51.683	128.947	135.063
std	1.174	1.932	1.584	2.665	2.262	12.558	13.348
rmse	1.175	2.681	2.539	3.434	3.744	18.311	15.032
% CV	1.710	0.908	8.008	1.513	4.377	9.739	9.882
iPhone 14							
mean	67.499	210.266	20.637	174.839	50.027	121.954	126.773
std	0.389	1.402	0.323	2.074	0.724	1.687	2.924
rmse	1.196	4.584	1.178	4.077	1.512	6.555	3.232
% CV	0.577	0.667	1.567	1.186	1.447	1.383	2.307
iPhone 15 Pro Max							
mean	66.058	206.470	20.669	167.950	49.726	122.765	128.392
std	1.059	2.203	0.298	1.584	0.959	3.312	3.704
rmse	2.781	8.452	1.141	10.520	1.404	7.876	3.712
% CV	1.604	1.067	1.443	0.943	1.928	2.698	2.885
iPhone 16e							
mean	65.641	205.335	20.529	170.521	49.074	117.659	121.400
std	0.837	2.013	0.709	2.210	0.868	0.667	1.325
rmse	3.104	9.511	1.430	8.135	0.946	2.145	6.879
% CV	1.275	0.980	3.455	1.296	1.770	0.567	1.091
iPad Pro (11") 3rd gen							
mean	71.623	221.718	22.001	185.177	52.972	125.642	132.504
std	0.832	3.045	0.492	4.248	1.576	1.867	3.908
rmse	3.107	7.714	0.544	8.041	4.554	10.194	5.851
% CV	1.162	1.373	2.238	2.294	2.976	1.486	2.949
iPad Pro 11" (M4)							
mean	68.496	215.474	20.304	184.990	50.160	116.968	125.721
std	0.567	0.614	0.323	1.012	0.622	1.304	1.558
rmse	0.582	1.044	1.501	6.716	1.587	1.876	2.886
% CV	0.827	0.285	1.589	0.547	1.241	1.115	1.239

Aggregate error analysis (Figure 8) reveals distinct accuracy patterns across foot measurement parameters. Arch Height and Width demonstrate good precision with tight error distributions, staying well within ±5mm with minimal variability. Foot length is perhaps the most important parameter and has a median error close to 1 mm which is similar to the uncertainty in the ground truth value. Metatarsal girth shows the largest variation among all parameters, displaying the widest error distribution.

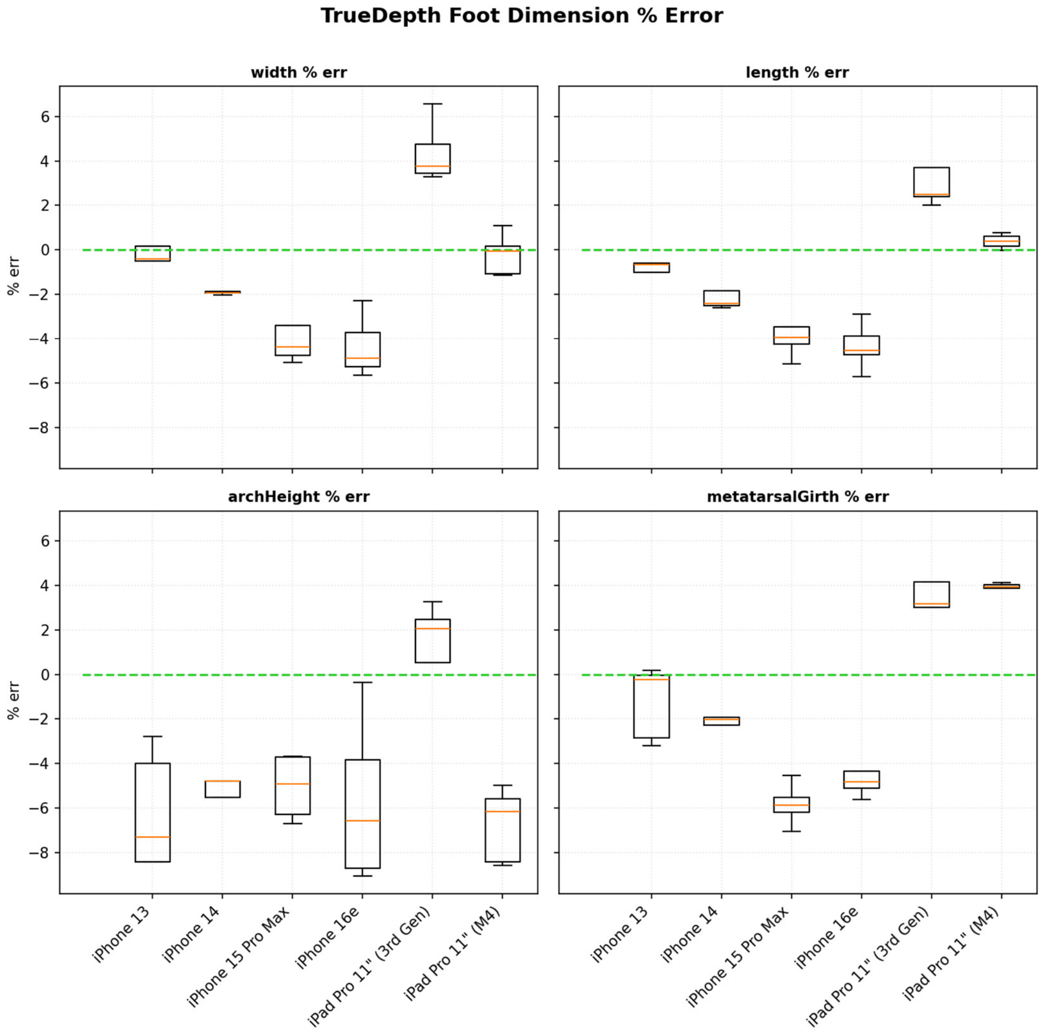

Figure 7 Foot metric performance for iOS TrueDepth devices

All measurement parameters maintain median errors within the ±5mm range, demonstrating overall system reliability. Most importantly, the critical parameters for foot sizing - width and arch height - consistently achieve sub-5mm accuracy, ensuring high precision for practical footwear applications. While some parameters show greater variability, consistently low median errors across all measurements confirm the system's effectiveness for foot measurement applications.

4. Discussion

In foot shape assessment, a wide variety of qualitative and quantitative metrics have been described, and what to measure becomes an important question [1]. The anthropometric measurements selected and implemented in Structure's SDK are a subset of possible candidates [6]. The detailed 3D surface geometry available with Structure's meshes could provide more complex and descriptive shape metrics for analysis [14].

The consistently low error rates in essential parameters - particularly width, length, and arch height - highlight the clinical value of modern 3D foot scanning solutions. Measurements for these crucial dimensions routinely fall within ±5 mm of reference values, a value that has been communicated by members of the orthotic community as comfortably meeting the precision required for orthotics and custom footwear design. This reliability ensures that clinicians and practitioners can confidently employ these technologies for daily foot sizing, shape analysis, and advanced biomechanical evaluation.

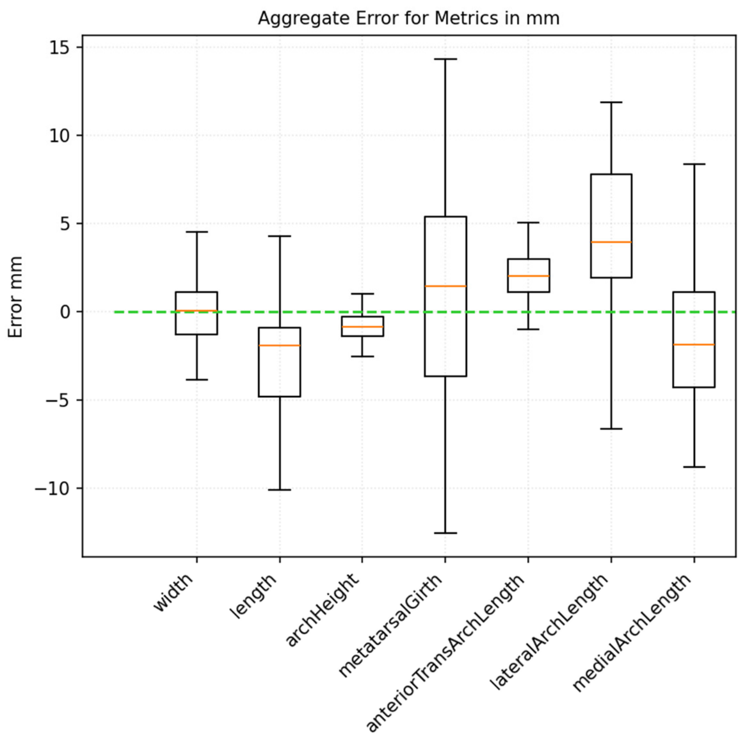

Figure 8 Aggregate foot metric error over all devices.

Within this technological landscape, a clear hierarchy in measurement accuracy and consistency emerges among sensor types and device models. Newer Structure sensors stand out, demonstrating tighter error distributions and lower variability across all major morphological features with estimated RMSE 0.28% accuracy for arms and legs [3]. This makes them particularly suitable for clinical scenarios where high measurement precision is required, such as pediatric orthotics or post-surgical follow-up. Moreover, the increased robustness and IP53 compliance of the Structure Sensor 3 ensures its suitability for daily use in busy clinical practices.

In contrast, TrueDepth cameras display greater variability [7], especially in parameters involving more complex foot geometry. These findings highlight how sensor choice directly impacts measurement quality, emphasizing the need for optimal hardware selection to ensure reliable clinical outcomes.

Taken together, these results show that advances in sensor technology and hardware selection have a tangible impact on clinical measurement reliability. Structure sensors are particularly well suited for most clinical needs, while sensors such as TrueDepth, which are not designed for measurement accuracy, struggle to satisfy requirements for detailed anatomical fidelity. Ongoing improvements in sensor design and mesh reconstruction will continue to enhance the clinical utility and robustness of 3D foot measurement systems.

5. Conclusions and Future Steps

Structure's foot anthropometrics framework is a capable tool for automated foot shape assessment tasks in the design and customization of shoes and orthotics, The SDK provides one with a convenient method to assess foot meshes from any source, automatically aligning the foot with respect to a ground plane and coordinate system, in addition to providing 9 relevant anatomic landmarks and 8 metrics. All measurement parameters were demonstrated to maintain median errors within the ±5mm range over a wide range of sensors.

Structure's anthropometrics also provide opportunities in personalized healthcare applications, including diagnostics and therapeutics such as measuring navicular drop [15]. Our analysis demonstrates that the Structure Sensor 3 and Structure SDK provide reliable and accurate mesh reconstruction and foot measurement technology. Reconstruction and measurement are also available based on Apple TrueDepth enabled devices but suffer somewhat from the variability of the depth data provided by the underlying hardware.

Beyond foot measurements, this research framework can expand into other anthropometric applications, such as facial parameter measurement for manufacturing headgear and protective equipment. This broader application demonstrates the potential for our standardized measurement protocols to transform various fields requiring precise human body measurements, from healthcare and sports to personalized manufacturing.

In the current study the authors chose to ensure accurate ground truth measurements and perform multiple scans with a diversity of devices. Those choices resulted in an important limitation: the use of a single foot model. Consequently, the authors are interested in future collaboration that provide us with the opportunity to perform a cross-sectional study, including ground-truth measurements from a range of subjects.

6. Acknowledgements

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