ISSN 1213–2489
e-ISSN 2787–9402

DOI: 10.21062/mft.2024.048 http://www.journalmt.com

Accuracy of Photogrammetric Models for 3D printed Wrist-hand Orthoses

Tuong Nguyen Van (0000-0002-6238-5458)[1], Natasa Naprstkova (0000-0003-4433-0581)[2]
[1]Faculty of Mechanical Engineering, Nha Trang University. 02 Nguyen Dinh Chieu, Nha Trang, Vietnam. E-mail: tuongnv@ntu.edu.vn
[2]Faculty of Mechanical Engineering, University of Jan Evangelista in Ústí nad Labem. Pasteurova 3334/7, 400 01 Usti nad Labem, Czech Republic. E-mail: natasa.naprstkova@ujep.cz

Today, 3D printed wrist-hand orthoses can be used to immobilize the arms instead of plaster or fiberglass casts. Typically, 3D arm models for modelling wrist-hand orthoses can be created using a 3D scanning system. Our previous study shows that smartphone cameras and photogrammetry techniques can be used instead of professional 3D scanning systems, but the accuracy of the photogrammetric models has not yet been fully investigated. This paper presents the results of accuracy verification of arm models reconstructed from 2D images captured with a smartphone camera. The forearm and wrist-hand parts of a photogrammetric model were subjected to a virtual inspection by comparing them with the corresponding parts of an arm model created with a 3D scanner. In addition, a physical verification was carried out by assessing the contact between the arm of interest and an actual 3D printed wrist-hand orthosis that was created with reference to the photogrammetric model. The test results show that the photogrammetric models achieve the necessary accuracy to serve as reference models for the construction of 3D printed wrist-hand orthoses.

Keywords: Photogrammetry, 3D printed, Wrist-Hand Orthoses, Smartphone

1 Introduction

Plaster casts (for centuries) or fiberglass casts (more recently) have been used to immobilize ill or injured limbs. Nowadays, three-dimensional (3D) printed casts can be used instead of the traditional ones which have some limitations such as being heavy, uncomfortable to wear, and not waterproof,... 3D printed orthoses are more expensive than the traditional ones, but they are waterproof, custom-fit, lightweight, diverse in colour, have high aesthetics, less itching, and are removable [1].

A wrist-hand orthosis (WHO) is a medical device that maintains the wrist and hand in a stable position. By its physical action, it can immobilize the limb to relieve the pain of a pathology and support recovery after an injury or an operation. A 3D printed WHO can be designed and fabricated by using reverse engineering and 3D printing techniques with some main steps as follows [2-6]: (i) Scanning the affected limb and converting the scanned model into a surface model, (ii) Designing the 3D model of the WHO, and (iii) 3D printing the WHO. The initial stage is associated with the process of reverse engineering, which allows for the digitization of a physical object and subsequently reconstructing its 3D model for additional applications [2, 5-10]. It is evident that expert 3D scanning systems can produce very good results, but they are still costly and need highly skilled workers to operate. Reconstructing a physical object's 3D model from its 2D images is now possible with photogrammetry [1, 11]. Therefore, instead of expensive 3D scanning systems, smartphone cameras and certain techniques can be used to obtain 2D images of an arm, which can then be further processed to create a CAD model of the arm [1]. According to this study, the proposed approach can create a photogrammetric forearm model that has recognized accuracy and could be used as input data for arm cast modeling. Nevertheless, this study does not examine the accuracy of the hand-wrist part of the photogrammetric model. The dorsal and palmar parts as well as the wrist all contribute to the more complex surface anatomy of the wrist-hand part compared to the forearm. Therefore, investigating the accuracy of the forearm and hand regions on the photogrammetric model can be considered for application in WHO modeling.

2 Methods

With some modifications, this study uses the method proposed in our previous study [1] to develop and produce WHOs. This method utilized photogrammetry, reverse engineering, and 3D printing. Fig. 1 provides the schematic diagram of this study.

In order to create 3D models of arms, Agisoft Metashape 1.8 (Agisoft LLC, Russia) was used for image processing of 2D images in this study.

In the image acquisition step, the volunteers' arms were captured using a 12-megapixel (MP) smartphone camera (Samsung Galaxy S10 Plus), a plastic cylinder, a light-emitting diode (LED) and some special techniques as described in our previous study [1]. Some camera parameters used are 52 mm focal length, automatic aperture, ISO number and shutter speed. The arm was photographed indoor with natural light, without flash or zooming. To facilitate photography and improve the quality of photos, instead of using a 13 W RED ring light, this study used a 20 W pocket LED video light (Ulanzi International Group, China) which was attached to the phone with a holder. In addition, the plain cylinder was replaced with a stepped cylinder made of monomer-cast nylon, painted in yellow with a random pattern as shown in Fig. 2. The larger cylindrical surface has a diameter of 36 mm, a cylindricity of 0.052 mm, measured on a Global S coordinate measuring machine (Hexagon, Sweden). To obtain a reference model, the arm of interest was scanned using the CR-Scan 01 scanner (Reality, China) immediately after photographing.

In the next step, the captured images were imported into Agisoft Mateshape and then processed to create the 3D model of the arm of interest. If an error occurs when aligning the photos, the volunteers' arms should be recaptured and the image processing process repeated. The successful unscaled Standard Tessellation Language (STL) model created by Agisoft Metashape would be imported into CATIA V5R2019 (Dassault Systemes, France) and then scaled to obtain an accurate 3D model (also called a photogrammetric model) based on the diameters of the virtual and the real cylinders. This step was performed on a workstation (3.7 GHz CPU, 16 GB RAM, 8GB GPU).

Obviously, the accuracy of the 3D arm model plays an important role in modeling WHOs. The photogrammetric model will only be accepted if its accuracy meets the modeling requirements. In this study, GOM Inspect 2017 (Zeiss Group, Germany) was also used to check the accuracy of the photogrammetric model through a dimensional comparison with the reference model. GOM Inspect has the capability to visually present the variations between two CAD models using a colour map [12, 13].

In addition to virtual verification, 3D printed WHOs were also produced to assess the fit of the WHOs on the desired arms. For this purpose, the photogrammetric models were used as references for designing WHOs in CATIA. The WHOs were printed on a low-cost 3D printer, using polylactic acid (PLA) material. After post-processing, a thin layer of powder was applied to the inner surface of the 3D printed WHO. The volunteer would wear the 3D printed WHO for 30 minutes. A visual colour inspection was then performed to determine the fit between the WHO and the arm.

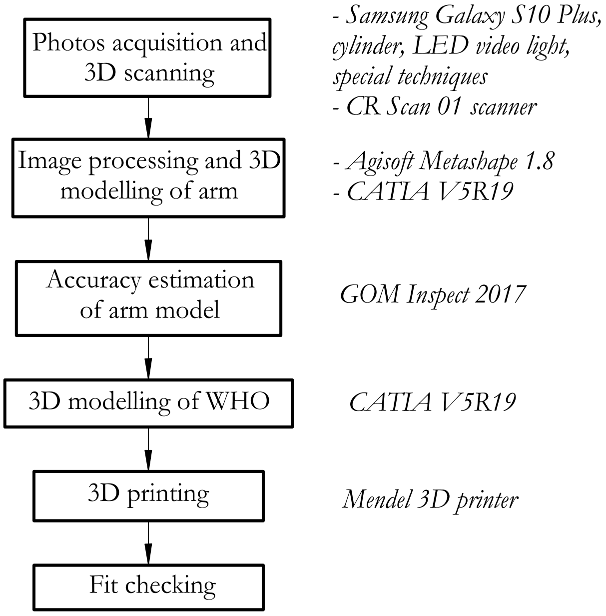

Fig. 1 *Schematic diagram of the study*

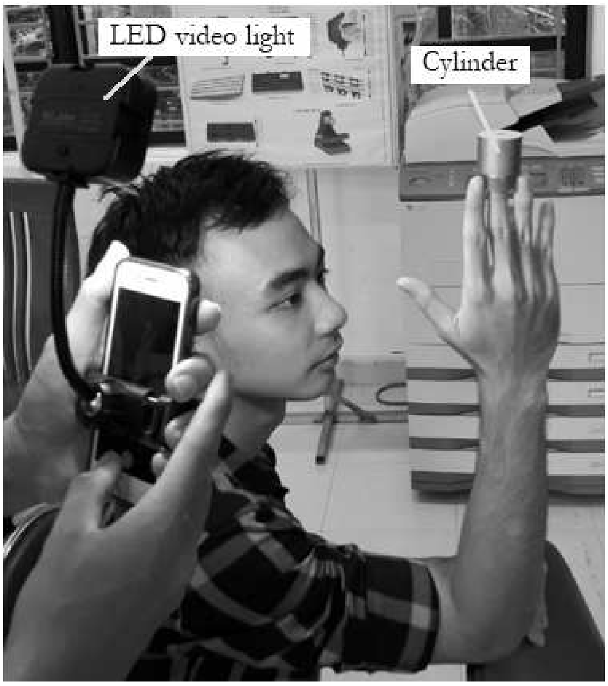

Fig. 2 *Picture capturing arrangement*

3 Application and discussion

Several Vietnamese volunteers participated in this study. This paper presents two typical cases for demonstration purposes. In the first case, 250 images, ranging in size from 1.5 MB to 3.1 MB, were taken of a woman's arm which has short and nearly colorless hair. In the other case, the arm of a man with long black hair was photographed in 261 image files, the size of each file is about 1.4 MB to 3.1 MB. For each case, the image processing procedure was executed successfully in about 1.5 hours with no errors in Agisoft Metashape. Since no error was detected, it can be inferred that the cylinder, the shooting scenarios, and the lighting conditions have contributed to the facilitation of image processing and 3D reconstruction processes. Fig. 3 shows the 3D texture models of the arms using the base texture type which retains the colours of the model surface. In general, it can be seen that there are differences in appearance of these models depending on the hair characteristics.

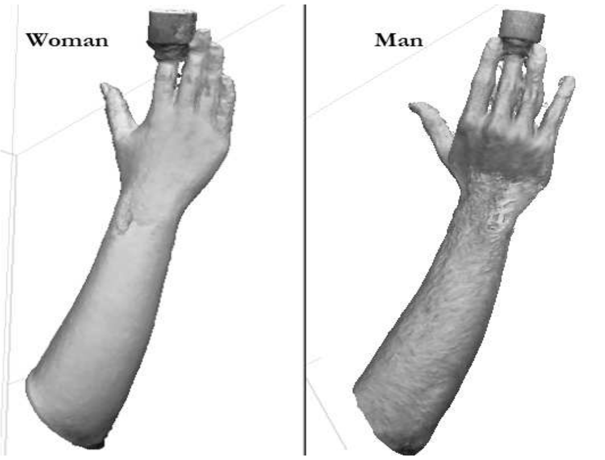

Fig. 3 *Textured models*

Fig. 4 presents two scaled models in CATIA with the scale ratio of 46.65 and 21.65, respectively. It can be seen that some parts of fingers of the photogrammetric model are not fully constructed. However, this is not a concern because the finger part is not used to model the WHOs, but the forearm and wrist-hand parts would be used as raw data for 3D WHO modelling.

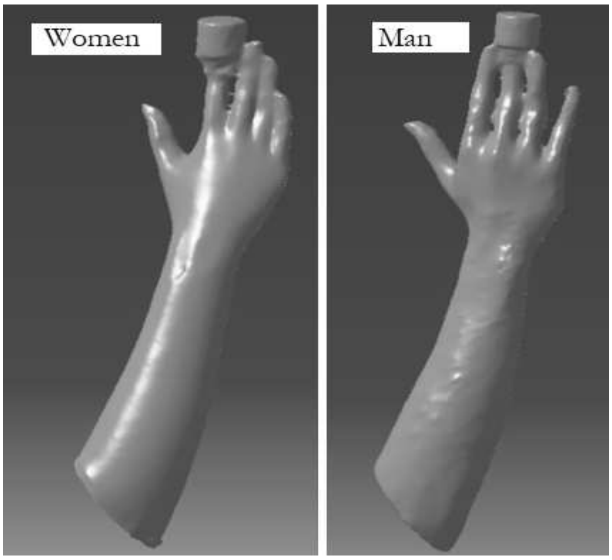

Fig. 4 *Scaled models (photogrammetric models)*

The scanned models of the two volunteer's arms are illustrated in Fig. 5. There is no doubt that these models look smoothing and can be very accurate.

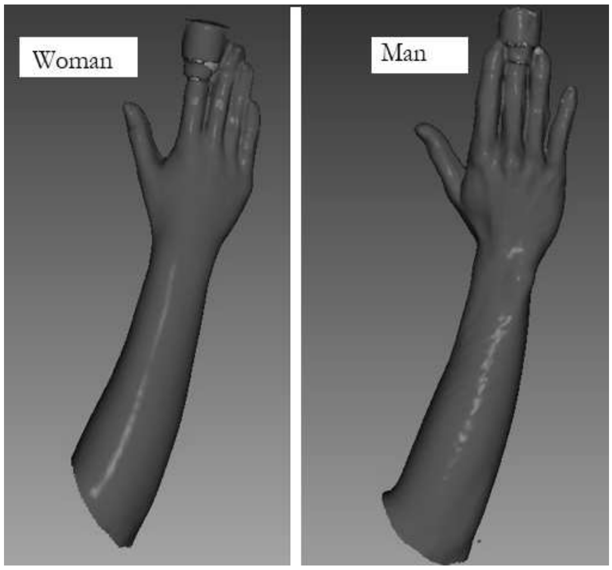

Fig. 5 *Scanned models*

For virtual verification of accuracy, for each case, the scanned model and the photogrammetric model were first imported into GOM Inspect, then they were automatically aligned and compared. Fig. 6 and 7 show the colour map of deviations and some selected deviations between two sets of CAD data for the forearm and wrist-hand parts. Regarding the woman, there are minor variations in the light blue, green, and yellow regions, whereas the dark blue and red regions exhibit greater deviations. Large deviations in the red and dark blue areas can lead to large errors in 3D modelling. However, it is important to observe that the red and dark blue regions have much smaller total areas than the other regions. As a result, these mistakes might not matter and can be disregarded. The situation is different in the man's case as the dark blue areas are slightly larger. The range and the average deviations between the scanned model and the photogrammetric model for these cases are given in Table 1.

In the woman's case, the deviations between the two CAD models are from -1.98 mm to +1,8 mm for the forearm part, whereas, a range from – 2.98 mm to +1.93 mm is found for the wrist-hand part. In the case of the man, these deviations are -1.29 ÷ 2.09 mm and -3.22 ÷ 3.13 mm for the forearm and wrist-hand parts, respectively. The significant differences between the extreme deviations in the man's case and the woman's case are evident. This could be due to noise during the image processing process caused by long, dark hair on the arm. For both cases, the range of deviations on the forearms of this study are much smaller compare to our previous study which was from -2÷2.59 mm [1]. The average deviation in the forearm part of this study is -0.04 mm for the woman's case, much smaller compared to the case (the same feature of the hair on the arm) that we reported in our previous study, where an average deviation of 0.22 mm was found [14].

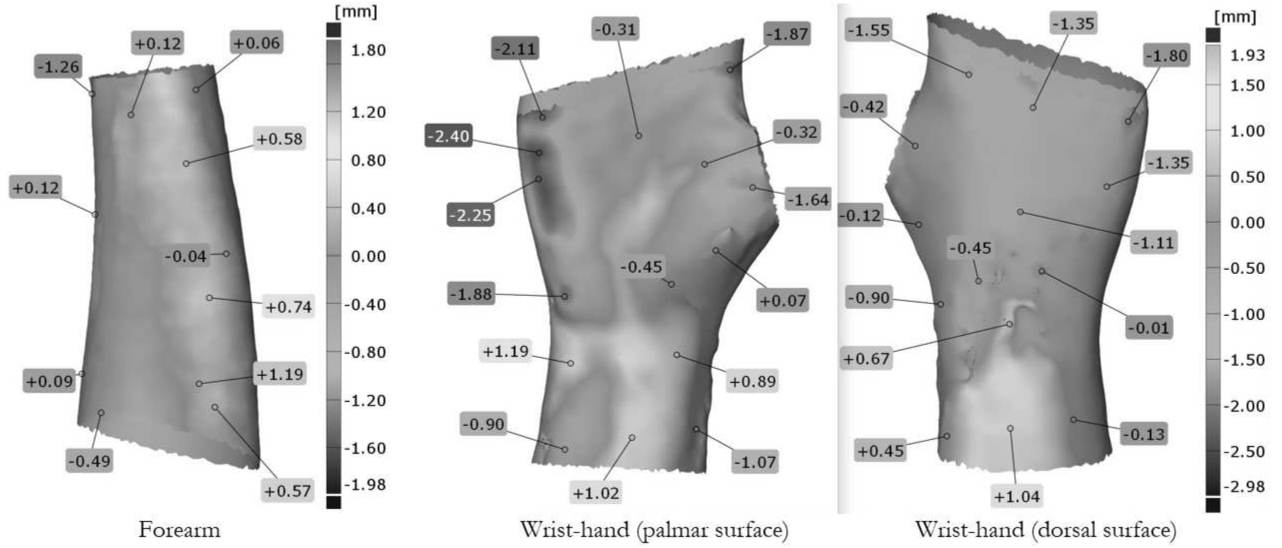

***Fig. 6** Clour map of deviations – woman's case*

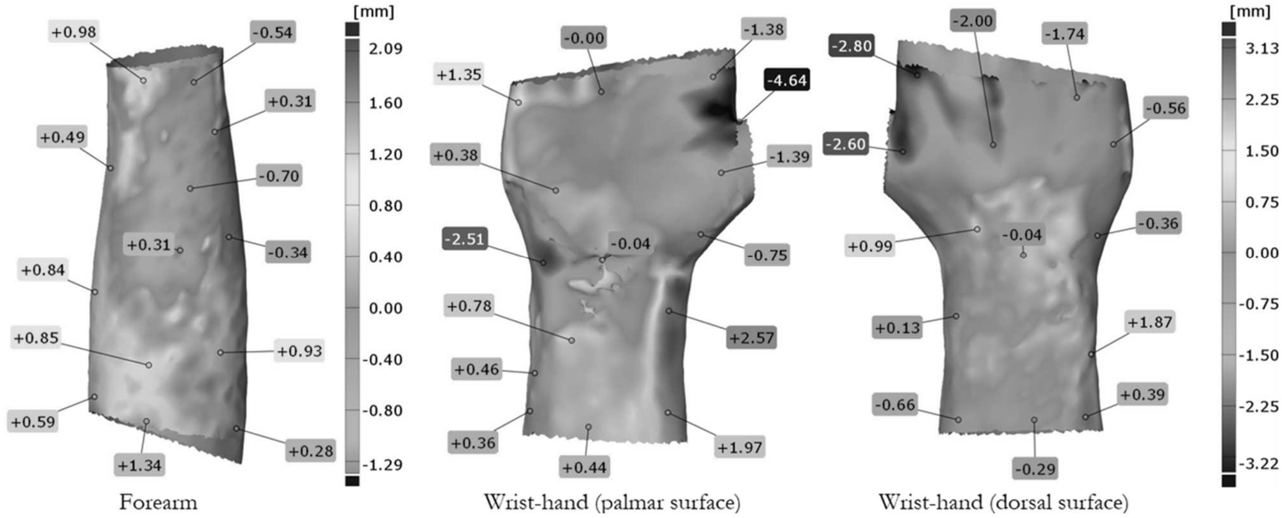

***Fig. 7** Clour map of deviations – man's case*

***Tab. 1** Deviations between two CAD models (mm)*

Case		Woman	Man
Forearm	Range	-1.98 ÷ 1.80	-1.29 ÷ 2.09
	Average	-0.04	+0.31
Wrist-hand	Range	-2.98 ÷ 1.93	-3.22 ÷ 3.13
	Average	-0.45	-0.04

It is evident in both situations that the wrist-hand part's extreme values of deviations are much greater than the forearm part's. This might be because the surface anatomy of the wrist-hand part is more complicated than that of the forearm part with superficial venous network and extensor digitorum tendons of the hand. On the wrist-hand part, the palmar surface shows greater extreme deviations than the dorsal surface. This may be because the skin on the palm of the hand is shinier than the skin on the back of the hand. In addition, the man's thumb position created a fold of skin between the thumb and index finger, which led to considerable deviations in the area between the two fingers. Therefore, it is necessary to maintain the thumb position to avoid wrinkles between the thumb and index finger and achieve higher modeling accuracy.

A few studies were conducted to test the accuracy of a photogrammetric model used for medical purposes. In the study of Salvador et al. [15], a mobile photogrammetry cart with Raspberry Pi camera module was developed to obtain 3D models of infant legs. To evaluate the accuracy of the 3D photogrammetric models, a deviation analysis was performed on two rubber clubfoot models. The average deviation between the photogrammetric models and the scanned ones is 0.4147 mm and -0.7129 mm. This analysis results show that the proposed system can create a high accurate model. However, this system is rather complicated. Olivier used an iPhone 6S with a 12MP camera and an A4 reference sheet placed under the foot of interest to capture the 2D images of a lower limb [16]. The photogrammetric model's largest deviation in the anterior-posterior axis was 7.4 mm from the scanned model made with a cheap 3D laser scanner. Hernandez and Lemaire [17] digitized 4 prosthetic sockets using a Samsung Galaxy S5 smartphone (16 MP camera) and some reference markers on the sockets. A comparison was made between the measured distances on the actual sockets and thoses in the CAD environment. They found that the smallest, the largest and the average differences of the photogrammetric models were 1.2 mm, 4.8 mm and 2.6 mm respectively. Tursi et al. [18] used an iPhone 6S (12 MP camera) and some markers taped to the lower limb of interest for image capturing. They investigated that there is an average deviation of 2 mm between the photogrammetric models and the scanned models. These studies used 2D scale reference objects such as A4 paper and markers, which can lead to large errors when measuring in the CAD environment, which in turn leads to errors when performing the scaling operations. In this study, the real cylinder was precisely machined and measured with a high-precision micrometer, and the virtual cylinder could be measured more accurately in CATIA. This means that there could be tiny size errors in the photogrammetric models. To some extent, it can be said that the photogrammetric models in this study are sufficient for WHO modeling.

For the fit test, the two photogrammetric models were used as reference parts to create two WHO models in CATIA. These are models whose inner surfaces are designed to be free of gaps compared to the reference models. It should be noted thats an offset should be added for wearing comfort when designing a 3D printed arm cast [19, 20]. Fig. 7(a) shows the result of fit checking for the woman's case. Visual examination reveals that the colour imprints on the forearm and wrist-hand regions are practically continuously visible and fairly evenly distributed. It is evident that the WHO fits the wrist-hand and forearm regions well. In the latter case, as shown in Fig. 7 (b), the colour prints are less uniformly distributed and occasionally discontinuous. This indicates a poor fit between the WHO and the arm. This test shows that the 3D printed WHO designed from the photogrammetric model with short, nearly colourless hairy arm has a better fit than the rest. The results of the fit test agree perfectly with the results of the CAD data set comparison above.

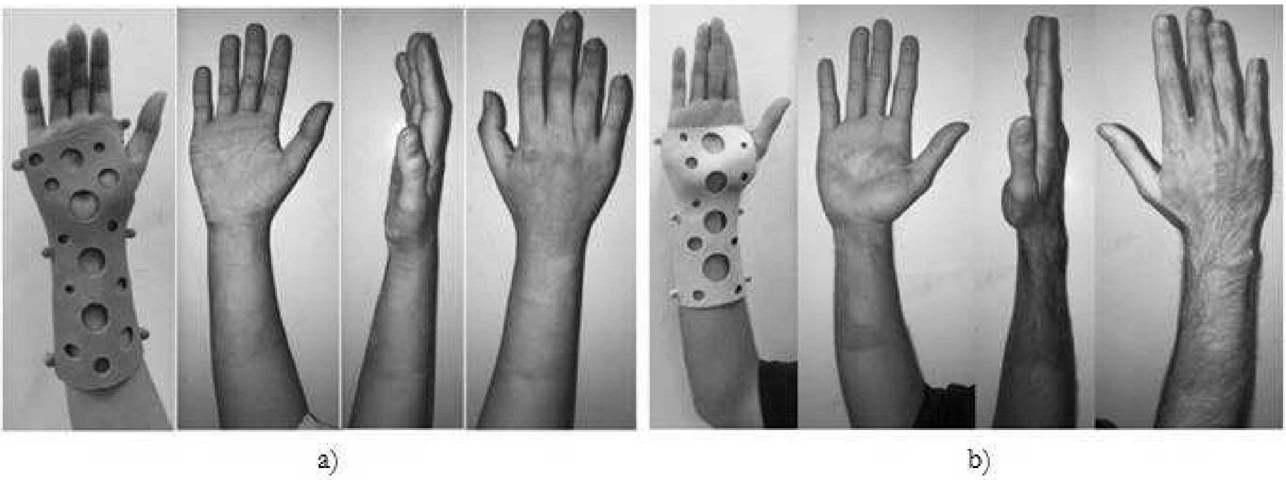

Fig. 7 *3D printed WHOs and the colour imprints on the arms, a) Woman, b) Man*

This study also conducted several other cases of men who had short, almost colourless hair on their arms, with similar results to those described in this paper for the woman's case. One could assume that the photogrammetric models developed using our proposed method have sufficient accuracy and could be used as reference models for modeling 3D printed WHO. However, long black hair on the arm could cause noise and then affect the accuracy of the arm models. Therefore, in order to obtain a more accurate photogrammetric model, noise reduction on the images of arms with long black hair should be performed before image processing in Agisoft Metashape.

4 Conclusion

In this study, the accuracy of the photogrammetric models of several arms was verified virtually and physically. For virtual verification, two CAD datasets of an arm were compared in GOM Inspect, one reconstructed from 2D images captured with a

Samsung Galaxy smartphone and the other created using an inexpensive 3D scanner (the reference model). The verification results show that the deviations of the forearm parts are smaller than those of the wrist-hand parts. The average deviations on the forearm and wrist-hand parts are very small, under 0.5 mm. In general, the photogrammetric models of the arms with short, nearly colourless hair have a higher accuracy compared to those models of the arms with long, black hair. Physical verifications were performed by assessing the contact between the arms of interest and real 3D printed wrist-hand orthoses fabricated with respect to the photogrammetric models. The accuracy of the virtually tested arm models is further supported by the physical verification. Both verifications demonstrate that the photogrammetric models achieve the required accuracy for WHO modeling. This also helps confirm that the proposed method of acquiring and processing 2D arm images using smartphones, cylinder, LED video light and some special techniques can be used for arm modeling and designing 3D printed WHOs. The future task of this study involves applying noise reduction techniques to the images of arms that are affected by long black hair before conducting image processing. This step aims to improve the accuracy of the photogrammetric model.

Acknowledgement

The work of this paper is supported by Nha Trang University, Viet Nam.

References

[1] VAN, T.N., LE THANH, T., VAN, T.N., NAPRSTKOVA, N. (2023). Smartphone-based Data Acquisition Method for Modelling 3D Printed Arm Casts. In: *Manufacturing Technology Journal*, Vol. 23, No. 2, pp. 260-267. J. E. Purkyně University in Usti nad Labem, Czech Republic. ISSN 1213-2489

[2] KELLER, M., GUEBELI, A., THIERINGER, F., HONIGMANN, P. (2021). In-hospital Professional Production of Patient-specific 3D-printed Devices for Hand and Wrist Rehabilitation. In: *Hand Surgery Rehabilitation*, Vol. 40, No. 2, pp. 126-133. Elsevier, Amsterdam, The Netherlands. ISSN 2468-1210

[3] VAN LIESHOUT, E. M. M., VERHOFSTAD, M. H. J., BEENS, L. M., VAN BEKKUM, J. J. J., WILLEMSEN, F., JANZING, H. M. J., & VAN VLEDDER, M. G. (2022). Personalized 3D-printed Forearm Braces as an Alternative for a Traditional Plaster Cast or Splint; A Systematic Review. In: *Injury*, Vol. 53 Suppl. 3, pp. S47–S52. Elsevier, Amsterdam, Netherlands. ISSN 0020-1383

[4] LAZZERI, S., TALANTI, E., BASCIANO, S., BARBATO, R., FONTANELLI, F., UCCHEDDU, F., SERVI, M., VOLPE, Y., VAGNOLI, L., AMORE, E., MARZOLA, A., MCGREEVY, K. S., CARFAGNI, M. (2022). 3D-Printed Patient-Specific Casts for the Distal Radius in Children: Outcome and Pre-Market Survey. In: *Materials*, Vol. 15, No. 8, 2863. MPI, (Basel, Switzerland), ISSN 1996-1944

[5] POPESCU, D., BACIU, F., VLĂSCEANU, D., MARINESCU, R., LĂPTOIU, D. (2023). Investigations on the Fatigue Behaviour of 3D-Printed and Thermoformed Polylactic Acid Wrist–Hand Orthoses. In: *Polymers*, Vol. 15, NO. 12, 2737. MDPI, Basel, Switzerland, ISSN 2073-4360

[6] JAN, Z., ABAS, M., KHAN, I., QAZI, M. I., USMAN JAN, Q. M. (2023). Design and Analysis of Wrist Hand Orthosis for Carpal Tunnel Syndrome using Additive Manufacturing, In: *Journal of Engineering Research*, Vol. 12, 001. Elsevier, Amsterdam, The Netherlands. ISSN 2307-1877

[7] SEDLAK, J., HRUSECKA, D., CHROMJAKOVA, F., MAJERIK, J. & BARENYI, I. (2021). Analysis of the Wear on Machined Groove Profiles Using Reverse Engineering Technology. In: *Manufacturing Technology*, Vol. 21, No. 4, pp. 529-38. J. E. Purkyně University in Usti nad Labem, Czech Republic. ISSN 1213-2489

[8] FABIAN, M., HUŇADY, R. & KUPEC, F. (2022). Reverse Engineering and Rapid Prototyping in the Process of Developing Prototypes of Automotive Parts. In: *Manufacturing Technology*, Vol. 22, No. 6, pp. 669-78. J. E. Purkyně University in Usti nad Labem, Czech Republic. ISSN 1213-2489

[9] BECHNÝ, V., MATUŠ, M., JOCH, R., DRBÚL, M., HOLUBJÁK, J., CZÁN, A., ŠAJGALÍK, M. & MARKOVIČ, J. (2023). Design of an Injection Mould Utilizing Experimental Measurements and Reverse Engineering. In: *Manufacturing Technology*, Vol. 23, No. 5, pp. 597-603. J. E. Purkyně University in Usti nad Labem, Czech Republic. ISSN 1213-2489

[10] CHEN, Y., LIN, H., YU, Q., ZHANG, X., WANG, D., SHI, L., HUANG, W., ZHONG, S. (2020). Application of 3D-Printed Orthopedic Cast for the Treatment of Forearm

Fractures: Finite Element Analysis and Comparative Clinical Assessment. In: *BioMed Research International*, Vol. 2020, Article ID 9569530. Hindawi Publishing Corporation, Cairo, Egypt. ISSN 2314-6141

[11] VAN, T.N., LE THANH, T., NAPRSTKOVA, N. (2021). Measuring propeller pitch based on photogrammetry and CAD. In: *Manufacturing Technology*, Vol. 21, No. 5, pp.706-713. J. E. Purkyně University in Usti nad Labem, Czech Republic. ISSN 1213-2489

[12] TUONG, N.V. (2018), Manufacturing Method of Spiral Bevel Gears Based on CAD/CAM and 3-Axis Machining Center. In: *MM Science Journal*, Vol. June 2018, pp. 2401-2405. MM Publishing, Czech Republic. ISSN 1803-1269

[13] MENDRICKY, R., SOBOTKA, J. (2020). Accuracy Comparison of the Optical 3D Scanner and CT Scanner. In: *Manufacturing Technology*. Vol. 20, No. 6, pp. 791-801. J. E. Purkyně University in Usti nad Labem, Czech Republic. ISSN 1213-2489

[14] TUONG N. V. (2023). Design and Manufacture 3D Printed Arm Cast from Data Taken by Smartphone. Research report, Nha Trang University, Viet Nam

[15] SALVADOR, T., SLAGLE, J., CHAPRNKA, G., AGRONIN, M, OETGEN, M., TABAIE, S., CLEARY, K, DAYAL, A., Development of a Novel Photogrammetry Method for Acquiring 3D Surface Models of Infant Clubfoot Anatomy. In: *Medical Imaging 2022: Image-Guided Procedures, Robotic Interventions, and Modelling*, Vol. 12034, 120342E-3. SPIE, Washington USA, ISBN 9781510649446

[16] OLIVIER, M. (2019). *A Low-Cost Custom Knee Brace via Smartphone Photogrammetry*. Master thesis, University of Ottawa. Ottawa, Canada

[17] HERNANDEZ, A., LEMAIRE, E. (2017). A Smartphone Photogrammetry Method for Digitizing Prosthetic Socket Interiors. In: *Prosthetics and Orthotics International*, Vol. 41, No. 2, pp. 210–214. SAGE Publications, California, United States. ISSN 1746-1553

[18] TURSI, A., KURILLO, G., BAJCSY, R. (2017). Automatic Detection of Body Landmarks in Human Body Scans - Lower Limb Analysis for Biomedical and Footwear Applications. In: *The 8th International Conference and Exhibition on 3D Body Scanning and Processing Technologies*, pp. 179-191. Montreal QC, Canada. ISBN 978-3-033-06436-2

[19] PALOUŠEK, D., ROSICKÝ, J., KOUTNÝ, D., STOKLÁSEK, P., NÁVRAT, T. (2014). Pilot Study of the Wrist Orthosis Design Process. In: *Rapid Prototyping Journal*, Vol. 20, No. 1, pp. 27-32. Emerald Group Publishing Ltd., United Kingdom. ISSN 1355-2546

[20] BARONIO, G., HARRAN, S., SIGNORONI, A. (2016). A Critical Analysis of a Hand Orthosis Reverse Engineering and 3D Printing Process. In: *Applied Bionics & Biomechanics*, Vol. 2016, Article ID 8347478. Hindawi Limited, London, United Kingdom. ISSN 17542103