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Investigating the accuracy of smartphone photogrammetry for remote 3D scanning transtibial amputees

Sean Cullen[a], Amir Mohagheghi[b] and Ruth Mackay[a]

[a]Department of Mechanical and Aerospace Engineering, College of Engineering, Design and Physical Sciences, Brunel University London, Uxbridge, United Kingdom; [b]Division of Sport, Health & Exercise Sciences, College of Health, Medicine and Life Sciences, Brunel University London, Uxbridge, United Kingdom

ABSTRACT
Capturing limb shape for amputees is critical in the fabrication and delivery of comfortable prosthetic limbs. Smartphone Photogrammetry offers a cheaper and more accessible alternative to digital shape capture than traditional handheld 3D scanners, opening possibilities for remote, or in home scanning. In this study we aimed to evaluate the accuracy of smartphone photogrammetry using a technique designed for in home scanning, comparing performance to an Einscan H2. The results indicated that photogrammetry was suitable accurate for scanning static limb targets (>95% volumetric accuracy), but was not accurate enough for direct amputee scanning (63.4% larger volumes). Whilst this technique was not sufficiently accurate for clinical use, the amputee surrogate trials did show increased accuracy, indicating the method shows promise and should be developed further, with a particular focus on home environment compatible techniques.

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Prosthetics; 3D scanning; photogrammetry; low cost

1. Introduction

Capturing the shape of amputee limbs is critical to creating comfortable sockets and well-fitting prosthetics [1–5]. Forming the first step in the rectification processes, any differences between the amputee and reference model will be compounded through the fabrication stages. The resulting socket will have areas that are tighter or looser than intended and the resulting skin contact pressures can create significant pain for the user [6–9]. This is particularly important for transtibial amputees, where socket pain is one of the leading causes of dissatisfaction with prosthetics [10,11].

Hand casting techniques are commonly used to capture limb shapes where a base model is produced from Plaster of Paris (PoP). Clinicians use artisan skill to rectify the model and produce a socket; however, the PoP cast is often sacrificial and destroyed during the process. This is a labour-intensive process, requiring the amputee to travel to their limb centre multiple times to be fitted for a prosthetic socket, contributing to the cumulative burden of disability [12]. If the socket is uncomfortable the process is often re-started from the casting stage. By contrast, 3D scanning offers the ability to capture limb shapes digitally, and therefore produce sockets without losing the original shape. Clinicians have reported that 3D scanning is less labour intensive, quick, clean, and convenient [13]. 3D scanning can also digitise post rectified socket moulds creating a complete design history for amputees without taking up physical space. Direct limb scans can be turned into foam models for manual rectification, or rectified using digital tools [14]. 3D scanning techniques, however, require different skillsets for clinicians, and has therefore received a mixed response and uptake in the sector [15,16].

Rectified 3D models can be used to create moulds for lamination or to produce sockets directly through 3D printing [17,18]. Studies have shown 3D printed sockets can be as strong and comfortable as laminated sockets, however this is a relatively new technology and is not as proven as laminated sockets [19]. The biggest advantage of 3D models is the ability to use remote manufacturing facilities allowing for larger throughput. It should be noted that Sanders et al. showed that sockets produced from centralised

CONTACT Sean Cullen sean.cullen3@brunel.ac.uk Department of Mechanical and Aerospace Engineering, College of Engineering, Design and Physical Sciences, Brunel University London, Uxbridge, United Kingdom.

manufacturing facilities also have deviations in shape, effecting the clinical utility of sockets [20,21].

For use in prosthetics, the impact of scan inaccuracy is difficult to define. Sanders et al. identified that a difference in Mean Radial Error (MRE) of 0.25 mm would have a clinically relevant impact [22]. Dickenson et al. suggested that a volume difference of 3.5% across the central 95% of the socket surface would be clinically relevant for fit [23]. Cutti et al. and Seminati et al. showed commercial grade handheld 3D scanners were capable of meeting these accuracy requirements as well as achieving high repeatability and validity, even with little training [24,25]. Other studies such as that by Armitage showed disagreement in the inter-rater reliability of 3D scanning reducing widespread clinical effectiveness using a lower cost scanner [26]. As scanning technology develops it is likely that adoption will increase along with training and agreement on how to evaluate scanner performance.

One of the largest barriers to implementation of scanning technologies is cost. The Einscan Pro 2X (SHINING 3D, Hangzhou, China) used by Cutti et al. costs approximately £6,000 representing the mid-range scanners [24]. This does not include the required computer to operate the scanner, representing a relatively large barrier to use in clinical and remote settings.

Whilst widely regarded as less accurate, smartphone photogrammetry represents a significantly cheaper method to capture limb shapes. Photogrammetry involves taking photos of an object from different orientations and using software to reconstruct the shape by comparing patterns between perspectives [27]. Hernandes et al. used photogrammetry to scan socket interiors with deviations of 2.6 ± 2.0 mm, suggesting the method was not accurate enough [28]. These results were cohobated by the authors in a prior study achieving a socket interior volume error of 6.76% [29]. Whilst photogrammetry was unable to accurately scan socket interiors directly due to the limited viewing angles, and variability in wall thickness, it did show promise for scanning socket casts, with an overall volume error of ~1% within the clinically acceptable limit [30]. Whilst scanning casts is less applicable to clinical use, it does provide a compatible benchmark to the 3D scanning papers. A more recent paper by Walters et al. showed that smartphones could be used to digitise amputee limbs directly, however the different photogrammetry software studied had mixed results [31].

The relative availability of smartphones reduces the costs of digital shape capture significantly, so much so that amputees could ultimately scan their own limbs at home without the need to travel to limb centres for initial casting. This would reduce the amount of travelling required for amputees as well as the financial and time burden of disabilities. Anecdotal evidence suggests many amputees travel to limb centres further than their nearest centre in hopes of receiving better quality care and fitting sockets. Remote scanning could allow clinicians to support amputees from anywhere, as shown by Cabrera et al. who successfully produced a 3D printed socket using a custom photogrammetry and rectification software package [32]. This is particularly important in the United Kingdom with the critical shortage of clinicians, remote scanning techniques could support resource relocation and telehealth opportunities, reducing overall service demand [33].

For smartphone photogrammetry to be used in a home setting, the technique must be simple enough for anyone to complete with minimal instruction and technical knowledge, as well as be compatible with different ability levels from both the amputee and person conducting the scan. Therefore, in this study we aimed to evaluate the accuracy of a simple to complete smartphone photogrammetry technique, comparing the performance to a commercial handheld 3D scanner.

2. Methods

A series of three scan experiments were conducted: static, standing, and direct amputee scans. The static and standing trials used reference models with known geometry, while the direct amputee scan was conducted on one individual with no reference values for the outcome measures. During all trials the Photogrammetry technique was conducted by a researcher with no prior photogrammetry experience. The 3D scans were taken by an experienced researcher using a scanner designed for prosthetics and body scanning, EinScan H2 (SHINING 3D, Hangzhou China) [34,35]. Ethical approval was granted for this study by the Brunel University College of Engineering, Design and Physical Sciences Research Ethics Committee (50101-LR-Nov/2024- 53198-2).

2.1. Static data collection

Four reference surrogate limbs were 3D printed on a P1S (Bambu Labs, Shenzhen China) with 0.2 mm layer height based. Three of the models were based on scans of rectified transtibial socket moulds with one model based on an unrectified cast. The models were covered in a patterned sleeve with reflective markers placed on the distal end and placed on a pedestal in the centre of a calibration plate, as per a prior study

[30]. The models were scanned using the EinScan H2 in Infra-red light mode with a rated accuracy of 0.1 mm ± 0.3 mm/m. Using the same experiment set up the models were photographed using an iPhone 14 Pro (Apple, Cupertino, California) with 8 circumferential photos being taken from 3 sets of radial positions (100 cm away from the calibration plate at the proximal end of the model, 50 cm away from the calibration model at the middle of the model, and 30 cm away at the distal end of the model). The photographing positions were approximated and the camera was left on automatic settings to simulate at home conditions.

The EinScan H2 files were processed using EXScan H (SHINING 3D, Hangzhou China). Holes in the models were filled using flat and curved surfaces, including the holes left by automatic removal of markers, and the base of the model was sliced to remove the pedestal. Ghost point clouds and other scan defects were manually removed. The same procedure was followed for the photogrammetry scans using Autodesk RecapPhoto (Autodesk, San Fransisco, CA, USA), with the addition of scaling the models using the reference grid placed under the pedestal.

2.2. Standing data collection

To simulate scanning a live biological limb, where small movements would be present, a series of standing trials were conducted. A standing position was chosen as it would be most compatible with home environments. Preliminary tests showed it was not practical to sit on a typical chair as there was limited space for photographing. The 3D printed reference models used in static scans were fitted with handles and held by hand in the approximate position of an amputate limb when standing (Figure 1, left). The handles were mounted to the base of the model, in the same place as the pedestal, with same markers and patterned sleeve used in the calibration trial. The photographing instructions were simplified based on anatomical markers for height, with the graphic in Figure 1 being provided to guide camera positioning. A total of five scans were taken for each of the four reference models using both photogrammetry and the EinScan H2.

2.3. Direct amputee data collection

A single transtibial amputee participated in this study who was an active 29-year-old male who uses his prosthesis daily and has had a stable limb volume for over one year. Prior to the trials the participant sat for at least 10 min with their prosthesis, followed by a period of 10 min without their prosthesis to stabilise limb volume [36]. For the testing period the participants liner was left on to help reduce movements in the soft tissues of the residuum. The participant stood without his prosthesis, being supported by two crutches during scanning periods as indicated in Figure 1. The participants residual limb had fifteen reflective markers placed on the fibula head, patella tendon, posterior, and distal regions of their residuum. A patterned sleeve was not needed as the liner had lines and visually identifying features. The participant was scanned five times using the EinScan H2 and photogrammetry using the same technique as the standing trials. To reduce the chance of volume fluctuations scans EinScan H2 and photogrammetry scans were taken in alternate order with sitting breaks in between.

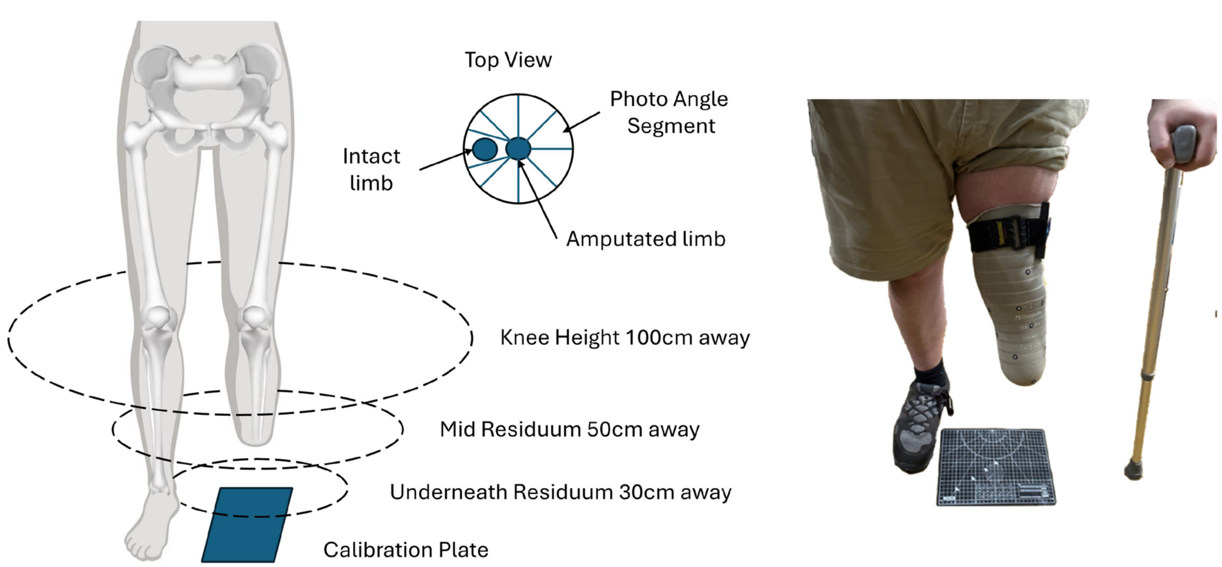

Figure 1. Simplified positions for photographing locations (left), amputee experiment photo (right).

2.4. Scan analysis

The static and standing scan files were cropped to the proximal end of the reference model, using the plane tool. Similarly, the amputee files were trimmed using the plane tool, aligned with a selected ring on the participants liner above the knee. Scan files were exported using an STL (Stereolithography) file format using native resolution for the 50k target face count for both the photogrammetry and EinScan H2 scans. The direct amputee photogrammetry scans were digitally smoothed (PGS) in ReCap Photo and exported as separate files for analysis. Using the open source Python package AmpScan, the files were digitally aligned to the reference models [37]. The scans were then sliced into 100 sections form the distal to proximal end of the stump. The circumference and surface area of the slices was extracted for comparison, as well as total scan volume.

The accuracy of scaling for the photogrammetry (PG) scans was evaluated by comparing the measured and real value for the calibration plate in the scan model after scaling. The edge used for evaluation was perpendicular to the one used for calibration.

To analyse the accuracy of the static and standing scans, the raw values were compared against the four respective reference models at 1% increments along the length of the reference model for the five repeat scans. For cross comparison the slice values for each scan were normalised by scaling the against the slices for the first reference model. As stated above, for the amputee trials, a digital reference model was not available to represent the true dimensions of the residuum. for evaluation the: percentage accuracy, Repeatability Coefficient (RC) (2.77*Standard Deviation) presented as a raw value and percentage of the reference value, co-efficient of variance (CV), and Intraclass Correlation Coefficient (ICC) of the static and standing trials were calculated for circumference and surface area using a 95% confidence interval [38,39]. In addition, the parameters for the most distal 20% of slices was extracted to provide additional insight into distal accuracy.

3. Results

3.1. 3D scan processing

The average times taken to conduct the scanning has been separated into data collection (photographing or scanning) and Editing in Table 1, the software processing time was not included in this table as it was only available for the static scans. Scanning times between the two methods where comparable taking between 1 and 2 min on average. The editing time for photogrammetry remained consistent across the trials taking less than 3 min on average. By contrast the EinScan H2 editing stages for the amputee trials took between 4 and 16 min with some scans taking significantly longer than the 4 min of the other trials due to the number of artefacts and holes in the scan surface. The average time for the respective software to process the images into a mesh file was 1 h 46 min (SD: 51 min Range: 32 min to 3 h 13 min) for ReCap and 4 min 35 s (SD: 1 min 34 s Range: 1 min 32 s to 9 min 5 s) for EXScan H. These averages were based on the static scans only as ReCap failed to timestamp completed files for the standing and amputee trials.

Table 1. Average capture and process times for photogrammetry and 3D scanning.

	Photogrammetry							
	Photographing				Editing			
	Avg	SD	Range		Avg	SD	Range	
Static	00:49	00:03	00:44	00:55	02:45	00:28	01:55	03:50
Standing	01:09	00:11	00:11	01:38	02:56	00:53	01:18	04:39
Amputee	01:21	00:15	01:10	01:47	02:46	00:26	02:13	03:26
	EinScan H2							
	Scanning				Editing			
	Avg	SD	Range		Avg	SD	Range	
Static	01:48	00:41	01:05	03:44	04:40	02:27	01:32	09:05
Standing	01:22	00:40	00:50	03:10	03:49	01:32	02:10	08:38
Amputee	02:18	00:46	01:28	03:10	08:48	05:08	04:18	16:07

Note: times are reported in mm:ss format.

The average similarity between the measured and true value for scaling marks were 99.6%, 99.2%, and 98.3% for the static, standing, and amputee scans respectively.

3.2. Static/standing scan analysis

The average volume of the digital reference models was 2,040 cm^3 with a length of 26 cm. Static scans by the EinScan H2 overestimated volume and length by <2.5% on average whilst the photogrammetry scans underestimated volume by 2.1% and overestimated length by 0.1%, as indicated in Figure 2. For the standing trials the EinScan H2 scans were within 0.2% of the control model volume and length whilst the accuracy of the photogrammetry technique fell significantly, and overestimated the volume by 6.9% and length by 0.4%.

A visualisation of the difference in surface topography can be seen in Figures 3 and 4 for the static and standing scans respectively. The heat map indicates the difference in surface location from a sample photogrammetry scan to a EinScan H2 scan, where green regions represent deviations of $<\pm 1$mm. The static

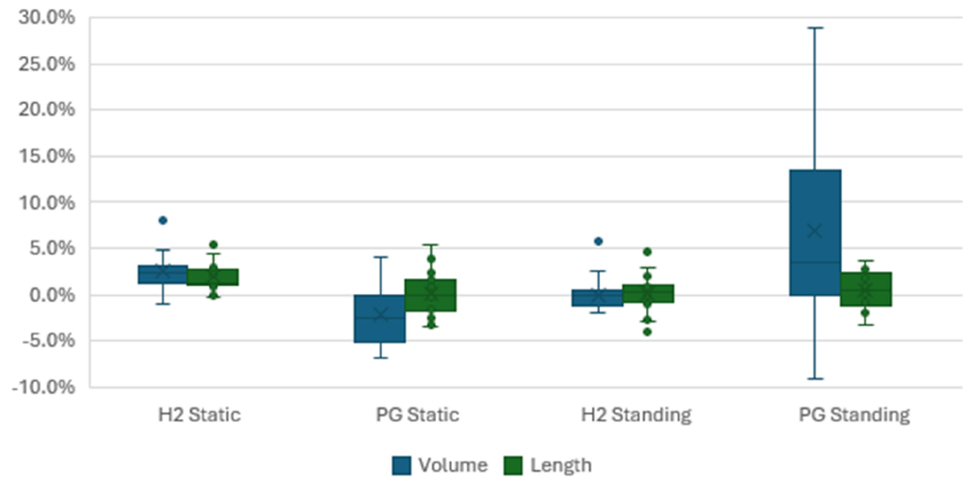

Figure 2. Box plot for scan volumes (cm^3) and lengths (cm) as a percentage difference from the digital reference model for EinScan H2 and photogrammetry (PG).

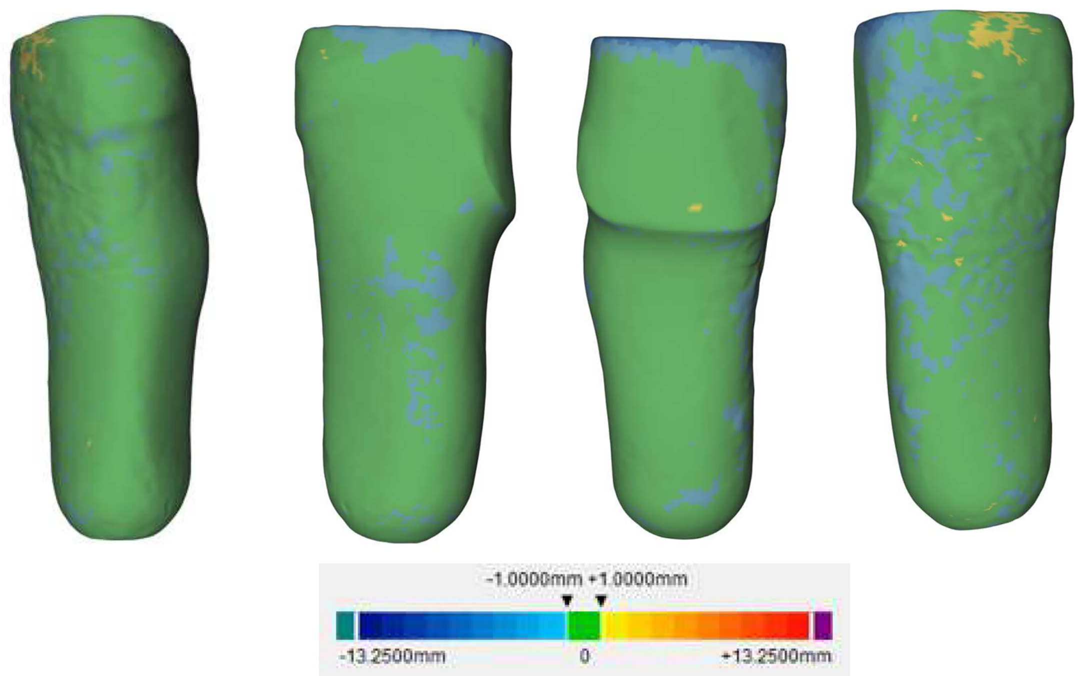

Figure 3. Heatmap topography comparison between a sample static EinScan H2 and photogrammetry scan for the first model, showing anterior, lateral, posterior, and medial views from left to right.

scan example does have slightly higher maximum difference (−13.25 mm) than the standing scan (+9.52 mm), located on the top cropping region of the model. Across the clinically relevant landmarks the static scans show very high agreement, with some small areas of deviations. Comparatively the standing scans show much larger concentrated regions of difference around the distal and tibial regions.

The scan surface accuracy across the central 90% of the model are reported in Table 2. For the standing scans the accuracy for the EinScan H2 was >99% in surface area (SA) and circumference. The average Photogrammetry accuracy was significantly lower, averaging 95.1% for circumference and 93.9% for SA with the scans being larger than the reference model.

For reliability was measured through the ICC for the scans. The EinScan H2 was >0.9 across all trials indicating excellent reliability. The ICC for photogrammetry was >0.9 in the static trials indicating excellent reliability, but was lower at >0.8 for the standing and amputee trials indicating a good reliability. The CV and repeatability values followed a similar trend with variation in scans increasing with the amputee trials, more significantly for photogrammetry than the EinScan H2.

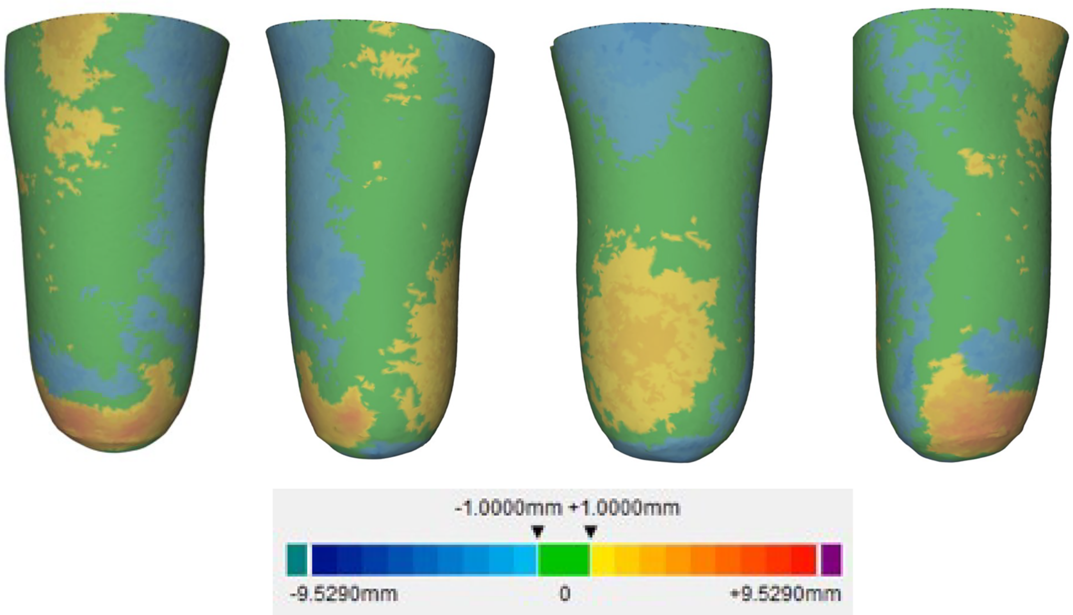

Figure 4. Heatmap topography comparison between a sample standing EinScan H2 and photogrammetry scan for the fourth model, showing anterior, lateral, posterior, and medial views from left to right.

Table 2. Accuracy comparison metrics between photogrammetry (PG) and EinScan H2 (H2) for static and standing trials.

	Circumference (mm)								
	Reference Value	Scan Average	Accuracy	RC (% of Reference)		CV	ICC	Distal Accuracy (SD)	
Static H2	329	335	98.4%	15	(4.5%)	13%	0.985	99.4%	(5.1%)
Static PG	329	334	98.8%	16	(4.7%)	13%	0.983	97.3%	(5.7%)
Standing H2	329	328	99.7%	13	(3.8%)	14%	0.986	99.5%	(6.1%)
Standing PG	329	347	95.1%	55	(15.8%)	15%	0.865	95.9%	(9.3%)
	Surface Area (mm^2)								
	Reference Value	Scan Average	Accuracy	RC (% of Reference)		CV	ICC	Distal Accuracy (SD)	
Static H2	8452	8762	96.5%	696	(7.9%)	24%	0.987	97.6%	(7.1%)
Static PG	8452	8600	98.3%	746	(8.7%)	24%	0.985	97.1%	(6.3%)
Standing H2	8452	8457	99.9%	458	(5.4%)	26%	0.991	99.3%	(8.8%)
Standing PG	8452	9004	93.9%	2463	(27.4%)	28%	0.881	95.8%	(14.6%)

The Distal Accuracy in Table 2 indicated the average deviation in the distal most 20% of the scan files, a critical region for socket comfort. Generally the EinScan H2 performed well with an accuracy of >99% for the standing and static models with the exception of the static SA at 97%. The photogrammetry scans had slightly lower accuracy in the distal region with accuracies >95% still within the clinically acceptable limit. Across the scans the EinScan H2 had lower variation in accuracy for the distal region (5-9% SD) compared to photogrammetry (5-15% SD).

The scan slice-by-slice comparison at every 1% of the model length for circumference can be seen in Figure 5.. The figure shows the average value and standard deviation across the five repeated scans and four models for the static and standing trials, comparing the values to the reference model. For simplicity only the circumference slices have been plotted, however the SA data showed a similar trend.

For both the EinScan H2 and Photogrammetry technique, the standard deviation was greater at the proximal end of the residuum (>80% position), due to differences in trim line position. However, the variation in scan surface roughness for photogrammetry was consistently higher across all scans and models, as indicated by the larger CV and ICC values. As mentioned before, for simplicity only the circumference trends have been plotted in Figure 5. indicating the overall lower repeatability of the standing photogrammetry trial across several repeats.

3.3. Direct amputee scan analysis

For the direct amputee scans the EinScan H2 scans averaged 2,990 cm^3 volume with a standard deviation of 1.9%, and 30.5 cm (SD 2.2%) in length, comparable to the static and standing scans. The photogrammetry scans were on average 63.4% (SD 18.2%) larger, with the post smoothed files being on average 20.1% (SD 20.4%) larger than the EinScan H2 scans. For length the photogrammetry scans were 7.8% (SD 3.6%) longer. The smoothed files had marginal reductions in length being 7.7% (SD 2.8%) longer than the EinScan H2 scans.

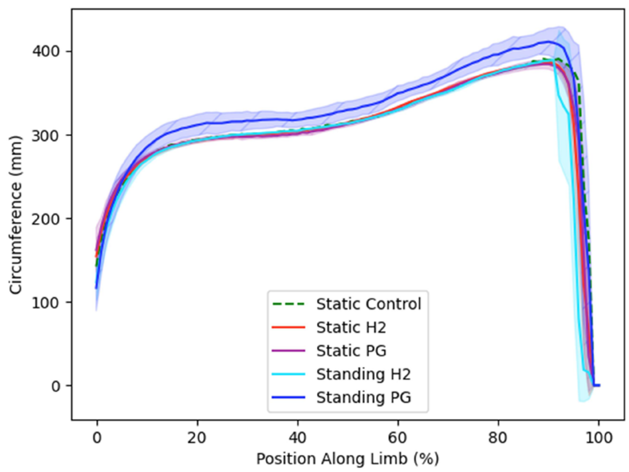

Figure 5. Scan circumference averaged across five scans from four models for H2 and photogrammetry (PG) compared to digital reference model (static control). Colour bands are standard deviations.

A visual comparison between the EinScan H2 and photogrammetry scans including the smoothed scans is shown in Figure 6. The majority of the surface of the photogrammetry scan is larger than the EinScan H2 for this example, with some notable expiations around the distal and medial tibial head which are smaller. The smoothed photogrammetry visualisation is for the same scan file, with the increase in green areas indicating the smoothing process has reduced the volume in some larger areas, however there majority of the scan surface is still significantly larger or smaller than EinScan H2.

The CR, CV, and ICC for the EinScan H2 scans were somewhat consistent with the static and standing trials, as indicated in Table 3, with CR being slightly smaller for the amputee scans. However, the Photogrammetry scans were on average 16.8% and 26.3 larger for circumference and SA respectively. When the photogrammetry scans were smoothed (PGS) the accuracy increased to 97.7%

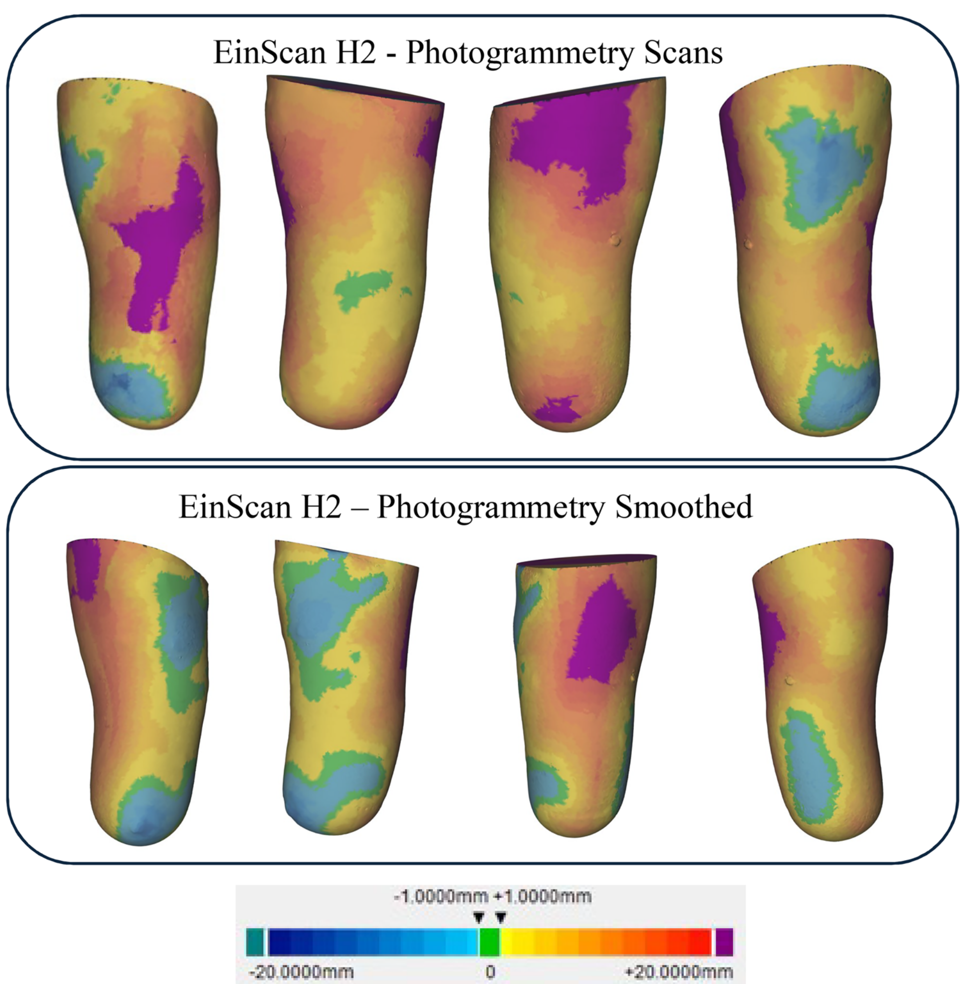

Figure 6. Heatmap topography comparison between a sample EinScan H2 and photogrammetry scan for the participant, showing anterior, lateral, posterior, and medial views from left to right.

Table 3. Accuracy comparison metrics between photogrammetry (PG) and EinScan H2 (H2) for amputee trials, and smoothed amputee trials (PGS).

	Circumference (mm)								
	Reference Value	Scan Average	Accuracy	RC (% of Reference)		CV	ICC	Distal Accuracy (SD)	
Amputee H2	367	367	NA	7	(2.0%)	14%	0.971	NA	(2.5%)
Amputee PG	367	441	83.2%	38	(8.6%)	23%	0.869	96.7%	(2.5%)
Amputee PGS	367	376	97.7%	42	(11.1%)	25%	0.872	87.9%	(4.8%)
	SA (mm^2)								
	Reference Value	Scan Average	Accuracy	RC (% of Reference)		CV	ICC	Distal Accuracy (SD)	
Amputee H2	10645	10645	NA	388	(3.6%)	26%	0.967	NA	(4.8%)
Amputee PG	10645	14444	73.7%	2237	(15.5%)	42%	0.869	98.2%	(5.0%)
Amputee PGS	10645	11322	94.0%	2417	(21.30%)	46%	0.844	74.8%	(10.7%)

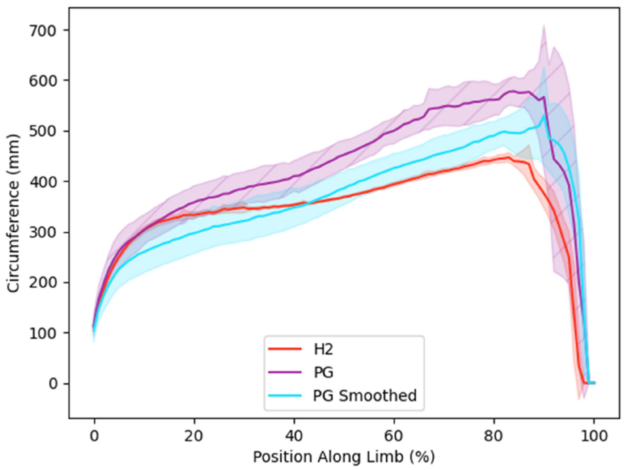

Figure 7. Average circumference and surface area of residuum scan with EinScan H2, direct photogrammetry, and smoothed photogrammetry scans, including shaded standard deviation bands.

and 94% for circumference and SA whilst still being larger than the EinScan H2 scans. However, the model proportions were distorted with the distal end of the residuum becoming smaller than the EinScan H2 scan, as indicated in Figure 4. Similarly, the CR for the Photogrammetry scans amputee trials fell between the range for the static and standing trials, whereas the smoothed scans had increased CR from 8% to 11% for circumference and 15% to 21% for surface area.

The accuracy of photogrammetry scanning the distal region (20%) of the models was comparable to the standing trials (>96%, SD <5%), however the smoothed files showed larger inaccuracies (75-89%, SD 5-10%) for circumference and SA indicating the smoothing process removed unnecessary volume from the end of the model. In addition the deviation in scan circumferences and SA is larger than the EinScan H2, 2.5% and 4.8% respectively.

4. Discussion

Across the static, standing, and amputee trials the EinScan H2 performed consistently well obtaining scans within the clinically acceptable limit of 5% in volume [40,41]. By comparison the photogrammetry technique was unable to meet the required accuracy standard for the standing and amputee trials including the smoothed files, being 6.9% and 63.4%/20.1% oversized respectively, with minimal changes in length. The accuracy for the static trials were consistent with the previous literature with volumetric accuracies between 96.5% and 99%, indicating the method could be used in a clinical setting for casts [23,30–32]. The reduction in accuracy is likely caused by the small natural movements in position of the limb between photos. This effect was exacerbated during the amputee trials as only one biological foot was available for stability and the angle of the knee could change. The standing method used in this study was specifically chosen to make photographing easier to mimic at home or remote scanning. Future studies could look to develop methods to support amputee residuum's to reduce the movements and examine if accuracies similar to the static trials could be achieved. Walters et al. and Cabrera et al. photographed amputee's limbs in a seated position, which could be more stable +1.7 to −0.4% error using different photogrammetry software (Poly Cam and Luma) compared to an Artec Eva scanner. However during preliminary testing for this study it was difficult to photograph the posterior of the residuum. It should also be noted that the number of photos in this study were lower (~38), based on prior work optimising the method, and other teams used more photos, with Walters et al. indicating that 75 photos was ideal despite both methods using similar principals [30,31].

During preliminary testing for the study seated trials were attempted in line with normal home seating options. However, the limited space under the residuum made taking photographs difficult. In many of the photos taken the researcher taking the photos was visible, photos were out of focus, and the limb was not fully in view, resulting in many failed meshes. In other studies, this has been avoided by the amputee sitting on high tables, and stools [31,32]. The seated position would inherently lead to less residuum movement, but would require more understanding of the technique and amputee mobility than the standing technique used in this study. This may limit application of the technique to the home environment.

Across all trials the EinScan H2 and photogrammetry showed good or excellent ICC scores indicating that both methods were reliability across scanning targets. Conversely the CV values for photogrammetry were significantly higher than the EinScan H2 during the amputee trials, 23-25% (circumference) and 42-46% (SA) and 14% (circumference) 26% (SA) respectively (Table 3), indicating poor precision. Similarly, the CR scores for photogrammetry were higher (8-11%) than ideal (5%) indicating the inconsistency between repeats. The lower precision would mean any sockets produced using this method could require further iterations and alterations before a comfortable fit is obtained, creating delays for the amputee and increase burden on prosthetists.

The accuracy in the distal region of the scans is critical as reduced distal space would create uncomfortable sockets for amputees. Generally the EinScan H2 performed well with accuracies ~99% (SD 5-8%). The photogrammetry technique performed comparatively well with distal accuracy ~97% (SD 2-5%), compared to the overall model accuracy of 73-83% for SA and circumference. When smoothed the distal accuracy decreased to 75-88% (SD 11-5%) accuracy for SA and circumference. This indicates that whilst smoothing increased the overall accuracy, it removed critical volume from the distal region. This may be accommodated for during the rectification process, but would add to clinician workload to process and modify scans.

The heatmaps shown in Figures 3, 4, and 6 indicate the surface differences between individual scans. As indicated by the volumetric and surface area analysis the static scans highlight the potential accuracy of photogrammetry with very close agreement to the EinScan H2, and only minimal areas of disagreement. For the standing scans there are some regions of larger and smaller volumes, indicating degermation in the photogrammetry techniques ability to recreate the surface topography. When averaged across the entire surface these deviations are less impactful, however in clinical practice concentrated regions of larger an smaller volumes will decrease amputee comfort and satisfaction in any socket produced form the scans. For the direct limb scans the surface deviations are much larger, for the example presented the entire medial region is larger on the photogrammetry and smoothed scans. As these areas of larger and smaller volumes appear randomly it is not possible to compensate through scaling or global changes to the mesh surface.

The tact time for the photogrammetry and EinScan H2 were comparable taking approximately five minutes. As sufficient time was given for the limb volume to stabilise, it is unlikely the scanning time will play a significant role in the accuracy of the scans. For clinicians the total time may be more impactful, processing the scans for photogrammetry took significantly longer, due to the cloud computing queues in ReCap. This increased time may create delays in clinical practice, however, multiple scans can be processed simultaneously using the cloud, and the local PC requirements are significantly less. Critically, the overall hardware cost for photogrammetry is significantly lower and more portable, making use of readily available smartphone cameras, compared to the ~£7,500 cost for the EinScan H2 and suitable laptop. The reduced cost, portability, and relative simplicity of smartphone photogrammetry could make it suitable for out of clinic use, reducing the travel burden for amputees and enabling support of amputees in remote environments.

It should also be noted that although the EinScan H2 was quicker, multiple scans failed on the standing and amputee trials where the point cloud position shifted creating two sperate surfaces requiring the scans to be discarded and retaken. Whilst none of the photogrammetry scans failed to mesh, the surface roughness and number of artefacts on many of the amputee scans was significantly higher. The inbuilt smoothing tools in ReCap were used in this study, however it did distort the shape of the model. Further studies could look at the effect of comfort on smoothing and scan surface roughness to determine if the smoothing operation is detrimental overall.

This study presents findings using Autodesk ReCap Photo. Whilst other software is available ReCap has previously shown to be sufficiently accurate for use and is simple to use, and freely available for education and research use. Previous testing had explored the use of Meshrooms, a free open software package, which struggled to reliably mesh photos [29–31]. Some smartphone apps were tested such as Polycam, Abound, and Objy however the software at the time was unreliable containing significant defects and failed scans, or had limited editing and export tools. Some of the apps tested also made use of LiDAR scanning which is not available on all smartphones, and came at varying levels of subscription cost (currently £14-24 per month for paid versions), and so were not used in this study. As photogrammetry becomes more common it is likely that the available software will continue to improve, other authors have reported successful use of Luma and Polycam [31]. In another study by Cabrera et al. bespoke software was developed to process images into 3D files for socket production and although the accuracy of the scans was not evaluated directly, they were able to produce comfortable sockets [32].

The calibration plate used in this study contained a grid system allowing different points to be used for scaling if some became obscured or distorted, making it more reliable than other calibration objects. A residuum mounted datum was included in this experiment, as can be seen in Figure 1, however it was inconsistently identified so was excluded from use in the study. The position of the plate meant it was viewable in most photographs, aiding in shape reconstruction and contributed to the >98% scaling agreement. This particular plate contained both metric and imperial grids, and whilst the metric grids were used in this study to be compatible with ReCap, the imperial grid was clearer and easier to identify in preliminary testing, suggesting 2-3cm grids in high contrast colours are better for calibration.

Conclusion

The aim of this study was to evaluate the accuracy of smartphone photogrammetry for direct amputee scanning. In the standing and amputee trials the scans were oversized by 6.9% and 63.4% for volume. The circumferential accuracy was 94.5% during the standing trials and 83% for amputee trials. Overall photogrammetry was not sufficiently accurate for clinical use as a direct amputee scanning tool with the method presented. With further developments to restrict limb movement, specifically inline with the static scans, it could be possible to use photogrammetry for remote scanning, making digital prosthetics manufacturing increasingly more accessible to clinicians and amputees regardless of location.

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ORCID

Sean Cullen http://orcid.org/0000-0002-9515-9000
Amir Mohagheghi http://orcid.org/0000-0003-4295-3718
Ruth Mackay http://orcid.org/0000-0002-6456-6914

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