Report on the TIDAL Network Plus Feasibility Project: Remote Scanning of Residual Limbs

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What we set out to discover

Background and research context

The socket is a critical part of any prosthesis, it is the interface between the rigid prosthetic frame and the soft tissue of the residual limb. If a socket is uncomfortable, most amputees will abandon the prosthesis [1]. Early adoption of a prosthesis can be very beneficial for the user, hence prosthetists aim to fit a socket as soon as possible post-amputation [2]. However, this aim is in contention with the variable volume of the residual limb post-amputation, as the residual limb undergoes significant reductions in volume due to chronic muscle atrophy and a decrease in post-surgical enema [3, 4]. Pezzin et al. conducted a survey finding that amputees typically visit clinics 9 times a year on average for socket adjustments, coming from a sample of mostly established amputees (>2 years post-amputation) [5]. Due to the consequentially rapid turnover of sockets, clinicians construct 'short-term' sockets from thermoplastic sheets that can be readily modified to compensate for small changes. During this course to stabilisation, the limb may lose between 17-35% [4] of its initial post-amputation volume, after which a long-term socket made of a more durable material such as carbon fibre may be fitted. Even once stabilised, the socket will have to contend with diurnal changes in volume caused by fluid transfer within the limb [3], varying anywhere between ±11% [6]. These changes can have a significant impact on comfort, especially for lower limb amputees [1] and necessitate the use of ply socks to ensure a snug fit, which may be adjusted multiple times over the course of a day [7]. Monitoring the magnitude and frequency of these volume fluctuations is important to determining the overall health of the limb, and whether changes need to be made to the socket.

Engineering / research challenge and why it matters

Current clinical measurement techniques are rudimentary, usually employing callipers and soft tape measures [8]. One common technique uses circumferential measurements to determine the volume, with results being between ± 8.1% of the standard water submersion method [9]. The water submersion technique, in which the residual limb is dipped in a full cylinder of water and the displaced volume of water is measured, is a more accurate method with a margin of error between 2.1-3.7% [10]. However, this method requires the amputee to remain very still. These traditional methods of capturing limb volume are labour intensive and have seen limited development in recent decades. An attractive alternative technique for measuring limb volume is the use of digital scanning, enabling the storage and sharing of three-dimensional models online. Additionally, this potentially allows for easy access and comparison between previous and current assessments. However, most state-of-the-art scanners are sizeable investments, typically costing upwards of £10,000 [11] in addition to the accompanying analysis software. This is a sizable investment for any clinic, especially when considering the current cost challenges facing the NHS. Therefore, a cost-effective and accessible scanning method is highly desirable. Few things are more currently accessible than a smartphone, with up to 85.4% of the world's population currently owning one [12]. Many companies have exploited the smartphone's camera capability when developing apps to allow users to recreate three-dimensional digital versions of objects around them by taking multiple photos, a process called photogrammetry [13]. As such, we wanted to determine whether these apps could be used to accurately scan patients' residual limbs, and thus if they could be used for clinical purposes. If successful, not only could this technology be integrated into clinics at minimal cost, but it's inherent accessibility and simplicity could allow it to be employed *outside* of clinics as well. Although there is no replacement for a clinician's skills and expertise, mobile scanning could provide a whole new avenue for patients struggling to access a clinic. Whether this be due to illness or mobility issues, the amputee may have a friend, family member or a carer who could scan their residual limb, with the data then sent to a prosthetist remotely for analysis. This potentially comes at a particularly pressing time in the aftermath of the Covid 19 pandemic, where the importance of having remote options available for assisting patients has become even more apparent.

Aims and objectives for the project

We investigated whether smartphone scanning applications could be used to collect residual limb data to an acceptable clinical standard. As such, the reliability and accuracy of such scans was examined. Additionally, whether the process of obtaining these measurements is reliably and repeatably achievable for a lay person was investigated.

What we did

The iPhone was chosen as the medium through which we investigated smartphone scanning potential, as the iPhone has the greatest market share of mobile users across the globe at 29% [14].Replicating the study on other popular mobile platforms such as Samsung, who account for 24% of market share, was deemed beyond the scope of this study. The iPhone 12 specifically was the smartphone used for all captures in this study, because it was the highest generation iPhone the authors had access to. A search was conducted into Apple Appstore applications that enable the capture 3D scans of objects to a high standard. After testing the applications detailed in Table 1. the majority were eliminated for producing poor quality scan data. This left two applications, namely *Polycam* and *Luma*. Polycam is the most popular 3D capture software on the Apple Appstore and employs photogrammetry to create 3D models from photos captured in-app [15]. The *Photo Mode* setting was used which does not require use of a LiDAR sensor, an integrated method of determining depth that has become common in 'Pro' iPhones, following the iPhone 12 Pro (after October 2020) [16]. This would allow our approach to be replicated by the iPhone 6S and later iPhone generations, as well as Android phones, at a subscription cost of £14.99 a month at time of writing. Luma uses NERFs (Neural Radiance Fields) [17], that generate a point cloud from which a mesh can be extrapolated [18]. Luma is free to use and is compatible with the iPhone 6S and later iPhone generations. In the interest of breadth, we also evaluated an open-source desktop application called Meshroom [19]. Meshroom locally converts a pre-captured set of photos into a 3D model, whereas Polycam and Luma operate through the Cloud. Polycam and Luma also have websites to which photosets can be uploaded, opening the door to users without access to these apps. As such these web services were also evaluated.

Table 1. Appstore applications investigated prior to testing with live participants. Only Polycam and Luma exhibited sufficient ease of photo collection and the ability to generate a good quality mesh.

Scanning Application	Camera	Scan Method	Passes Criteria?
Polycam	Rear	Photogrammetry	Yes
Scaniverse	Rear	Photogrammetry	No
Metascan	Rear	Photogrammetry	No
ScandyPro	Front-facing	Photogrammetry	No
3D Scanner App™	Front-facing	Photogrammetry	No
Luma	Rear	NeRFs	Yes

Ten residual limbs in total were scanned across seven participants, as listed in Table 2. There were five distinct levels of amputation covered, with the most represented being transtibial (TT), accounting for four of the ten, followed by transfemoral (TF), accounting for three. Lower limb amputations account for eight of the ten limbs investigated, aligning with the typical prevalence of major lower limb amputations over major upper limb amputations [18]. Infection accounted for five of the ten amputations, with the next most prevalent being trauma. Limb volumes ranged between 550 ml – 2530 ml, and the average participant was 56.6 years old, living as an amputee for 12.6 years.

Table 2. Data of the seven participants scanned, each having one residual limb scanned apart from participant E, a quadruple amputee, who had all four residual limbs scanned (TR = transradial; TH= transhumeral).

Participant	Limb Class	Mass (kg)	Height (m)	Years since Amputation	Age (Years)	Cause of Amputation
A	TF	103	1.87	1	43	Orthopaedic Surgery Failure
B	TT	67	1.64	13	56	Infection
C	TT	92	1.89	7	60	Trauma
D	KD	140	1.72	6	56	Trauma
E	TR, TH, 2xTF	65	1.67	10	43	Infection
F	TT	73	1.61	6	73	Orthopaedic Surgery Failure
G	TT	95	1.85	45	65	Trauma

All measurements were conducted by the lead author of this study, following several hours of experience with each application spent scanning 2 different static residual limb models, in different environments. However, it must be noted that hours of training would not be required for new users, due to each applications user-friendly interface and in-application tutorials. It is likely that a scan of comparable quality to those taken in this study could be achieved by a user within just a small amount of practice time. The participant doffed their prosthesis at least ten minutes prior to scanning , as swelling of up to 6% can occur within just an 8-minute period [3, 8, 20]. A reference object was attached to the anterior side of the limb, which was used to rescale the generated meshes in post-processing to match the real dimensions. Small stickers were dispersed on the limb's surface to aid tracking and scan alignment, ensuring two stickers were visible from any viewpoint. Between 80-150 photos were taken for each scan, with at least a 70% overlap between consecutive photos to ensure there was enough shared data between photos for correct orientation [21]. Scanning stopped once the whole surface of the limb had been captured from multiple angles and levels of elevation, which took on average 4 minutes per scan. This typically required the operator to get into awkward positions, such as laying in a supine position on the ground to gather photos of the limb's posterior.

The Artec EVA structured light scanner was used as the control, having previously been proved by Seminati et al. to provide both accurate and reliable scan data, within 1.4% of the control volume [22] . The capture procedures were similar for each application, requiring overlapping frames of the limb to be caught at multiple angles and elevations, ranging from 80 to 150 frames per capture. This process was repeated three times for the two apps, with the same photoset used for each web application and Meshroom. The participant was asked to remain as still as possible during each scan, and to position their limb in a way they found comfortable, as exemplified in Figure 1a.

Figure 1. a) Transtibial limb of Participant C during scanning. Tracking stickers are placed randomly around the limb, enough such that at least two are visible from any angle, and the scaling object is placed with double-sided tape around the bony prominence on the knee to minimise movement during scanning; b) Transtibial model in the home environment with natural lighting. Tracking stickers are placed around the limb, and the scaling object is connected to the limb with a Velcro strap to improve adhesion.

All scans required post processing in the mesh editing software Blender 3.3.1 to remove unnecessary information such as background geometry and the rest of the participant. The measurements were then conducted in *Artec Studio 12*, by aligning each participant scans with the control scans, and splitting each limb into ten cross-sections along its length, as shown in Figure 2b. Analysis was conducted on three key attributes, these being the volume, perimeter, and cross-sectional area (CSA). For each of these, a validity and reliability assessment were performed along the length of the limb for each of the applications, from which the bias and Pearson correlation coefficients were determined, together with reliability coefficients. The surface quality of each scan was assessed qualitatively with visual analysis.

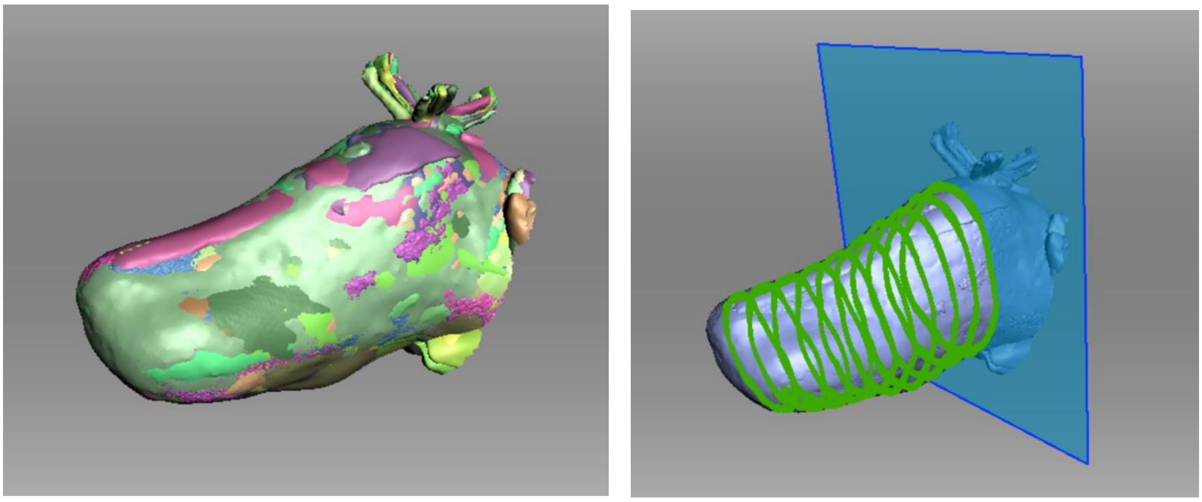

Figure 2. (a) All 18 scans of participant F's transtibial limb aligned with the control scan in Artec Studio 12. b) Corresponding scan being split into 10 even sections just past the knee joint, each measuring the perimeter, cross sectional area, and volume of the limb.

What we found

Validity

Scanning Method	Bias		Limits of Agreement		Average Deviation from Criterion (%)	RMSE (mm)	Pearson Coefficient
	Raw (ml)	Standardised (%)	Raw (ml)	Standardised (%)			
Polycam	-20.68 *(-37.2, -4.2)*	-2.9 *(-5.3, -0.6)*	86.4	12.2	1.3 *(0.3, 2.3)*	1.99	0.999
Polycam *(Web)*	-50.13 *(-91.8, -8.5)*	-7.1 *(-13.0, -1.2)*	218.5	30.9	3.0 *(0.5, 5.5)*	2.31	0.989
Luma	-7.1 *(-23.0, 8.8)*	-1.0 *(-3.2, 1.2)*	81.9	11.5	1.4 *(0.9, 2.0)*	2.36	0.999
Luma *(Web)*	-6.5 *(-25.5, 12.5)*	-0.9 *(-3.5, 1.7)*	96.1	13.3	1.7 *(0.6, 2.8)*	2.04	0.998
Meshroom	-145.7 *(-270.9, -20.5)*	-22.3 *(-41.5, -3.1)*	594.5	91.1	8.3 *(0.7, 15.9)*	2.50	0.886

Table 2. Validity chart marking each applications performance in volume measurements against the criterion.

Polycam and Luma were both found to have very low bias, within 20.7 ml and 7.1 ml of the control, or 2.9% and 1%, respectively. In addition, they both achieved volume results within 1.4% of the control volume, which is well within the underprediction margin of 2.5% for comfort determined by Fermi and Holliday [23]. The results were similar for the perimeter and CSA, with Polycam and Luma achieving a similar level of accuracy, within 3% of the control for both measurements. A trend was observed in which the typical error and bias across all three metrics increased along the length of the limb, and this was true for all applications tested. This is due to the smaller volume of the limb, but a similar value recorded raw error, resulting in a proportionally higher volume error. The root mean squared error (RMSE) was also close between Polycam and Luma. Whilst the criterion has an RMSE of 1.1 mm, Polycam and Luma have RMSEs of 2.0 mm and 2.4 mm, respectively. Figure 3b. exemplifies the RMSE distribution across the surface of each scan and shows their surface quality. Polycam shows good agreement with the control on the upper side of the limb, but largely underpredicts on the lower side of the limb. Luma shows similar behaviour, but with much more variation in the surface itself with an uneven surface. In the worse cases, Luma produces large crevices in low-light regions of the scan, which have a negligible effect on the CSA and volume measurements but a significant effect on the perimeter measurements. These surface features make Luma suitable for certain measurements but should not be used in the digital creation of sockets using CAD/CAM technology without considerable modifications.

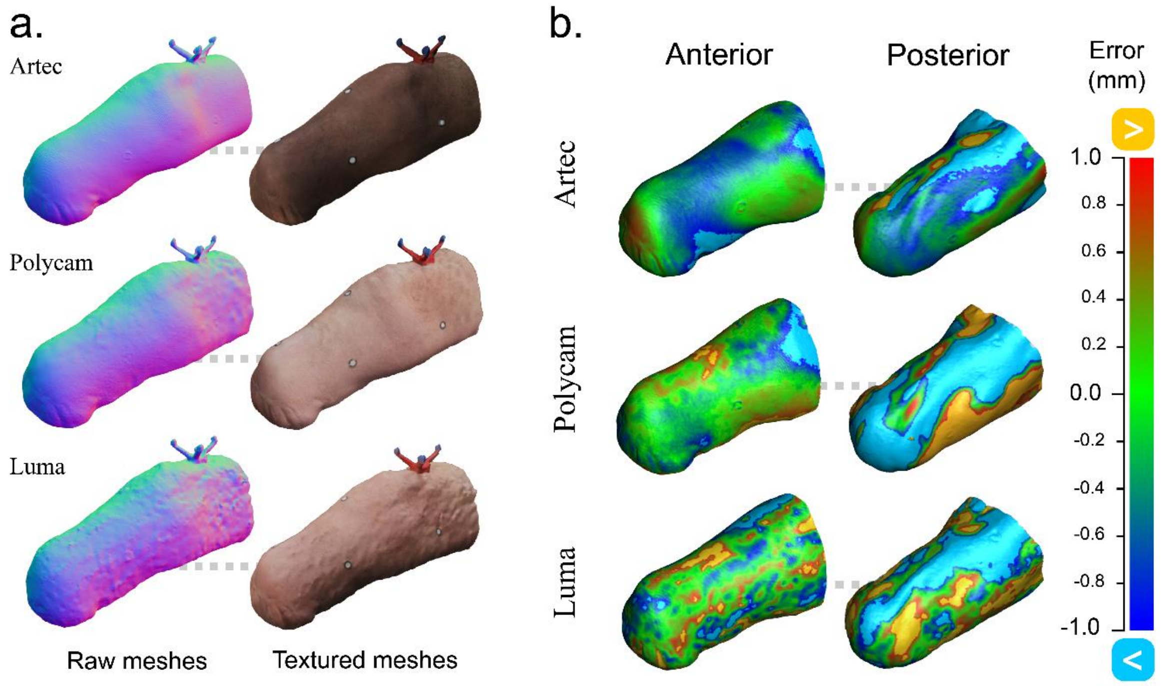

Figure 3. (a) The processed scans of Artec, Polycam, and Luma, of the transtibial limb of participant C. The surface quality of each scan is shown on the left, and the textured meshes are shown on the right. (b) RMSE values for Participant C across the Artec, Polycam and Luma Scans. Green indicates areas closely matching the control surfaces, whereas red and blue indicate areas within 1 mm of the criterion. Orange and cyan bands indicate areas exceeding the 1 mm boundary.

Reliability

Scanning Method	Change in Mean		TEM		CoV (%)	Correlations	
	Raw (ml)	Standardised (%)	Raw (ml)	Standardised (%)		Pearson	ICC
Artec	-1.7 *(-15.5, 12.0)*	-0.2 (*-2.1, 1.6*)	12.8 *(9.4, 21.6)*	1.8 *(1.3, 2.9)*	0.78 *(0.44, 1.13)*	1.000	1.000
Polycam	2.5 *(-18.4, 23.3)*	0.4 *(-2.6, 3.3)*	21.0 *(15.6, 34.7)*	3.0 *(2.2, 4.9)*	1.14 *(0.73, 1.55)*	0.999	0.999
Polycam *(Web)*	11.8 *(-73.9, 97.4)*	1.7 *(-11.0, 14.4)*	84.7 *(62.1, 133.7)*	12.5 *(9.1, 19.7)*	2.59 *(0.84, 4.35)*	0.987	0.989
Luma	-2.4 *(-28.5, 23.8)*	-0.3 *(-4.0, 3.3)*	25.3 *(18.6, 41.3)*	3.5 *(2.6, 5.7)*	1.37 *(0.80, 1.95)*	0.999	0.999
Luma *(Web)*	-3.0 *(-43.4, 37.5)*	-0.4 *(-5.8, 5.0)*	38.6 *(28.5, 65.5)*	5.2 *(3.8, 8.8)*	1.46 *(0.53, 2.39)*	0.998	0.998
Meshroom	-86.2 *(-397.4, 224.9)*	-15.5 *(-71.9, 40.8)*	285.1 *(202.7, 509.1)*	45.6 *(32.4, 81.4)*	10.27 *(-1.26, 21.80)*	0.885	0.841

Table3. Reliability chart marking each applications performance in volume measurements against the criterion.

Both Polycam and Luma performed with high reliability, with coefficients of variation (CoV) of 1.1% and 1.4%, respectively. This provides greater reliability than anthropometric measurements such as tape measures and callipers, measured between 2.4-5.7% [8, 24], as well as live participant measurements performed with water displacement, which are between 2.1% - 3.7% [7 - 9]. This suggests Polycam and Luma provide volume measurements more reliably than current clinical standards. They also boast high intraclass correlation coefficients (ICC), which measures the resemblance of multiple instances of a group. The clinical threshold is considered 0.9, and both Polycam and Luma each stand at 0.999. However, this is only the case for volume measurements. Regarding perimeter, Luma performs less reliably than Polycam due to surface artifacts that can cause inconsistent results between measurements.

What this means

Both Polycam and Luma have been shown as potential tools to be utilised inside and outside of clinical practice for the measurement of residual limb volumes. The capture process is simple for each, and although Polycam requires a paid subscription, an agreement could be struck between the developers and clinics for use by clinics and their patients. Although both apps performed well, it is recognised that Polycam is likely the better candidate for adoption, as it does not require rescaling, which significantly reduces the human error and produces much better surface geometry than Luma. Polycam's textured models do an especially good job of capturing the details of the limb, which could prove useful for remote analysis of limb health by clinicians. However, should a clinician or amputee not have access to a mobile smartphone with access to Luma or Polycam, it is recommended that the photoset is uploaded to Luma (Web). This is due to Luma (Web) producing similar results to Luma across the board, whereas Polycam (Web) consistently exhibited lower accuracy and reliability. Meshroom however shows no potential for clinical practice as it is vulnerable to movement between captures, an unavoidable consequence of in vivo scanning that results in meshes with significant distortion.

What next

Additional research is recommended into Polycam regarding whether the results found in this study are reproducible by multiple operators (including lay people) and a variety of smartphones. As only one operator with the same smartphone was used in this study, the variability and reliability of results between multiple operators and phones needs to be investigated further to determine the interclass correlation. In addition, due to how closely Polycam can reproduce the surface geometry of the control, it would be interesting to determine whether using CAD/CAM technology could produce viable sockets from Polycam surface scans. A paper is in draft format, with the target of publishing our detailed findings from this study in the Journal Plos One. Submission is expected by March of 2024. Future funding proposal developments are ongoing, with discussions taking place with additional academics, clinicians, and companies. Funding schemes that will be targeted include NIHR Challenge i4i, EPSRC responsive mode and Impact Acceleration Awards.

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Appendix

Carbon footprint calculations

Train to Manchester and 1 night in hotel, plus mileage (driving) for patients who came to volunteer to the project at the University of Bath: total carbon emission = 0.66 tCO2e