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

Sam Walters[1], Elena Seminati[2], Nicola Bailey[3]

1 Department of Mechanical Engineering, University of Bath, Bath, United Kingdom
2 Department for Health, University of Bath, Bath, United Kingdom
3 Department of Engineering, King's College London, London, United Kingdom

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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]. Therefore, prosthetists aim to fit a socket as soon as possible post-amputation since early adoption can be very beneficial for the user's overall satisfaction with the prosthesis [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 a chronic muscle atrophy and a decrease in post-surgical enema [3] [4]. Pezzin's survey found 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 to +10.9% [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 can 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 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 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 wanted to investigate whether smartphone scanning applications could be used to collect residual limb data to a clinical standard. As such, the reliability and accuracy of such scans will be examined. Additionally, whether the process of obtaining these measurements is achievable for a lay person will be investigated.

What we did

The iPhone was chosen as the medium through which we investigated smartphone scanning potential, as it 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. A search was conducted into Apple Appstore applications that enable the 3D capture of objects using the phone's built-in camera. After trialling the apps detailed in Table 1. in a preliminary investigation, the selection was narrowed to two, 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]. *Photo Mode* was used which does not require use of a LiDAR sensor, an integrated method of determining depth that has only become common in later-generation iPhones [16]. This allowed our approach to be replicated by iPhones 6 and later, 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 also available on iPhone and Android and is free to use. In the interest of breadth, we also evaluated an open-source desktop application called Meshroom [19]. Meshroom locally converts an already 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, but less focus will be placed on them.

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, accounting for four of the ten, followed by transfemoral, 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 half the amputations, with the next most prevalent cause 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.

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	Trauma
F	TT	73	1.61	6	73	Orthopaedic Surgery Failure
G	TT	95	1.85	45	65	Trauma

All measurements were conducted by the same operator, using an Apple iPhone 12 and consistent camera settings for each capture. Prior to scanning the participant doffed their prosthesis, 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.

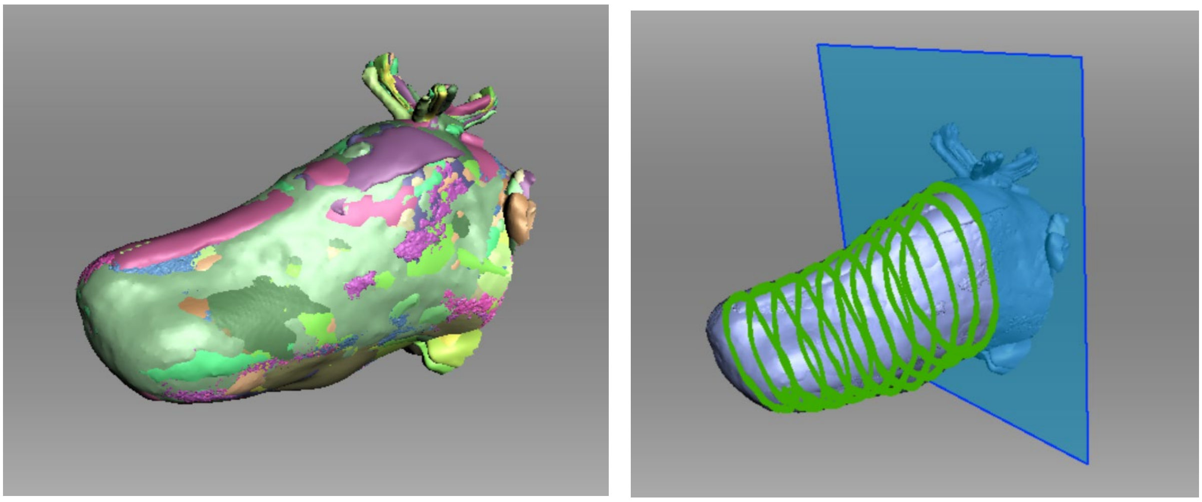

Figure 2. (a) All 18 scans of participant F's transtibial limb aligned with the control scan in Artec Studio 12. b) Corresponding scan being split into 10 even sections just past the knee joint, each measuring the perimeter, cross sectional area, and volume of the limb.

What we found

Validity

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

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

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 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.

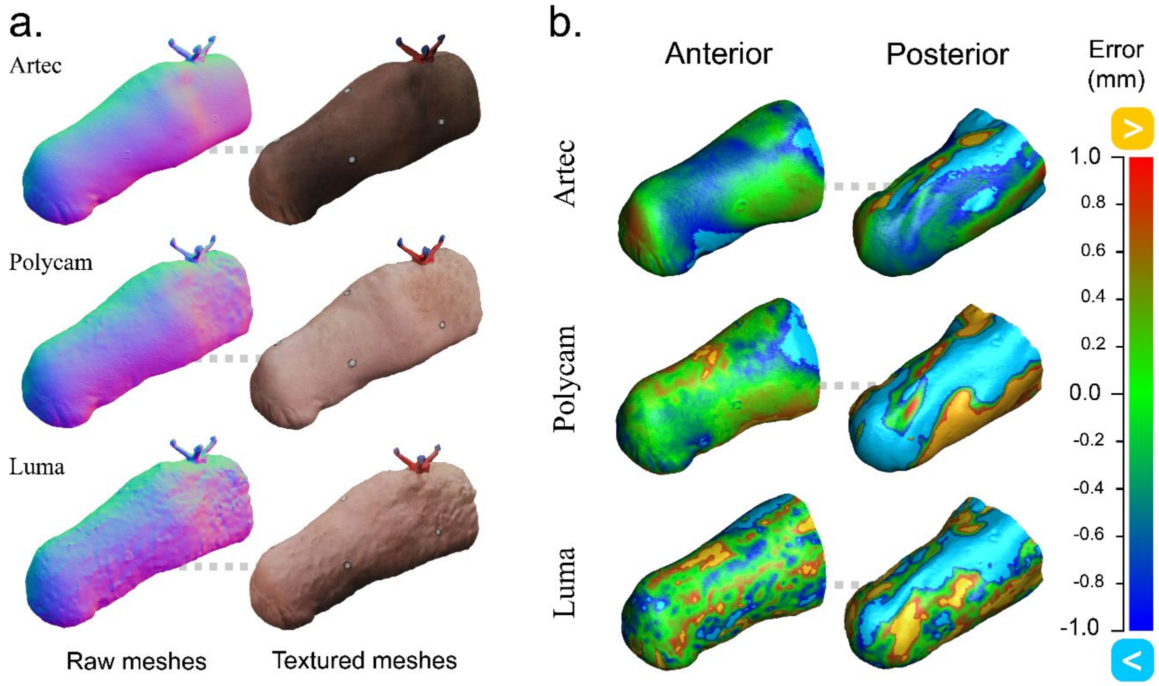

Figure 3. (a) The processed scans of Artec, Polycam, and Luma, of the transtibial limb of participant C. The surface quality of each scan is shown on the left, and the textured meshes are shown on the right. (b) RMSE values for Participant C across the Artec, Polycam and Luma Scans. Green indicates areas 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

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

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

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% [9, 22] [8] [24], as well as live participant measurements performed with water displacement, which are between 2.1% - 3.7% [7, 9] [6] [8]. 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 volatility 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 January of 2024. Future funding proposal developments are ongoing, with discussions taking place with additional academics, clinicians and companies.

TIDAL extension – Socket development

Although a compelling case is presented for how mobile phone scans can produce accurate measurements of residual limbs that may be used or referenced by clinicians to inform their decision of when to prescribe a definitive socket to the patient, the question of whether the scans may be used to produce a usable socket in of themselves remains unanswered. It goes without saying that there is no replacement for a prosthetist's skills in the production of definitive long-term sockets, a skillset that takes many years to effectively implement and perfect. However, the realm of test sockets for research purposes remains fertile ground for the implementation of scan-and-print sockets. Researchers employ a wide range of methods for testing upper limb prostheses with people that have a limb difference, from commissioning an official socket from a clinic, which can be costly and time consuming, to using tape and splints to build a makeshift single-use socket around the limb. There is a clear need for a simple, inexpensive, standardised solution for accelerating the process of producing individualised sockets. To investigate the feasibility of producing such sockets from phone scans, a scan of a transradial limb from participant E was used to construct a test socket (Figure 4a and 4b). The 3D model was created from the Polycam tool, since it was confirmed to be the best one in the first part of the project described in our published paper[25], as an outcome of the TIDAL project.

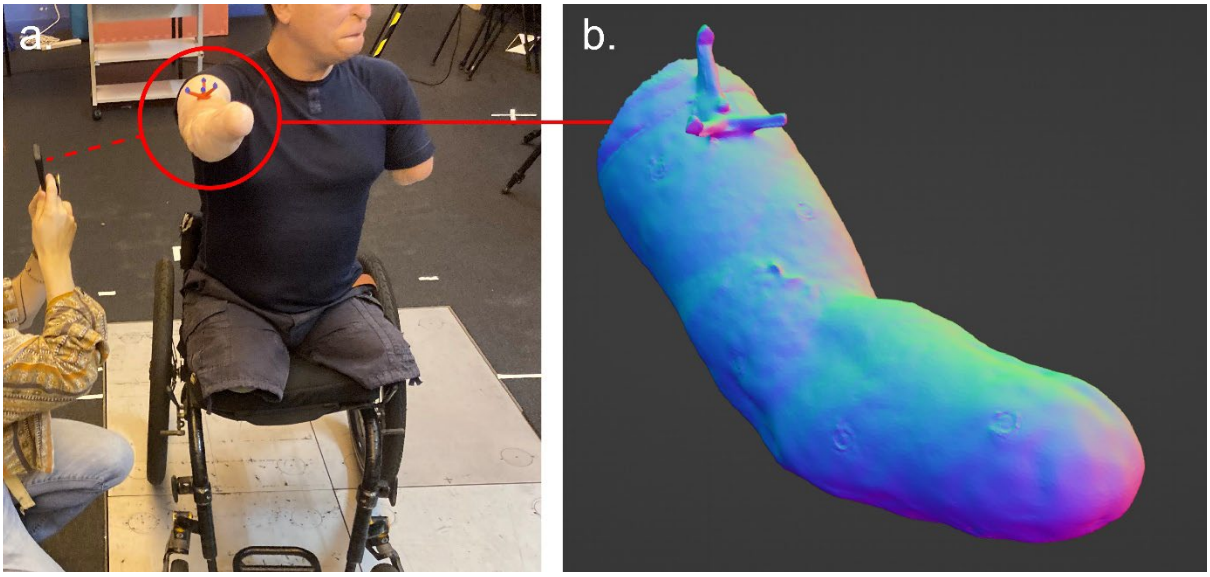

Figure 4a: Original scan session recorded during the first part of the TIDAL project with participant E, captured using Polycam on an iPhone; 12 4b: 3D model representation obtained with Polycam.

This scan was imported into Blender, a mesh editing platform, before the steps shown in Figure 5 are completed. First, a simplified mesh was shrink-wrapped over the residual limb scan (shown as stage 1.), then expanded outwards (stage 2.), and separated into panels that fasten to a wrist unit (stage 3.). The wrist was designed to be compatible with a standard series of wrist prototypes made by the author, such that any terminal device and wrist unit could be easily slotted into place with no socket modifications necessary, as shown by the complete test socket in Figure 5. The complete test socket was then 3D printed with an Ultimaker 3.

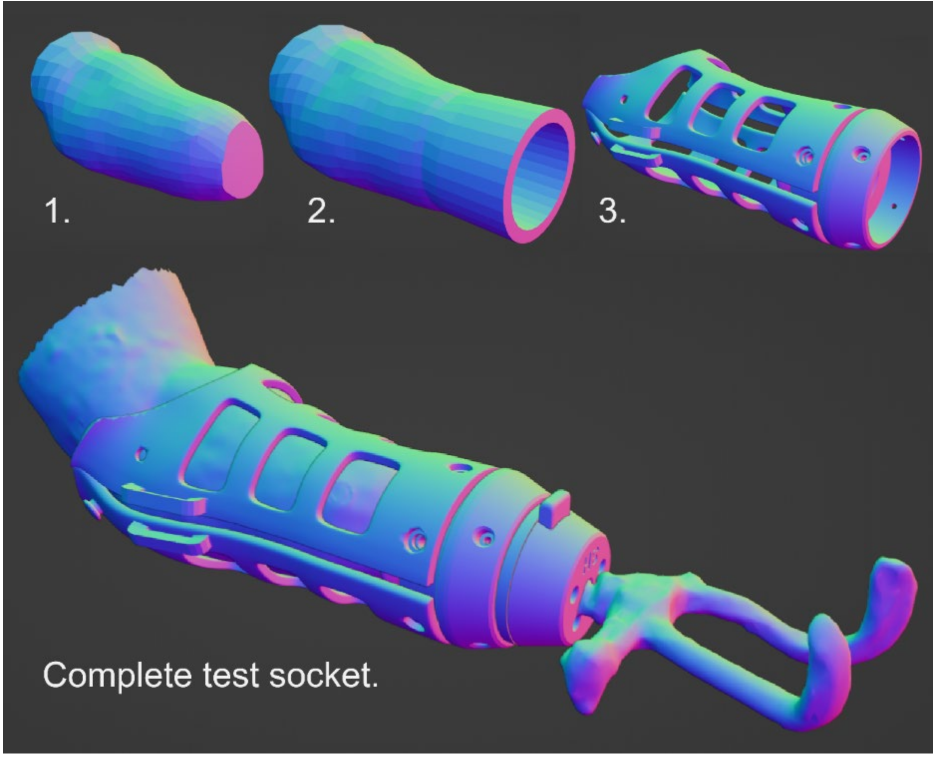

Figure 5. A demonstration of the process used to create the primitive socket before implementing functional features such as the wrist adaptor, socket holes, webbing supports and harness connection points. The complete test socket is shown with a simple split hook connected to the socket via a passive rotation wrist unit.

Socket Testing

Participant E was invited to try the socket and perform a few standardised tests to determine its performance and fit. Several activities from the Southampton Hand Assessment Procedure (SHAP) [26] were conducted, including the movement of several abstract objects, the unbuttoning of a shirt, the picking up and placing of coins, and a variety of other similar tasks. These were conducted with both the participants existing body-powered prosthesis and socket to serve as a control, and the 3D printed socket and voluntary-closing prehensor (Steeper, UK), pictured in Figure.6. The voluntary-closing prehensor was chosen because any force the user wishes to exert on the object in question must actively be provided by them, unlike with voluntary-opening split hooks which provide a passive closing force via an elastic band. This means any imperfections with the sockets design in how it transfers force to the participants residual limb will be made much clearer, highlighting areas for improvement and informing the socket iteration process.

Figure 6. Participant E using the 3D printed socket and voluntary-closing prehensor during the lateral grasping task of the SHAP test.

Due to the limited time available with the participant, a qualitative approach was opted for to determine socket fit rather than using the SHAP tests numerical outcomes. The participant was able to complete all the tasks with both their personal prosthesis and the test socket with prehensor. However, all tasks completed with the prehensor took longer. The participant reflected that this was due to their inexperience with the voluntary-closing socket design, as it is the reverse operation of his personal prosthesis. Following completion of the tasks, the participant was asked a range of questions regarding the socket, including how it felt, what improvements could be made to make it more comfortable, and how it compares with their day-to-day socket and liner.

The participant commented that they very much appreciated the holes in the socket panels that allowed their residual limb to breath without getting overheated, in addition to allowing them to view their residual limb and easily identify where irritation may be occurring. They commended the adjustable nature of the socket, but complained that when tight, the skin of their residual limb got nipped between the two halves of the socket, causing discomfort. As such, they suggested integrating foam into the interior of the panels and around the edges to distribute any pinching forces and improve comfort. They also suggested more opening around the elbow region, due to the ridge digging into the skin during full extension of the prehensor. The areas of irritation highlighted during the SHAP activities are shown in Fig. 7, showing where the ridges of the socket created irritation on the ventral and dorsal regions of the residual limb, respectively. Despite these areas of irritation, participant E was largely positive about the design, stating that the fit was good and that they can see themself wearing it comfortably for extended periods of time, providing the previously documented areas of irritation are addressed.

Figure 7. The residual limb of Participant E following the end of testing with the printed socket and voluntary-closing prehensor. Pictures a. and b. highlight the regions of localised force from the socket, providing excellent insight as to where reliefs in the socket need to be placed in the next iteration

Next Steps

Initial testing of the socket has proven promising. From a simple mobile phone scan, a socket was digitally fabricated, printed, and used to complete a series of tasks even with an unfamiliar terminal device. Areas of irritation were documented and will be addressed in the next iteration of the socket, by adding additional reliefs into the socket and incorporating foam padding to eliminate direct contact with the plastic surface. Once the revised approach has been validated, the ultimate goal will be for the participant to be scanned by a friend or family member at home, and sent to researchers such that a socket can be designed and 3D printed ready for their visit. This will save a significant amount of time for both the researcher and participants in future research endeavours.

Additional follow up fundings have been granted from the following funds:

- ALUMNI fund (University of Bath, £5,000): project title: Empowering limb diversity: bridging the gaps in paediatric prosthetic care.
- MRC-IAA fund (King’s College London, £79,859.54): project title: Scanning the world; an accessible and sustainable approach for limb difference care.

These additional fundings are supporting the collaboration between the University of Bath and King’s College London, with the final aim to apply for a larger grant aimed to bring this technology forward via larger clinical trials.

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