# Smartphone-Based Photogrammetry for Craniofacial 3D Modelling: A Preliminary Test

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## Abstract

Craniofacial 3D models are used for various purposes, such as cranial morphological analysis, surgery planning, and prostheses, among others. Today, three-dimensional (3D) scanners are commonly used to obtain 3D models of patients' heads. Similarly, there is a chance to apply mobile devices (smartphones and tablets) that implement photogrammetric techniques to build craniofacial 3D models. In this paper, a new photogrammetric solution to analyse cranial deformation, PhotoMeDAS (Photogrammetric Medical Deformation Assessment Solutions), is used to evaluate the quality of the system standalone or as part of an integrated photogrammetric pipeline.
Two preliminary results for achieving craniofacial 3D models with a current premium smartphone, the Samsung Galaxy S22, are presented. The first solution considered the Agisoft Metashape software which produced a dense point cloud and the textured craniofacial 3D model. The second result runs the mobile application PhotoMeDAS v. 1.7 to obtain a cranial 3D model of the same volunteer. The two results were compared with a reference 3D model obtained with the white light 3D scanner Academia 50.
The photogrammetric 3D model obtained with Metashape allowed the visualization of the morphological characteristics of the volunteer's head and face, similarly as with the Academia 50, even though its processing time required extensive filtering. However, PhotoMeDAS was extremely fast and delivered pinpoint accuracy for the cranial area after just a few minutes of data acquisition and subsequent autonomous processing.

**Keywords:** mobile devices, photogrammetric, craniofacial 3D models, PhotoMeDAS, 3D scanner

## 1. Introduction

Three-dimensional (3D) craniofacial models have been verified to be valuable tools in various areas of medicine and research, for instance for identifying cranial morphology [1], quantifying plagiocephaly [2]–[5], evaluating cranial deformities [6], and creating personalised facial prostheses[7]. These models allow detailed visualisation of craniofacial structures, facilitating diagnosis, treatment and clinical decision-making. Worth noticing is that positional or postural plagiocephaly suggests a prevalence of up to 48% of children under 1 year [8].

Traditionally, 3D scanners have been used to generate body models [9]–[11]. Furthermore, special facilities are required. A lower-cost alternative is the use of photogrammetry, which is a technique that uses digital images to reconstruct 3D models [12]–[14]. Photogrammetry allows the reconstruction of the patients' 3D model after taking overlapping images from different angles. Close-range image or video photogrammetry on mobile devices offers a practical solution for 3D human head reconstruction [12].

In recent years there has been a growing interest in the use of mobile applications that allow obtaining 3D craniofacial models by executing photogrammetric processing [15]. The advantage of using mobile devices is that they are more affordable, portable and accessible, which makes them an attractive option for creating craniofacial models. In this article, the evaluation of the accuracy of the creation of craniofacial 3D models using a smartphone, in particular the Samsung Galaxy S22, using both a conventional structure-from-motion (SfM) photogrammetry implemented in Agisoft Metashape software and a fully autonomous solution achieved with the PhotoMeDAS application.

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## 2. Materials and methods

### 2.1. Materials

*2.1.1. Scanner 3D*

The Academia 50 3D scanner (Fig. 1) is an advanced handheld 3D data capture device. Its main goal is to create accurate and detailed 3D models of objects. It is easy to set up and use. According to the manufacturer's specifications, the user can scan objects made of any material, colour, and type of surface, with an accuracy of up to 0.250 mm and a spatial resolution of up to 0.250 mm [16]. To enhance the capture data with the 3D scanner, round reflective stickers were added to the head's surface.


(a) (b) (c)

*Fig. 1. Scanner setup:(a) Academia 50;(b) calibration plate; and (c) 3D model output with round reflective targets.*

The resulting 3D model (Fig. 1c) will be considered as ground truth to validate the other two photogrammetric approaches.

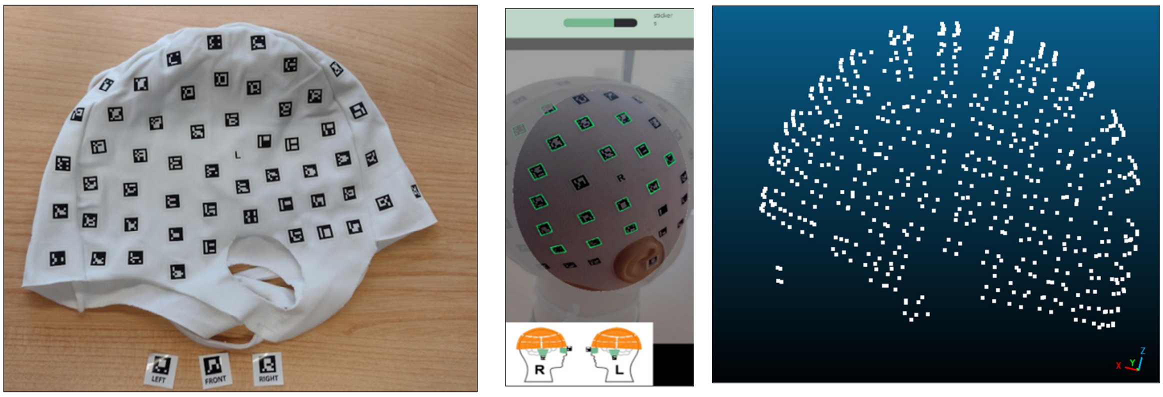
*2.1.2. Smartphone PhotoMeDAS app*

To use the PhotoMeDAS app, it is necessary to use a coded cap (see Fig. 2). This innovative accessory is covered with a high number of markers [17]. The cap is made of an elastic material, which allows an optimal adaptation to the patient's head. The app can detect automatically the coded markers (four corners per marker). Additionally, three markers have to be manually placed in three positions (front, left and right) on the patient's head. These additional markers will be used to set the coordinate system.

PhotoMeDAS application v. 1.7. has an interface similar to recording a video [18] at a resolution of 960x720 pixels. The implemented solution is already patented [19]. It is required to target the entire head (Fig. 2b), moving the smartphone around the patient. The application will detect the visible markers of the cap in each frame and record their positions. Once the entire head has been recorded, the app will notify the user and upload the data for server-based processing. Eventually, the 3D data will be computed (Fig. 2c).

*2.1.3. Smartphone camera*

The image capture with the smartphone for the SfM photogrammetric solution was taken in automatic mode, allowing fast and convenient processing that uses advanced technology to automatically adjust exposure, focus and white balance parameters. This allows users to capture high-quality images without the need for advanced technical knowledge. The Galaxy Samsung S22 ultra-wide lens images with a resolution of 4000x3000 pixels (12MP, F2.2, FOV 120˚) were recorded. Worth noticing is that the lens with maximum FOV and minimum resolution on the smartphone was selected.



*(a)* *(b)* *(c)*

*Fig. 2. PhotoMeDAS equipment: (a) Coded cap plus three additional markers; (b) smartphone PhotoMeDAS app; (c) 3D point cloud computed without human intervention.*

## 2.2. Methods

Two different devices have been used for delivering the head's 3D models: Samsung Galaxy S22 (camera mode and video mode) and Academia 50. The workflow for evaluating the accuracy of the two reconstructed head 3D models obtained with the two photogrammetric approaches and their comparisons with the reference 3D model from the 3D scanner is presented in Fig. 3.

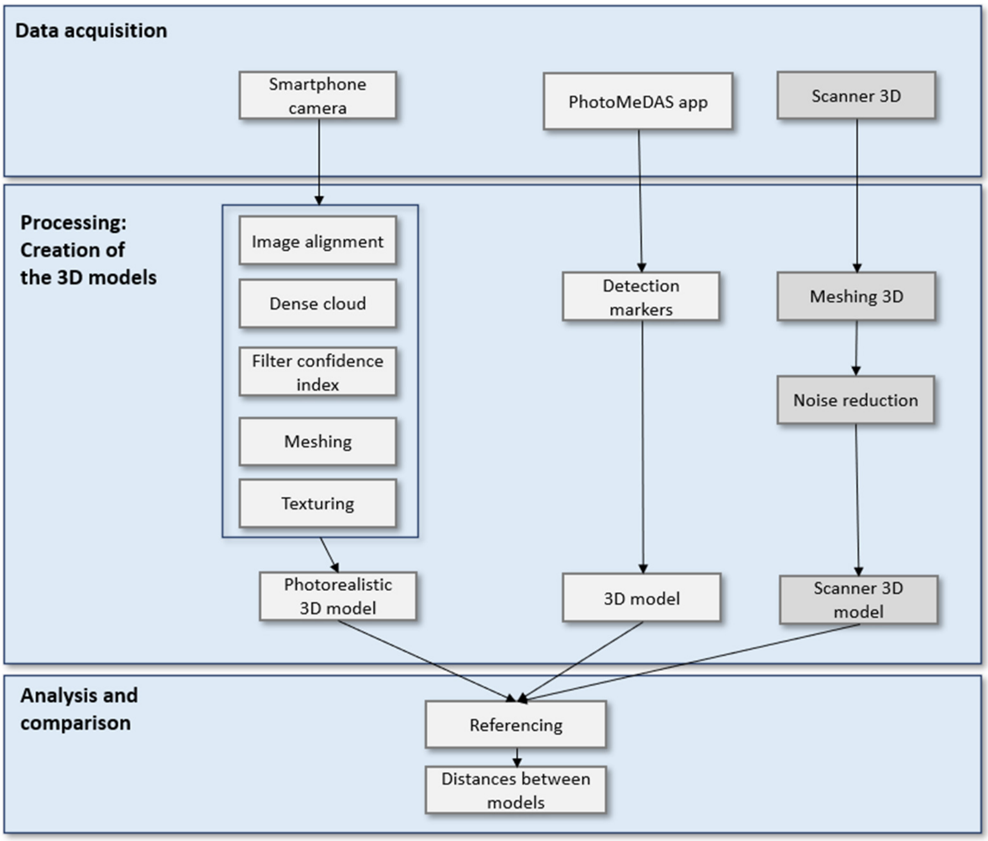



*Fig. 3. Research workflow.*

## 2.3. Data acquisition

Before performing the data acquisition using the three methods mentioned above, a coded cap was placed on the volunteer's head, along with the necessary three manually-placed markers required by PhotoMeDAS (Fig. 2a). In addition, 15 round targets automatically recognised by the 3D scanner were placed on the cap and the skin (Fig. 1c). No special lighting was used during data acquisition.

During the data acquisition with both the smartphone and the 3D scanner, the volunteer was instructed not to move his head; this instruction was set in order to guarantee the quality of the images captured with the smartphone camera, and not loosing the tracking with the 3D scanner. In the case of using the PhotoMeDAS application, it is possible to move the head slightly for the comfort of the volunteer.

#### *2.3.1. Data acquisition with the 3D scanner*

First, a calibration of the 3D scanner Academia 50 was performed using a rectangular pattern plate and the VXelements software. Then, using the functionalities of the VXelements software, the scanner parameters were established, which included the specification of the resolution with a value of 0.5 mm.

Finally, the scanner was constantly moved around the head to capture data from all angles. The quality of data capture was checked. The resulting 3D model (Fig. 4) was exported in OBJ format and stored for further processing in Agisoft Metashape v. 1.7.

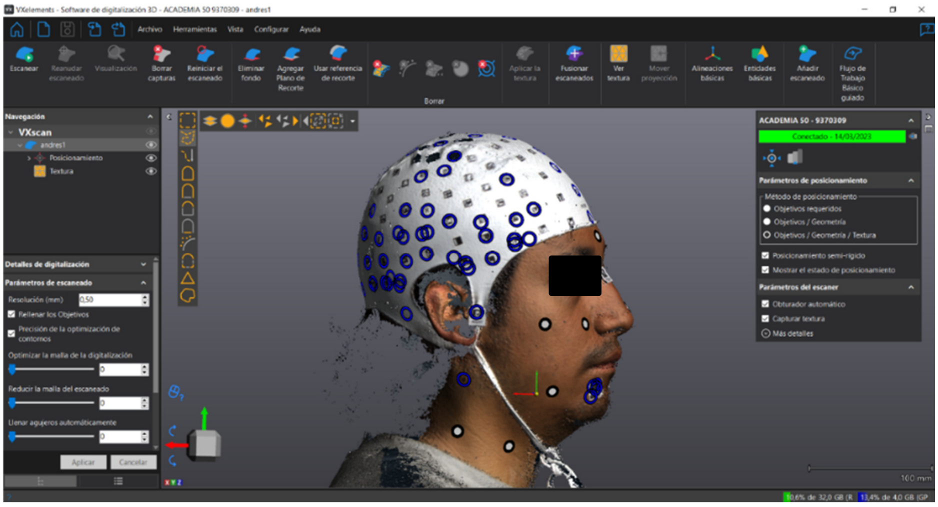
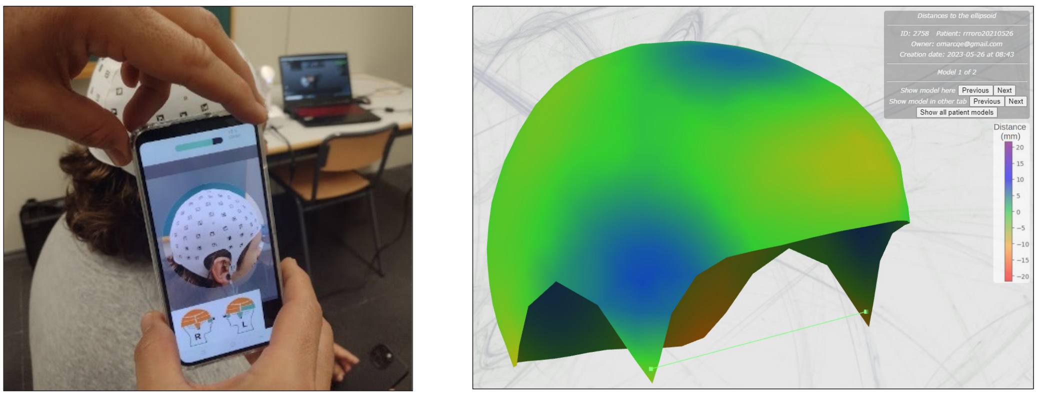


*Fig. 4. Output 3D model from Academia 50.*

#### *2.3.2. Data acquisition with PhotoMeDAS*

During the measurement process, it must be ensured that the entire visible surface of the coded cap is centred on the screen. To facilitate this process, a circle is shown on the screen where you want to show the maximum number of codes possible (Fig. 5a). It is also important to record from a distance of approximately 15 to 25 cm to ensure the correct marker readout. The user can start the recording from any patch, although it is recommended to acquire the three manual markers first. Once enough data has been recorded, it is sent to the server for fully autonomous processing. The software will provide the resulting 3D model (Fig. 5b), as well as the full anthropometric records [18] which can be accessed on the PhotoMeDAS.eu website.

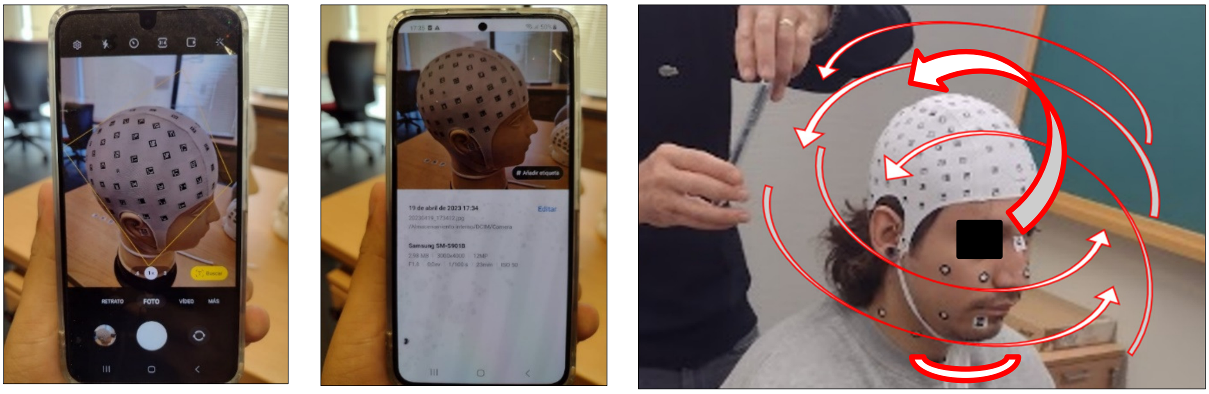


*(a)* *(b)*

*Fig. 5. (a) PhotoMeDAS app; (b) Output head's 3D model.*

*2.3.3. Data acquisition with the camera smartphone*

Photos were captured in JPG format using the smartphone's default autofocus settings. The volunteer's head was placed in the centre of the frame and remained focused throughout. Photographs were taken from multiple angles around the head, maintaining a constant angle with the cell phone and making sure not to lose sight of the volunteer's head (Fig. 6). The distance between the mobile and the head remained roughly constant, and a photo was captured every second. Two complete routes were made around the head and another partial one to cover the chin, as well as a perpendicular route across all.



*(a)* *(b)* *(c)*

*Fig. 6. Smartphone photogrammetric acquisition: (a) Approximate shooting distance; (b) Image characteristics; and (c) Strips (three along and one across the head).*

## 2.4. Creation of the 3D models

*2.4.1. 3D scanner*

The Academia 50 3D scanner allows users to obtain the 3D model directly. However, a noise-cleaning process is carried out using the Agisoft Metashape software applying the gradual selection of the imported 3D model. A total of 1,717,956 faces and 939,809 vertices were obtained.

The time for the 3D scanner (equipment installation, calibration, data acquisition, data export, processing and editing) is roughly 30 to 40 minutes.

*2.4.2. PhotoMeDAS*

From each measurement with PhotoMeDAS, a cranial anthropometric report has been obtained, in addition to the XYZ point cloud of the coded markers and the final 3D model in PLY format. The time for processing and obtaining the cranial head's 3D model is usually less than 5 minutes.

*2.4.3. SfM photogrammetry with Agisoft Metashape*

*2.4.3.1. Data preparation*

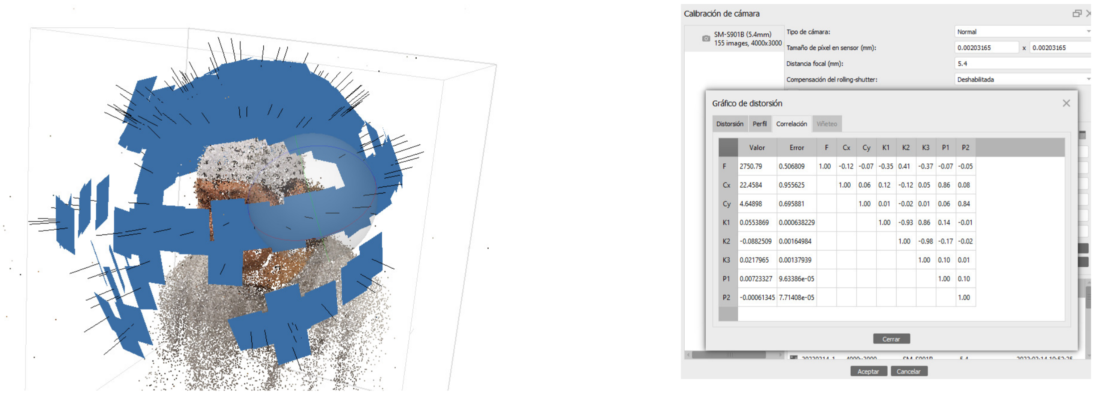
To ensure the quality of the data obtained with the mobile camera, visual verification of the images was carried out to rule out those that could be moved or have objects that obstruct the proper visualisation of the volunteer's head.

*2.4.3.2. Image selection*

In this project, 155 images were used after passing a quality filter. Each image was approx. 3.26 MB and metadata included information such as date, time, camera type, focal length, ISO and capture speed, among other relevant details.

*2.4.3.3. Image orientation and camera calibration*

In the photogrammetric pipeline, it is important to perform the calibration of the camera to ensure the maximum performance of the acquired data. Fig. 7 shows the visual results after the bundle adjustment, including the determination of the geometric camera calibration parameters.

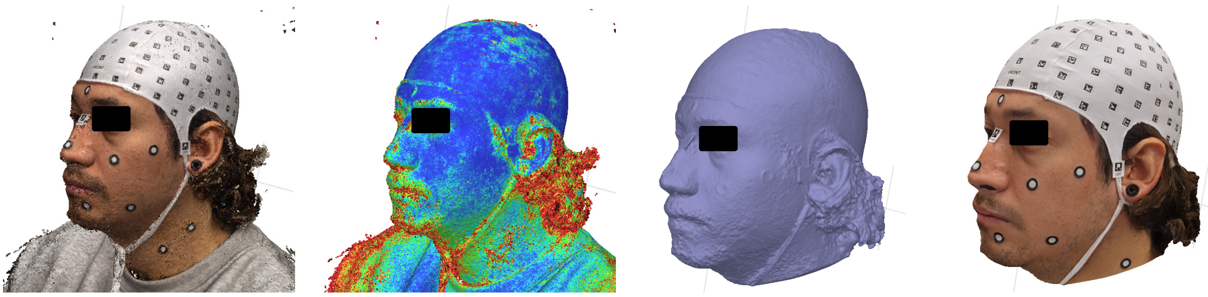


(a) (b)

*Fig. 7. Results of the bundle adjustment: (a) External orientation; (b) Interior orientation of the camera during on-the-job camera calibration.*

*2.4.3.4. 3D modelling*

After the orientation stage [20], dense point cloud densification was carried out. An important step is the application of filtering to select only the most reliable points. These selected points will be used for the generation of the 3D model and the final photorealistic texturing of the model (Fig. 8).



(a) (b) (c) (d)

*Fig. 8. (a) Dense point cloud; (b) Confidence points; (c) Mesh;(d) Textured mesh.*

The time used to carry out the photogrammetric procedure in the Agisoft Metashape software was roughly 86 minutes.

## 2.5. Analysis and comparison

*2.5.1. Referencing*

The 3D model obtained through Academia 50 was set to fix the reference coordinate system thanks to the three manually-placed markers on the model. The 3D model obtained with SfM photogrammetry was transformed using Agisoft Metashape; for PhotoMeDAS, it was decided to carry out the referencing in CloudCompare [21] (Fig. 9).

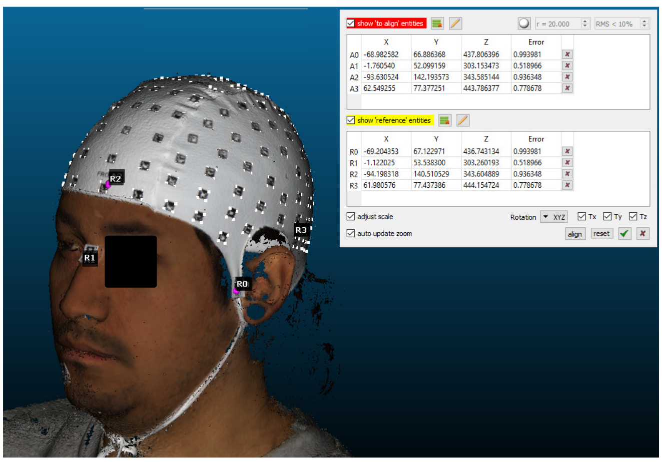
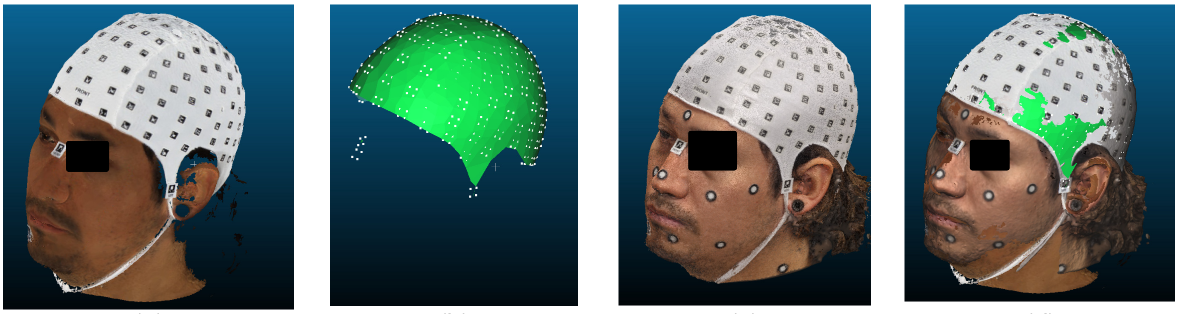


*Fig. 9. 3D transformation in CloudCompare software.*

In the case of the 3D model obtained with PhotoMeDAS (Fig. 9), the referencing was carried out with 4 points to determine the translation, rotation and scaling of the model; a scale factor of 0.97 and a root mean square of 1.02 mm were obtained in this stage.

In Fig. 10 the different 3D models achieved with the different solutions can be visualised: (a) final 3D model obtained with Academia 50 after noise-cleaning (Fig. 10a); (b) 3D point cloud and mesh obtained with PhotoMeDAS (Fig. 10b); and (c) 3D model obtained with Agisoft Metashape (Fig. 10c). The superposition of the three previous 3D models is displayed in Fig. 10d.



(a) (b) (c) (d)

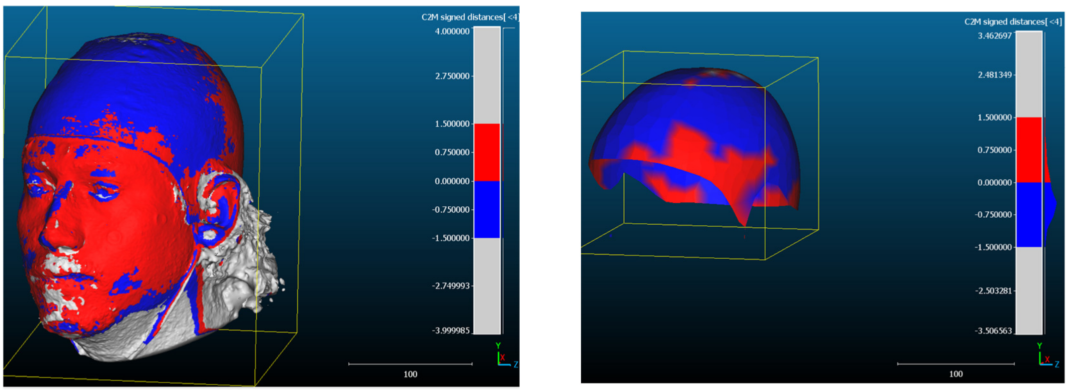
*Fig. 10. 3D models: (a) Academia 50; (b) PhotoMeDAS; (c) Metashape; and (d) superposition of a, b and c.*

### *2.5.2. Distances between models*

First, a visual comparison was carried out between the meshes obtained in Section 2.4. It can be asserted that the quality of the 3D model obtained with the 3D scanner is very high (Fig. 10a), allowing users to appreciate the minimum variations, such as the skin, the fabric joints present in the cap, and even the limits of the stickers of the marks, among other irregular details on the head.

The photogrammetric 3D model obtained with the smartphone ultra-wide lens camera presents a relief similar to that of the scanner. However, there is a presence of noise and some irregularities can be identified, mainly in the area of the head uncovered by the coded cap. Besides, the photorealistic (textured) 3D models obtained (Fig. 10c) allow for capturing maximum texture head detail; 1 mm marks were recorded with up to 10 pixels.

CloudCompare tools were used to carry out the numerical comparison among the two 3D models obtained with the two photogrammetric solutions, considering the distances between 3D points and the 3D meshes; the C2M command was selected. In this way, precise estimates can be obtained on the differences between the 3D models. For these comparisons, 3D points or meshes were coloured according to the distance to the mesh (Fig. 11).



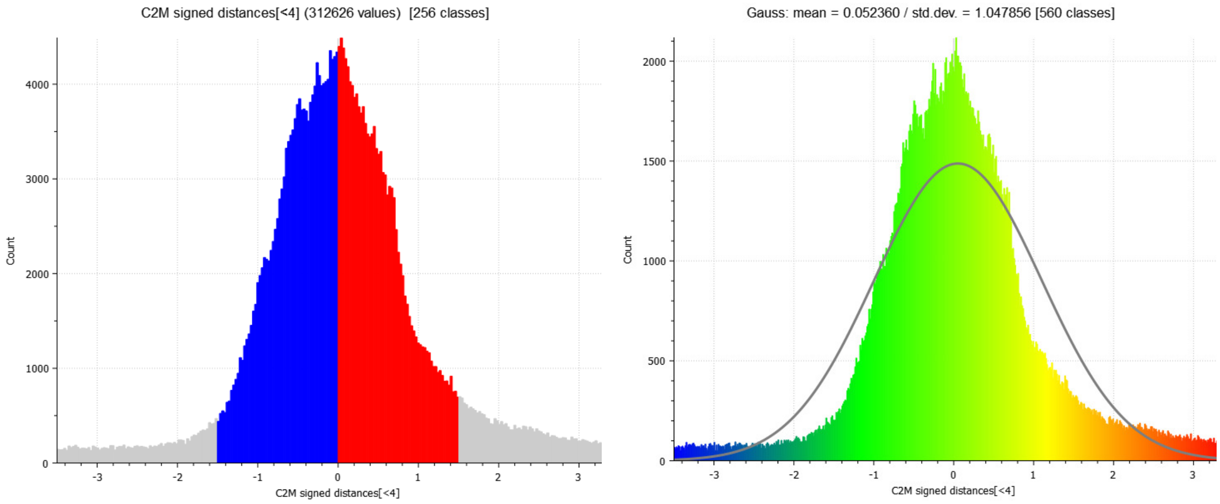

**(a)** **(b)**

*Fig.11. Distance: 3D scanner – Agisoft Metashape; Distance: 3D scanner – PhotoMeDAS. Threshold up to 1.5 mm.*

# 3. Result

## 3.1. Agisoft Metashape vs Academia 50

Of a total of 312.626 distances recorded, the grouping of values below and above 1.5 mm in reference to the 3D scanner is considered. Considering a Normal distribution, an average value of 0.052 mm with a standard deviation of ±1.048 mm (Fig. 12).

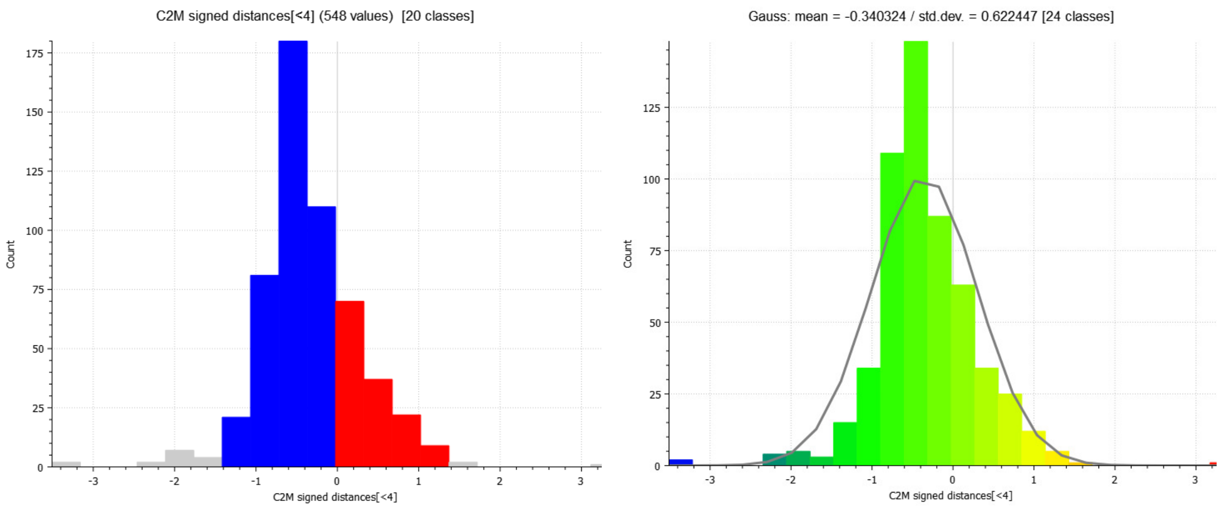



(a) (b)

*Fig.13. SfM Photogrammetry-3D scanner: (a) C2M distance histogram; (b) Gaussian distribution.*

## 3.2. PhotoMeDAS vs Academia 50

Of a total of 548 distances recorded, the grouping of values below and above 1.5 mm in reference to the 3D scanner model is again considered; the Normal distribution yields a mean value of -0.34mm and a standard deviation of ±0.62 mm (Fig. 13).




(a) (b)

*Fig. 13. PhotoMeDAS-3D scanner: (a) C2M distance histogram; (b) Gaussian distribution.*

# 4. Discussion

This research highlights the potential of smartphone photogrammetry for head 3D modelling. The accuracy comparison between 3D scanning and two smartphone photogrammetric solutions let us determine the preliminary strengths and limitations of each method. The 3D scanner, provides accurate and high-quality results, although it can be an expensive device and requires dedicated equipment and personnel to use it. It is especially useful in applications where high accuracy and detailed representation of facial and cranial structures are required.

Photogrammetric processing with Agisoft Metashape generates a detailed 3D model. However, the results are dependent on software and specialized personnel to develop the image processing. In addition, different estimates can be achieved depending on the lens selected for the 3D modelling. The bias achieved herein with the ultra-wide angle lens is 0.052 mm, but its standard deviation is slightly higher, ±1.048 mm.

The smartphone-based photogrammetric solution with the PhotoMeDAS app offers a quick, portable, easy-to-use and economical alternative for creating 3D models in minutes. Although its submillimeter accuracy is slightly lower compared to the other methods (bias -0.34 mm, standard deviation of ±0.62 mm), it is a viable option in clinical practice using medium to high-end Android smartphones (iOS implementation is actually on the way). In fact, in medical applications accuracy is not always the primary factor, but security, service benefit, reliability, accessibility and portability; in case the accuracy was a limiting factor, the PhotoMeDAS can also be internally calibrated for each smartphone.

The SfM photogrammetric solution with a single smartphone camera requires the data acquisition of non-moving objects. Furthermore, the PhotoMeDAS coded cap was beneficial for data acquisition. However, it should be ready to deal with natural personal patient movements and even more for children. This movement constraint was minimised while using the 3D scanner, and additional round targets were added to the volunteer head's surface and cap; for the PhotoMeDAS app, the movement is not a constraint: it allows the volunteer to move the head naturally without losing the accuracy of the final 3D model.

## 5. Conclusion

This study has shown that smartphone-based photogrammetry is an efficient tool that allows the generation of craniofacial 3D models. However, there are differences in facilities required, processing complexity, processing time, costs and limitations. These approaches offer an accessible and portable alternative to state-of-the-art handheld 3D scanners, offering comparable results in terms of accuracy and quality of the 3D models.

However, more research and development are required to overcome technical limitations and explore their usefulness in different clinical contexts. Ultimately, the integration of smartphones and specialised applications into clinical practice could have a significant impact on disease treatment, cranial orthosis personalisation and detection of craniofacial abnormalities. The choice of 3D modelling method depends on the specific needs of the application, the clinical or research environment and the resources available.

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