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Smartphone-Based Data Acquisition Method for Modelling 3D Printed Arm Casts

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In recent years, 3D printed arm casts can replace traditional arm casts to treat bones fractures. 3D printed arm cast modelling often uses professional 3D scanning systems to capture 3D data of the arm. These systems are very expensive and may not be available in many hospitals. In order to overcome this disadvantage, inexpensive methods should be developed. This paper introduces a new data collection method based on smartphones. The photos of an arm were taken with a smartphone camera using some special techniques that could facilitate the process of image processing and 3D modelling in Agisoft Metashape and CATIA. To validate the proposed method, the photogrammetric model was compared with the scanned model (obtained by a low cost scanner) in GOM Inspect. Besides, a fit check of real 3D printed arm casts attached on the volunteer's forearm was also performed. The test results indicate that the photogrammetric model could be used as raw data for 3D arm modelling.

Keywords: Photogrammetry, 3D printed, Arm cast, Smartphone, Data acquisition

1 Introduction

An arm cast is a sleeve used to encase and protect an injured arm. It holds a broken bone (or bones) in place for several weeks or longer and is removed when bone healing is confirmed. Traditionally, arm casts are usually made of plaster or fiberglass. In general, plaster or fiberglass arm casts can be very effective for treating some specific types of fractures, but they also have disadvantages. For example, they are heavy and uncomfortable to wear, not waterproof, and can cause unpleasant odors and skin irritation. Recently, three-dimensional (3D) printed arm casts can be used instead of traditional ones. A 3D printed arm cast is one that can be printed layer by layer using a 3D printer. 3D printed arm casts are more expensive than traditional arm casts, but have some advantages such as waterproof, custom-fit to patient's arm, durable, lightweight, diverse in colour, high aesthetics, less itching and removable.

It can be seen from the literature that some novel concepts for the design and manufacture of 3D printed arm casts have been presented. In general, an engineering process consisting of reverse engineering and 3D printing technique could be used to develop a 3D printed arm cast. Some major steps of this process are as follows [1, 2, 3]: (1) data acquisition of an injured arm surface, (2) designing a 3D model of an arm cast in Computer Aided Design (CAD) environment(s), and (3) fabrication of the arm cast with a 3D printer. In the first step, professional 3D scanning systems were often used to capture digital data from the arm. Some examples of these systems are commercial 3D scanners [1-5], computed tomography scanning or magnetic resonance imaging systems [1, 2, 6, 7]. It is clear that very good results can be achieved with professional 3D scanning systems, but these systems are still expensive and require highly qualified personnel to operate. These obstacles could be overcome by using photogrammetric methods.

Today, photogrammetry can be used to obtain 3D coordinate points on an object using a set of 2D (2 Dimensional) images captured by digital cameras. For this application, a single camera, such as a smartphone camera, could be possible. Some studies show that instead of 3D scanners or other expensive devices, smartphones with integrated high-resolution cameras could be used in some medical applications [8]. Smartphones are now widespread in everyday life and very cheap compared to professional 3D scanning equipment. Using a smartphone to photograph an arm requires the use of photometric software and some special 3D modelling techniques to ensure the required accuracy of the virtual model. This work describes a novel method that can be used for data acquisition of arms using a smartphone. From this data, a 3D CAD model of an arm could be reconstructed. The accuracy of this model was also estimated by comparing it to a 3D scanned model of the arm and checking the fit between the 3D printed arm cast and the forearm of interest.

2 Methodologies

The following section describes the procedure for obtaining data to create a 3D model of hand in experiment.

2.1 Image acquisition

Agisoft Mateshape 1.8 (Agisoft LLC, Russia) was used for photogrammetric processing of 2D images to create 3D models of arms in this study. Arm position, camera position and orientation and some unique techniques for image acquisition are presented below.

In the first the arm position was necessary to realize for scanning. In this study, the photos of the volunteers' arms were taken with a smartphone camera. When taking pictures, arm should be kept in a suitable position without moving (theoretically). The volunteer could sit on a chair and put his/her elbow on a desk or on the wingback of the chair (Fig. 1) and his/her forearm was up at any angle provided that it could be displayed in the captured frame.

Fig. 1 *Picture capturing arrangement*

It was also necessary to solve the camera position and orientation. The smartphone was attached to the phone holder of a 13 W LED ring light (Shenzhen Kasin Technology, China). The photographer held the LED (Light Emitting Diode) ring light in his hands and kept it at a distance of about 0.5 m from the volunteer's arm. The phone should be tilted and oriented in portrait mode to ensure that the part from the elbow to the top of the cylinder (as in Fig. 1) is captured in each photo, and the larger this part the better (in camera view). This is because maximizing the area of this part could yield optimal image features and ease the process of image alignment in Agisoft Mateshape.

The data collection process was carried out according to the instructions provided by Agisoft Mateshape. Through many tests, we found that errors in the image processing process can occur if the object to be photographed has a smooth and uniform surface. In order to facilitate the image processing task in Agisoft Mateshape and obtain a highly accurate virtual model, a cylinder can be used [9]. In this study, this cylinder is made of plastic with a blind hole to put on any finger. The cylindrical surface of the cylinder was turned, then painted and drawn with arbitrary curves by a pen maker as in Fig. 2. The diameter of the cylinder is 28.186 mm, measured using a new Mitutoyo digital micrometer. In the 3D modelling step, the cylinder was used as a reference to scale the reconstructed model to its real-world dimensions.

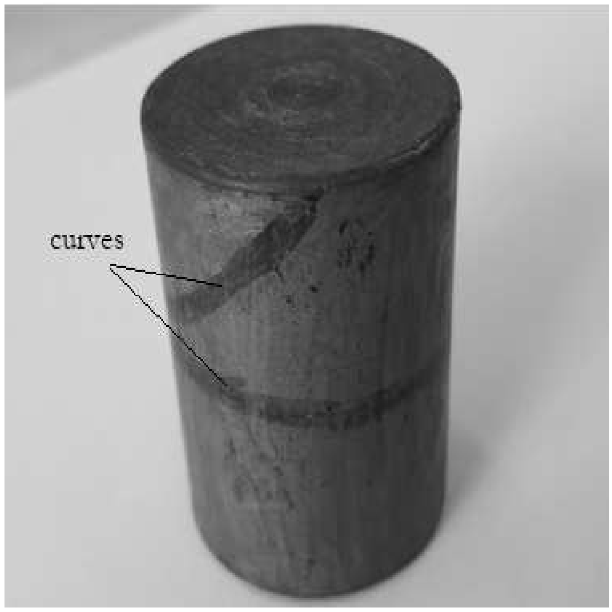


Fig. 2 *A cylinder with some arbitrary curves*

It was also necessary to deal with the capturing technique and the lightning condition. Photos for image processing in Agisoft Metashape should be taken with a digital camera that has at least a resolution of 5 megapixels and a focal length of 20 to 80 mm interval in 35 mm equivalent [10]. In this study, a Samsung Galaxy S10 Plus, which has a 12-megapixel camera with a focal length of 52 mm, was used.

In photography, it is obvious that photo quality is affected by lighting conditions. Using a series of photos with different lighting conditions for 3D reconstruction can lead to bad results like failed reconstruction process or incomplete models. Therefore, in this study, a special solution was applied to take the photos of arms as follows:

- Taking photos indoors without overhead lighting but with an LED ring light.
- Taking photos without flash or zooming.
- Using the automatic value of ISO (International Organization for Standardization) number, aperture and shutter speed.
- Setting an exposure compensation mode so that the skin of the arm is not displayed too bright or too dark in the picture frame, as shown in Fig. 3, and performing an auto focus lock.

The above settings also ensure that the photos were taken sharply and not blurred.

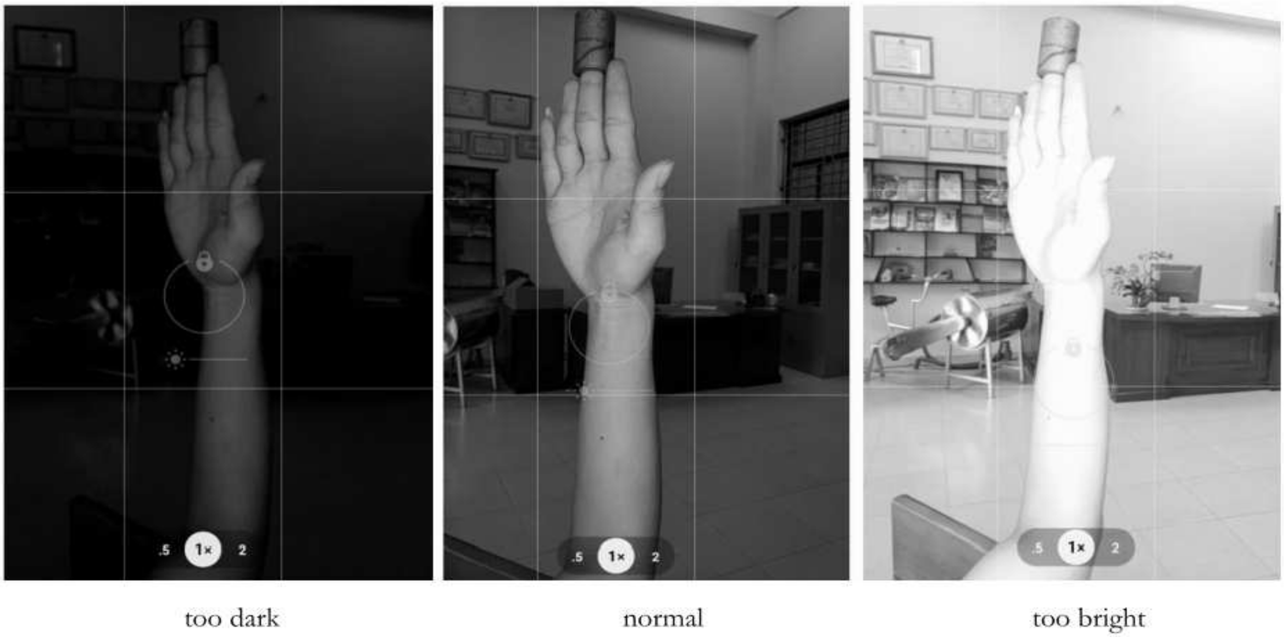


Fig. 3 *Three example of exposure compensation mode*

When taking photos, the arm was taken from different positions while the photographer was moving around the volunteer, and two consecutive images should have an overlap of about 60-80% [10].

2.2 Image processing and 3D surface modelling

In Agisoft Metashape, there are four main stages for image processing and 3D surface modelling [9]. First, photos are loaded and camera alignment is performed, then a sparse point cloud and a collection of camera positions is constructed. The next stage is the creation of a dense point cloud based on the recieved camera positions and their photographs. This point cloud can be edited and processed for the next stage. In the third stage, based on the dense point cloud, a 3D polygonal mesh model is generated that represents the object surface. This surface can also be textured. In the final stage, the 3D polygonal mesh model is exported to a neutral format for further processing. In this study, the STL (Standard Tessellation Language) file format was used as input data for modelling arm casts in a CAD environment.

The output of Agisoft Metashape is an unscaled model. It is not suitable for performing arm cast modelling task. Therefore, this model should be scaled to achieve an appropriate one. In this study, a 4-step procedure was employed in CATIA V5R2019 to obtain an accurate 3D model for modelling 3D printed arm casts. Firstly, the STL model was imported into the Digitized Shape Editor module. Secondly, the Basic Surface Recognition tool was utilized to recognize the cylindrical surface of the meshed model and approximate it into a perfect cylindrical surface. Thirdly, Measure tool was chosen to define the diameter of the approximate cylindrical surface. Finally, a scale action was performed for the arm and the cylinder by the Scaling tool, where the scale ratio was the ratio of the diameter of the real cylinder and the virtual cylinder. The scaled model (also called the photogrammetric model) was also saved in the STL file format.

The task of image processing and 3D surface modelling was performed on a desktop (CPU: AMD Ryzen 7 2700X 3.7 GHz, RAM: 16 GB, GPU: NVIDIA Geforce GTX 1070 Ti 8 GB).

2.3 Accurate estimation

Immediately after photographing, the arm of interest was also scanned with the CR-Scan 01 scanner (Reality, China). This is a handheld 3D scanner with an accuracy of 0.1 mm. The arm was held as the same posture as in the task of taking photos and the distance between the scanner and the arm was about 0.8 m. Only one scan of the arm was taken, and the virtual model of the arm was created automatically in CR Studio software. The scanned model was also saved as an STL model.

This study used GOM Inspect software (Zeiss Group, Germany) to check the accuracy of the photogrammetric model. GOM Inspect enables 3D inspection of CAD data sets. The accuracy of a component can be analysed based on the dimensional comparison of two CAD models, one of which is regarded as the reference model and the other as the model to be checked. The analysis results can be presented quantitatively and in the form of a coloured deviation map, which can easily visualize the deviation of one CAD model from another in 3D space [11, 12]. In this study, the arm casts were designed and fabricated only for the forearm portion of the arms. Therefore, the STL models for comparison were those having only the forearm part which was obtained from clipping the arm model. The reference model was the forearm model created with a 3D scanner (scanned model) and the other was the photogrammetric model. Two CAD models should first be imported into GOM Inspect. Next, the Alignment function can be used to automatically align these models to each other. At the end, a surface comparison can be carried out with the CAD Comparison function in order to display deviations in colour.

2.4 Fit checking

In addition to evaluating the accuracy of the photogrammetric model using GOM Inspect, 3D printed arm casts were also produced to assess the fit of the arm casts on the forearm of interest. To do this, the two STL models of the forearm, one is the scanned model and the other is the photogrammetric model, were imported into a CAD modeller. These models would serve as references for designing arm casts. This study used CATIA V5 R2019 (Dassault Systèmes, France) to create the arm casts. The modelling procedure is as follows:

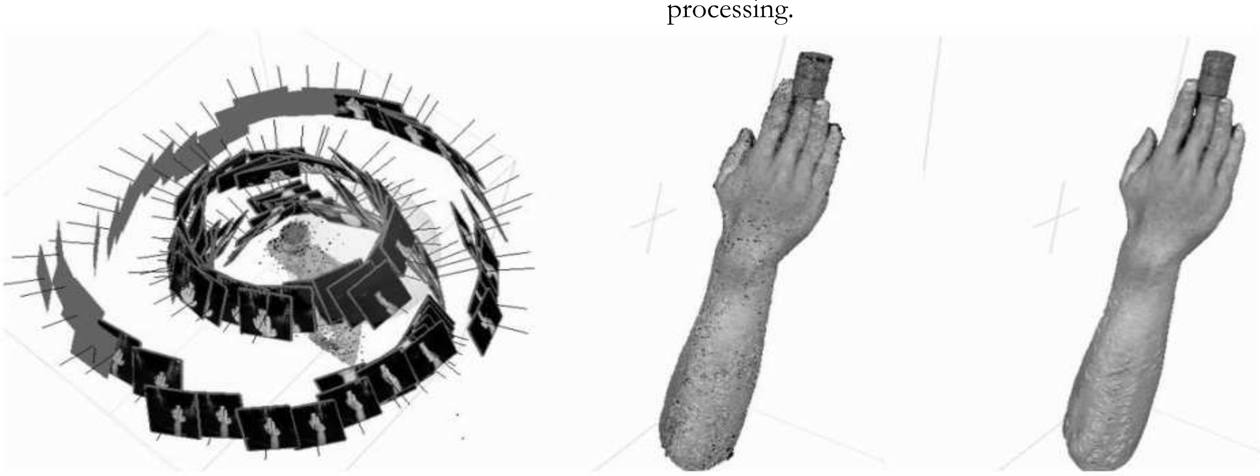
- Regenerate a mesh and then create a surface that represents the forearm surface. This surface is automatically approximated from the mesh.
- Create a thick surface from the forearm surface with a thickness of 3 mm. This value is also the thickness of the arm cast.
- Divide the thick surface into 2 parts by a cutting plane containing the axis of the forearm.
- Develop ventilation openings.
- Create clamp features.

Two arm casts were printed on a big Mendel 3D printer. This 3D printer uses PLA (Polylactic Acid) material for both part and support. The thickness of the print layer was set to 0.2 mm. After removing the support structures on two parts of the 3D printed arm cast, the inner surface of the 3D printed arm cast was coated with a thin layer of powder. The volunteer would wear each arm cast in one hour. A visual colour check was performed to assess the fit between the cast arm and the forearm.

3 Application and discussion

Five Vietnamese volunteers between the ages of 20 and 24 took part in this study. Their arm hair is very short, thin and almost colourless. This paper presents one of these cases for demonstration purposes.

121 photos of one arm were taken in about 3 minutes, the size of each file is approximately 2.243 MB to 3.339 MB. All of photos were accepted and the image processing process was successfully completed. Fig. 4 shows the sparse point cloud model with camera positions, dense point cloud model, and textured model of the arm at different stages of image processing in Agisoft Metashape. It took about 1 hour and 18 minutes for the first three main steps of image processing.



a) b) c)

Fig. 4 *Different stages of image processing: (a) sparse point cloud; (b) dense point cloud; (c) textured model*

Without considering the time for making the cylinder, it took very short time for preparing and capturing photos. This is because the camera setting is quite simple and the use of the LED ring with the smartphone is also convenient. Creating some arbitrary curves and shapes on the object to be photographed can ease the image processing process [3, 13]. However, in some cases, drawing objects on an injured limb can make the patient uncomfortable and unable to cooperate. Because there is no need to create curves and shapes on the limb in this study, patients can feel more comfortable and fully cooperate. Due to the fact that no error was found, it can be assumed that the cylinder, the capturing scenarios and the lightning condition have been facilitated the process of image alignment and processing as well as 3D reconstruction in Agisoft Metashape. On the other hand, auto focus lock technique helps reduce noise, so background processing is not required. These techniques could help Agisoft Metashape find the common points on the imported images and match them correctly, and also easily find the camera position for each photograph. The result is that the sparse point cloud and the set of camera positions are created successfully.

Fig. 5 presents the scaling definition in CATIA. In this application, the scale ratio was about 58.598. In spite of the fact that the scaling action was fulfilled based on the real and virtual cylinder diameters, the size of the scaled arm model could be similar to that of the real one. It can be seen that some portions of fingers of the photogrammetric model are not fully constructed and the forearm surfaces are not very smooth. In fact, it is not a problem as the part to be modelled is the wrist and/or forearm and this is just raw data for 3D modelling of arm casts.

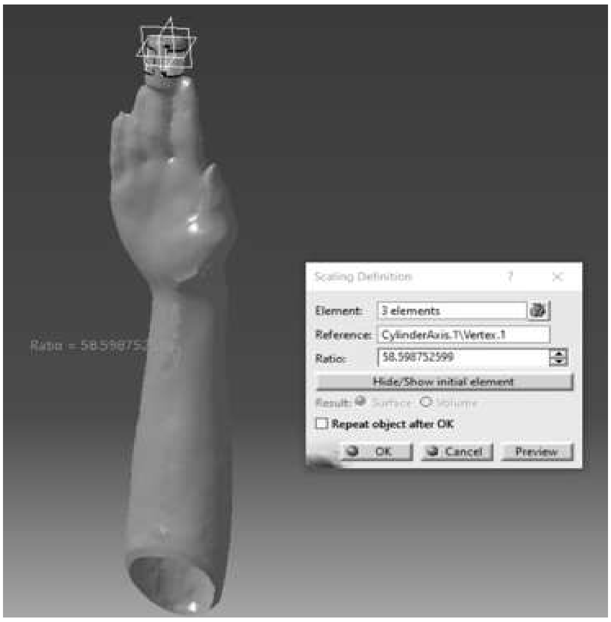


Fig. 5 *Scaling the cylinder to its real diameter*

The scanned model of the arm of interest is displayed in Fig. 6. The scan time was about 2 minutes. It is evident that this model is very precise and looks very smooth.

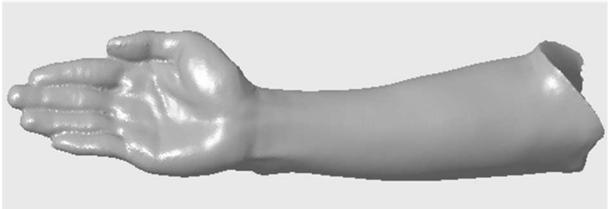


Fig. 6 *Scanned model of the arm*

Fig. 7 shows the two CAD models in different colours before (on the left) and after (on the right) automatic alignment in GOM Inspect.

Fig. 7 *CAD models alignment in GOM Inspect*

The colour map of deviations and some selected deviations between the two CAD models is shown in Fig. 8. It can be seen that the deviations were found everywhere. The light blue, green and yellow areas are the areas where very small deviations can be observed. In these areas, the deviations are between 0 and ± 1.5 mm. They are the areas of greatest similarity between two given data sets. In contrast, the red and dark blue areas have the least similarity. The deviations between the two CAD models are up to -2 mm in the dark blue areas and up to +2.59 mm in the red areas. These deviations are a bit large. This can be due to slight movements of the arm or even the fingers when taking photos. These movements can cause contraction and expansion of muscles and skin. This means that the state of the arm when photographed and scanned were not completely the same. Deviations in the red and dark blue areas can lead to big errors in 3D modelling. It should be noted that the total area of the red and dark blue regions is very small compared to the others. Therefore, these errors may not be relevant and can be ignored.

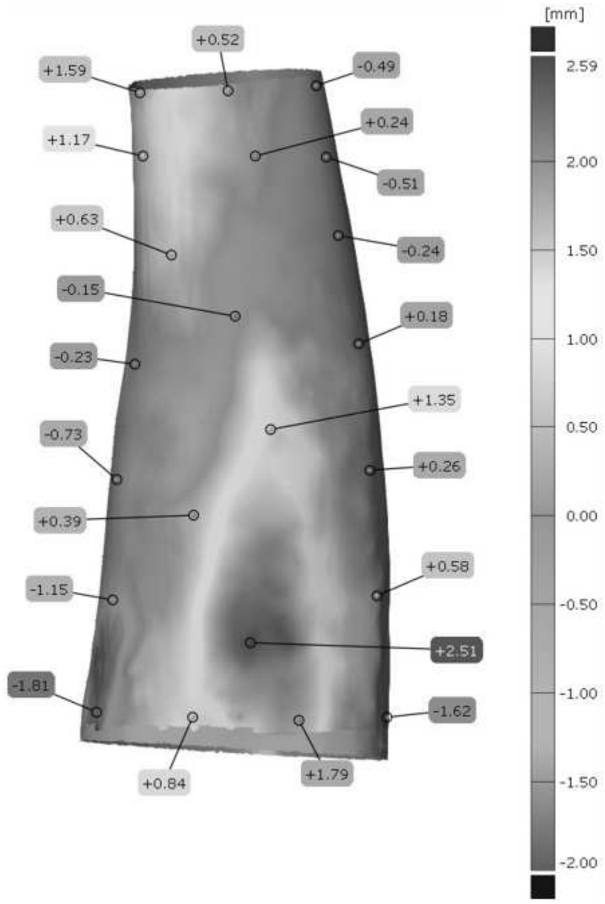


Fig. 8 *Colour map of deviations*

In medicine applications, some studies investigated the accuracy of photogrammetric model which was reconstructed using smartphone camera. Olivier Miguel [8] collected the photos of a lower limb by an iPhone 6S (12-megapixel camera). An A4 paper sheet was put on the floor and under the participant foot as a scale reference. The biggest bias between the model reconstructed by photogrammetry method (using Autodesk Recap) and the one created by a low-cost 3D laser scanner was 7.4 mm in the anterior-posterior axis. Hernandez and Lemaire used a Samsung Galaxy S5 smartphone (16-megapixel camera) to digitize 4 prosthetic sockets [13]. Eight makers were stick on the interior surface of the socket and two of them were used as a scale factor. Some distances inside the real sockets were measured and compared with those measured from the photogrammetric models which were also created in Autodesk Recap. The smallest and the biggest difference between them were 1.2 mm and 4.8 mm respectively, and the average accuracy in 3D reconstruction was 2.6 mm. In the study of Tursi et al. [14], a standard deviation of average 2 mm between two foot models created by a laser scanner and an iPhone 6S (12-megapixel camera) was found. Scale reference objects such as A4 paper and makers can be considered as 2D objects and big errors may exist when measuring their sizes on the real objects. On the CAD models, the same thing can take place due to manual selections and measurement capabilities of virtual measurement tools in photogrammetry software. In this study, the diameter of the cylinder can be measured with a high accuracy micrometer for the real cylinder and the Measure tool in CATIA for the virtual model. As a result, the photogrammetric model can have small size errors, and it can be good enough for 3D modelling of an arm cast.

Fig. 9 illustrates the results of three modelling steps of the arm cast where the input data was the photogrammetric model. It took about 20 minutes to create an arm cast model in CATIA. The modelling results show that it is easy to create the 3D model of the arm cast from the photogrammetric model. To a certain extent, it can be stated that the photogrammetric model is good enough for 3D arm cast modelling.

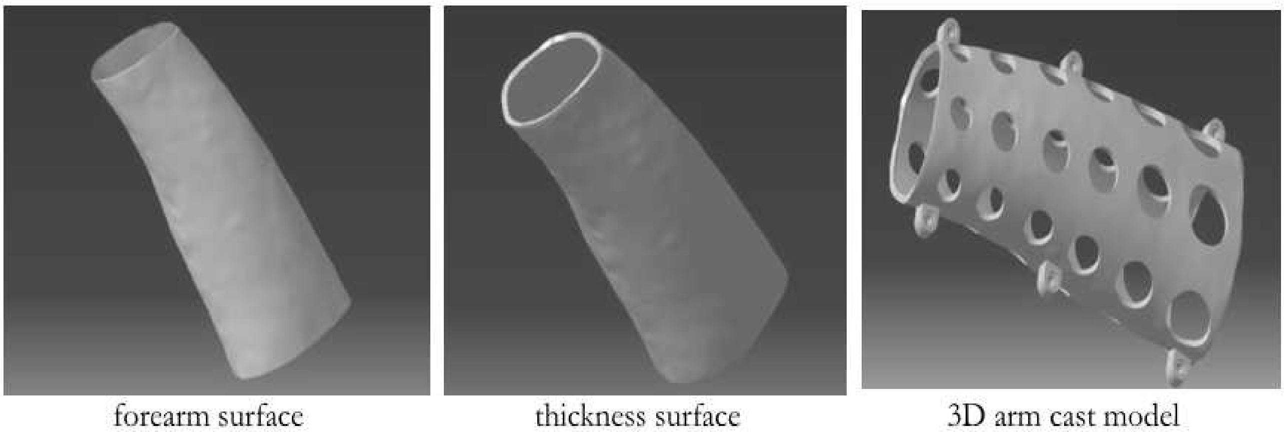


Fig. 9 *Three modelling steps of the arm cast*

An arm cast was printed and attached to the volunteer's limbs to verify fit. The two parts of the arm cast were fastened with 6 screws. The arm cast, in which the scanned model was the input data was also modelled, printed and assembled in the same way. Fig. 10 shows two 3D printed arm casts worn on the volunteer's limb and the colour imprints on the forearm.

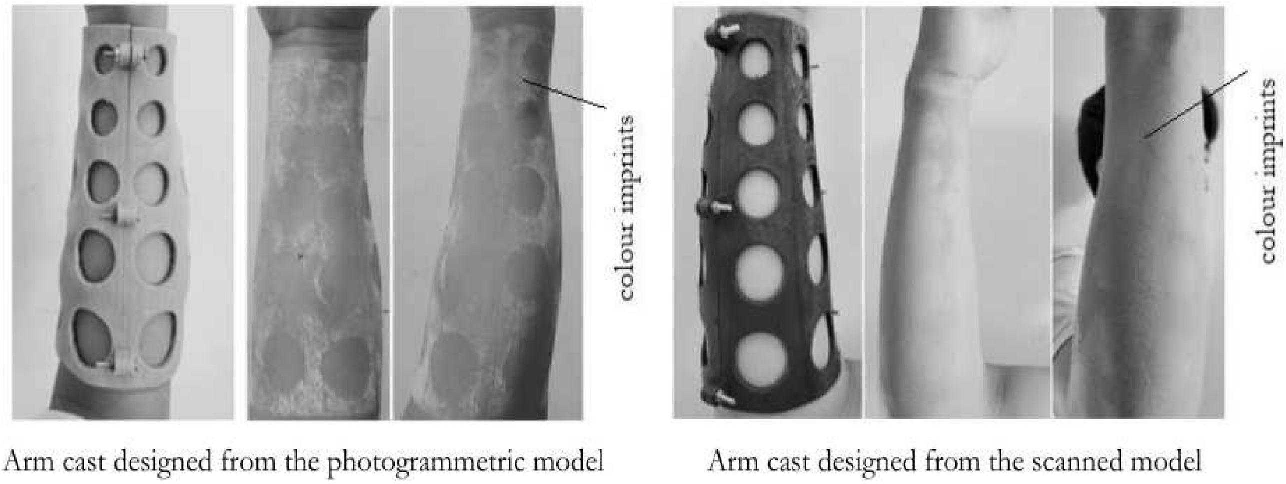


Fig. 10 *Two 3D printed arm casts and the colour imprints on the forearm*

It was important that the volunteer had no discomfort during the time of wearing two 3D printed arm casts. By visual observation, it can be found that both arm casts fit well with the forearm. However, according to the colour imprints on the forearm, it can be assumed that the arm casts designed from the scanned model has a better fit. In this case, the blue imprints are relatively evenly distributed and they appear almost continuously on the surface of the forearm. In the remaining case, the yellow imprints are less unevenly distributed and they are discontinuous at some places. This test demonstrates that although the 3D printed arm cast designed from the scaled model is less fit with the forearm than the one designed from the scanned model but it can also be suitable. Hence, the accuracy of the photogrammetric model can be accepted for arm cast modelling.

In this study, for the purpose of fit checking, there was no offset between the inner surface of the arm cast model and the forearm surface. To design a real 3D printed arm cast for bone fracture treatment, an offset of 1.8-3 mm should be applied for wearer comfort [15, 16]. The forearm model of this study is available for creating an offset surface, then a real arm cast model can be developed.

Other cases of this research also demonstrated that the 3D models of arm casts could be successfully constructed by using the proposed method and the accuracy of the final models could be acceptable for 3D modelling of arm casts. It can be considered that the proposed method is easy to conduct with low cost equipment. However, it should be aware that this method needs longer time for image processing. Reducing the number of images (but still maintaining the quality of the arm model) can reduce the image processing time.

4 Conclusion

A new method for data acquisition of arms with low cost equipment is presented in this study. In this method, the photos of an arm can be collected with a Samsung Galaxy S10 Plus smartphone using a special capturing technique, an LED ring light and a cylinder, and then successfully processed in Agisoft Metashape. The smartphone camera was not zoomed and the automatic value of ISO number, aperture and shutter speed were used. To prevent the skin on the arm from appearing too light or too dark in the photo, the smartphone camera was set to exposure compensation mode and autofocus lock. The LED ring light provided sufficient brightness when shooting in a room without a flash and overhead lighting. The cylinder with some arbitrary curves on it could facilitate the process of image processing and 3D modelling Agisoft Metashape. Thanks to the cylinder which used as a reference, the task of scaling the 3D model of the arm to the real world can be correctly performed in CATIA.

For a specific case, the comparison results of two CAD data sets, one with a hand-held 3D scanner and the other with the proposed method, show that the deviations between them are mainly smaller than 1.5 mm. Besides, the fit check also shows that the 3D printed arm cast designed from the photogrammetric model fits well with the real forearm.

These results can prove that the photogrammetry model could be good enough and could be used as input data for 3D modelling of the arm cast. It means the 3D models of arm casts could be successfully reconstructed by using the proposed method. Although the proposed method is time consuming, it is quite cheap and easy to use.

Determining the optimal number of images to reduce the time for the image processing process is another work of this study.

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