Creating a Digital 3D Model of the Dental Cast Using Structure-from-Motion Photogrammetry Technique

https://doi.org/10.3991/ijoe.v19i03.36289

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Abstract—Photogrammetry is a technique used to obtain a reliable database of any physical object, by creating a digital 3d model using multiple photos taken at different angles around the object. Recently, several fields have used this technique to build digital 3D models, such as topography, architecture, engineering, and medicine. Many recent dentistry studies have used the Structure-from-motion (SfM) Photogrammetry technique to reconstruct a digital three-dimensional (3D) model of a dental cast as an alternative to conventional scanning. In this research, the dental casts are constructed by applying the SfM Photogrammetry technique in which a guide to stepwise workflow is provided by utilizing simple tools which are: a smartphone camera, homemade photo studio setup, and Agisoft Metashape software. The agreements between the generated models and the reference dental casts are assessed using the Bland Altman method by calculating the mean value differences. All the calculated differences are not statistically significant (P-value > 0.05), and they are also clinically accepted as the range of the mean differences (−0.042 to 0.355) is less than 0.5mm. this demonstrates that the resulted 3D models closely approximate the overall geometry of the dental casts.

Keywords—dental cast, smartphone camera, photo studio setup, digital 3D model, accuracy, SfM photogrammetry

1 Introduction

The dental plaster cast copies the clinical information of human teeth and oral structure. The digital 3D model of the dental plaster cast represents the digital copy of the dental information, which has an important role in the diagnosis, planning, execution of treatments, and cast archive. It is also used as an auxiliary tool for clinical research and teaching [1–5].

Many technologies such as computed tomography scanning and laser scanning are used in the 3D construction of the dental and oral structures, thus being similar to traditional dental impressions. The high price of these 3D technologies requires costly hardware devices and special system software, which in turn, forms an impediment factor for dentists in individual clinics and primary hospitals [6–9]. Therefore, many recent dentistry studies have used the Structure-from-motion (SfM) Photogrammetry technique to construct the digital 3D model of a dental cast as an alternative to conventional scanning [10–12].

In the field of dentistry, several studies evaluated the accuracy of the using the SfM Photogrammetry technique as a 3D dental cast scanning [13, 14]. To be clinically accepted, some studies compare measurements made digitally in Photogrammetry software with manual measurements of actual plaster casts using a caliper [15, 16], one study assesses fine-scale surface details of the SfM Photogrammetry model by comparing it with a model scanned using a high-resolution structured light scanner [17]. Another study uses a projection of light texture to improve the surface texture of the dental cast when using Photogrammetry technique [18]. This research field requires further development to shed light on the working steps and how to find a methodology to get the best results every time, such as designing a photo studio setup and preparing the sample before photographing in order to increase the surface details and what happens if a phone camera is used instead of a digital camera.

The Structure-from-Motion (SfM) Photogrammetry technique represent a set of overlapping sequences of 2D images can be converted to 3D structures, this set which must cover all parts of the dental plaster cast on many levels at different angles passed through a series of processes, firstly, the correspondences between images are matched in order to extract key points [19, 20]. Then, depending on these extracted features, the camera position, alignment, and scene geometry are adjusted to generate an initial 3D cloud of points. Finally, a 3D mesh and texture representing the topography of the dental plaster cast surface are developed after adding further points to the dense point cloud, which is constructed from the sparse point cloud which was previously an initial 3D cloud [21–26]. The objective of this research is to evaluate the use of smartphones and an accessible and low-cost tool in SfM Photogrammetry as a technique for digitizing dental casts. In addition, it focuses on obtaining a methodology to achieve good performance for all cases by paying attention to some factors that affect the accuracy of 3D models to avoid them in the design of the photographic studio, finally this research aims to make SfM photogrammetry technique as an alternative tool for dentists to convert physical casts to digital models. The quality of the resulting SfM models is defined by examining and comparing the linear measurements of the digital dental model with the actual dental cast statistically and clinically. the clinically acceptable boundary for the differences between the measurements is set at 0.50 mm [14, 27, 28]. Both the null and the alternative hypotheses are used to predict if there is a difference between measurements or not.

2 Method

In this research, the use of the SfM Photogrammetry technique for digitizing dental plaster casts required a homemade photo studio setup, phone camera, and computer software. Some variables used in the photo studio setup were chosen as a result of using the phone camera as well as others. This was done to increase the efficiency of the captured images. The studio is designed in the shape of a box, with the turntable and a circular platform mounted on the floor of the box. All sides and the floor of the box are lined with black fabric, except for the top side, where the lamp is mounted at about 40 cm to allow light to pass through (light source type: LED; color temperature: 8000 Kelvin; lumen: 3200 lm; shape: round; size: 300*32mm). while the front side is used to mount the camera for taking photos, see Figure 1. The printed pattern is designed and pasted on the top of the circular platform. This pattern was designed using a scale bar of 8 × 8 cm and four markers (circular 12 bit) as shown in Figure 2. This printed pattern helps take the exact measurements of the photographed model and transfer them to the resulting 3D model. The semi-closed studio avoids the extraction of unwanted features from the background and also prevents unsuitable lighting conditions. Lighting should be diffused to avoid intense shade, which causes holes in the final point cloud during processing.

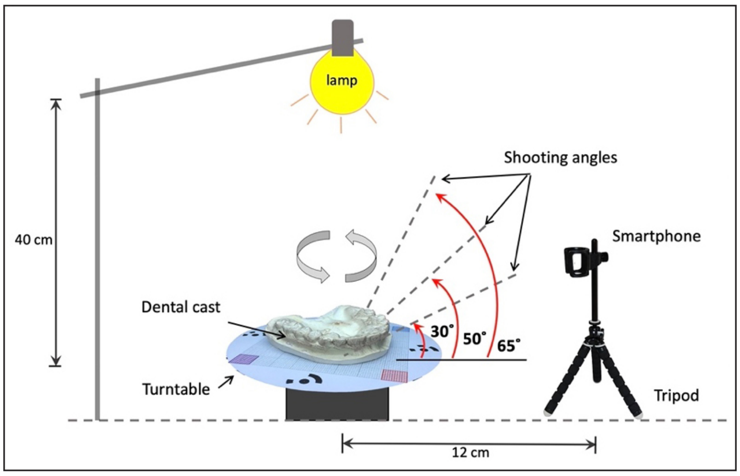


Fig. 1. Schematic diagram of photogrammetry homemade photo studio setup

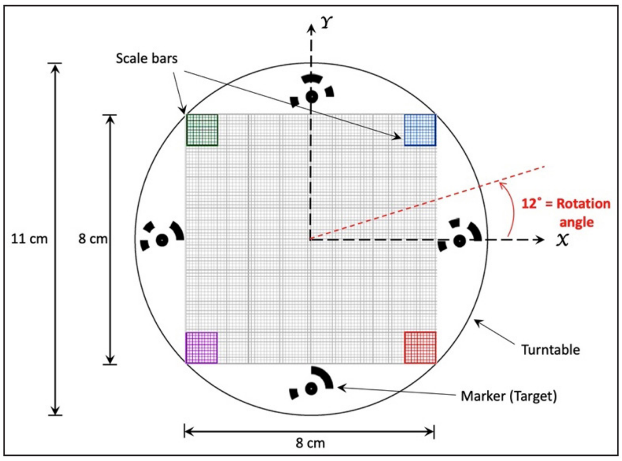


Fig. 2. Platform printed pattern

2.1 Materials

Twenty sets of dental plaster study casts were selected from the database of the teaching hospital. The inclusion criteria are: the complete arch model from the right second molar to the left second molar; all teeth have normal morphology without heavy corrosion, broken, or non-intact crowns; Because the surface characteristics of the dental plaster cast (i.e., texture) represent an important factor that affects the quality and resolution of the digitally reconstructed 3D model, this surface texture is enhanced by the physical application of paint powdering on the dental cast to avoid shiny, transparent, and featureless objects.

2.2 Image acquisition

The Smartphone camera (Apple iPhone 6s plus) is used for image capturing, the device parameters are listed in Table 1 [29, 30], The smartphone is fixed on a tripod with object distance (12 ± 2 cm), object distance is the distance between the camera and the sample, the tripod could be adjusted at different levels to achieve the shooting angles of (30º, 50º, 65º) to the turntable, as shown in Figures 1 and 3. At each shooting angle, the dental plaster cast is rotated 360º using the turntable, every 12º the rotation is stopped to take the photo, and the total number of photos taken at each shooting angle is 30. While the total number of captured photos for the dental cast model is 90 photos, the normal range of total number of captured photos is 70 to 100, photo sets of > 100 mark no improvements in point cloud density, whereas photo sets of < 70 cause a steep decrease in point cloud density. the overlap between convergent photos is about 80% to ensure the correctness of the features extraction and matching steps.

Table 1. Basic parameters of the smartphone camera (Apple iPhone 6s plus)

Camera	Apple iPhone 6s Plus
Sensor size	1/3″
Pixel size (µm)	1.22
Image resolution	4032*3024
Focal length (mm)	4.15
Aperture	f/2.2 (fixed)
Autofocus	Yes
Output format	JPEG

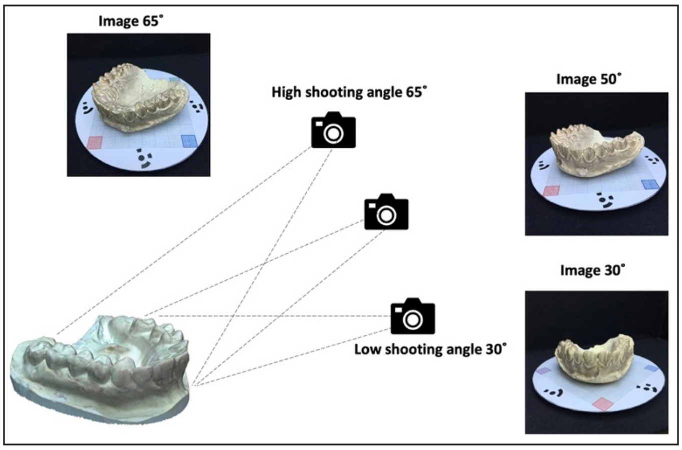


Fig. 3. The three used shooting angles

2.3 Construction the 3D digital dental model

After the acquisition of photos, transfer the photo set into the computer software (Agisoft Metashape) to start the processing based on the Structure-from-Motion algorithm, this software works semi-automatically, Figure 4 indicates the Work-flow sequence and settings. The first processing stage is aligning photos: creating a point cloud by automatically detecting and matching the 3D position of significant feature points in two or more photographs. The database of the extracted features is used to resolve the position and calibration parameters of the camera. Subsequently, the detected markers (target) and the identified scale bars are used to transfer the real dimensions to the resulting 3D model. The second stage of processing is creating dense point clouds by integrating the camera positions and feature points. Finally, the 3D mesh of the object and its texture is generated.

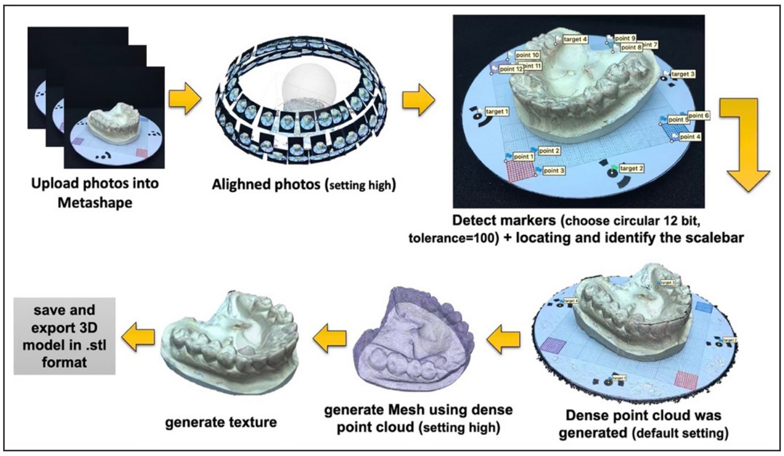


Fig. 4. Agisoft Metashape workflow used for 3D model generation

2.4 Measurements of the models

Measurements will be collected for both models to evaluate how well the generated and reference models match each other; the measurement of each parameter was repeated for all samples (n = 20) [27]. Figure 5 shows the height and width of four teeth (right 1st premolars, right central incisors, left canines, and left 1st molars), as well as arch measurements (intercanine distance, inter 1st molar distance). Manual measurements were taken for the reference models using a digital caliper, and measurements for the digital 3D models were collected using the Agisoft Metashape program. Figures 6 and 7 show the box plot of all measurements. Millimeters are the metric units of measurement.

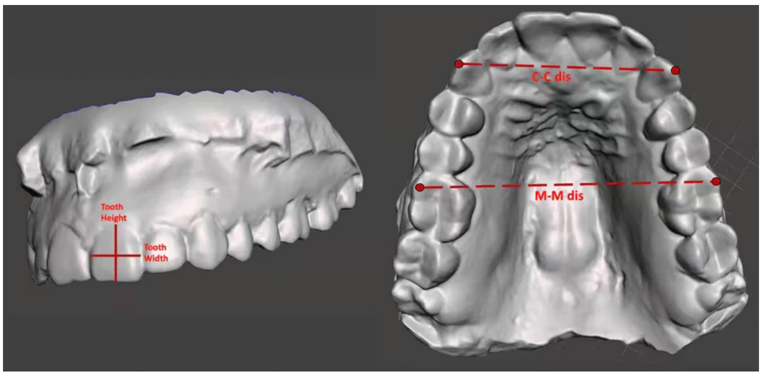


Fig. 5. The measurement of tooth width and height display on model in the left, the intercanine distance and intermolar distance display on the model in the right

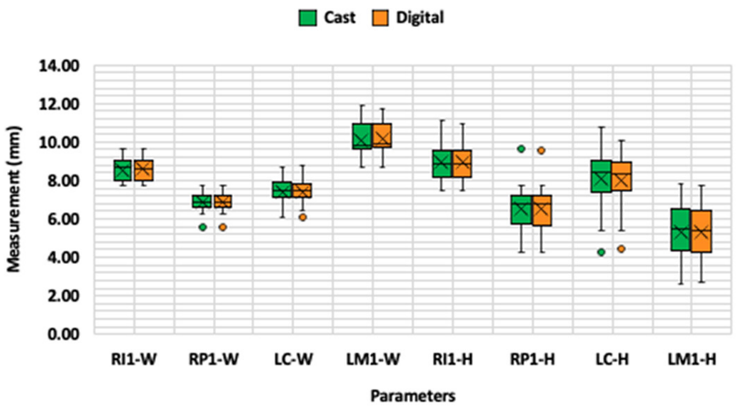


Fig. 6. Illustrate the box plot of the teeth measurements, the height (H) and width (W) of four teeth (right 1st premolars: RP1, right central incisors: RI1, left canines LC, and left 1st molars: LM1)

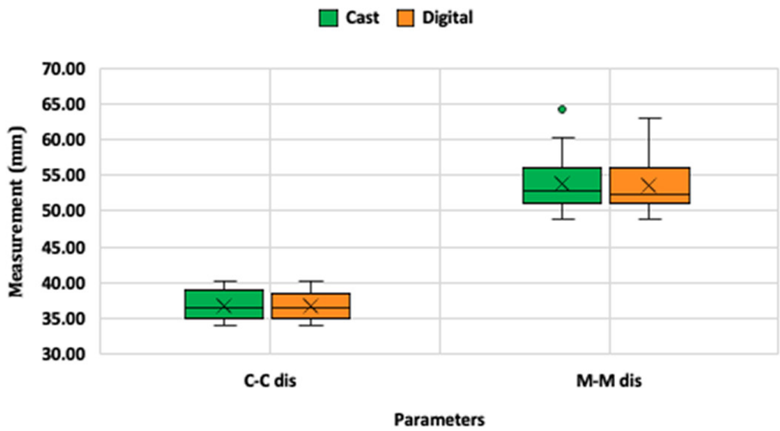


Fig. 7. Illustrate the box plot of the measurements (intercanine distance: C-C dis, and intermolar distance: M-M dis)

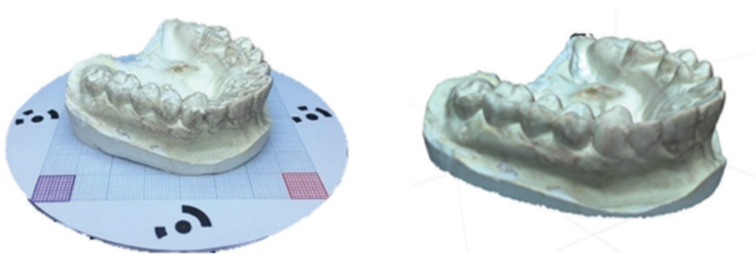
2.5 Statistical analysis

The dissimilarities between the measurements of the resulting and reference models (n = 20) are evaluated by applying the paired sample t-test method. In this method, the mean value for each parameter is calculated and compared between the resulting and reference models. The significance level was set at 0.05, and p-values greater than 0.05 were not statistically significant [15, 16, 31]. Additionally, the similarity between the measurements is assessed by applying the Bland-Altman method [16, 31]. The mean difference of each parameter represents the average of the difference in measurements made on the cast and the digital models of all 20 samples [27, 31]. All statistical analysis methods are executed using SPSS statistics software.

3 Results

Each 3D digital dental model constructed using the SfM photogrammetry technique clearly shows the morphologies of the anatomical structure, which are distinctly recognized when visually compared with the reference dental plaster casts. Figure 8 shows the physical model of the dental plaster cast in Figure 8a and the digital 3D model of the dental plaster cast in Figure 8b. The paired sample t-test was used to compare the mean of the two measurements assembled from the resulting and reference models, where the mean differences between measurements ranged between −0.042mm and 0.355mm, which makes them clinically acceptable (< 0.5 mm) and not statistically significant (p-value > 0.05), as shown in Table 2. Compared with the mean differences of another research, they are (−0.4 to 6 mm) in [16] and (0.011 to 0.402 mm) in [15].

The other comparison between the measurements was done by using the Bland-Altman analysis, Figures 9 and 10 exhibits a good concurrence between the resulting and reference models as all the differences have been grouped within the range of the mean difference ± 2SD (Standard deviation). In summary, the analytics comparison results show that all constructed digital 3D models show overall dimensions with high quality, while the visual comparison appears to have poor surface topographic features, especially on the occlusal surface.



(a) (b)

Fig. 8. The morphologies of the anatomical structure (a) physical model (b) 3D digital model (mesh with texture)

Table 2. Paired sample t-test

Parameter		Mean Differences	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	df	p-Value
					Lower	Upper			
Right 1st Premolars	H*	0.01800	0.05085	0.01137	−0.00580	0.04180	1.583	19	0.130
	W**	−0.02450	0.06134	0.01372	−0.05321	0.00421	−1.786	19	0.090
Right central incisors	H	0.03600	0.09225	0.02063	−0.00717	0.07917	1.745	19	0.097
	W	−0.03600	0.11137	0.02490	−0.08812	0.01612	−1.446	19	0.165
Left canines	H	0.07300	0.17217	0.03850	−0.00758	0.15358	1.896	19	0.073
	W	−0.01550	0.08876	0.01985	−0.05704	0.02604	−0.781	19	0.444
Left 1st molars	H	0.01150	0.12300	0.02750	−0.04607	0.06907	0.418	19	0.681
	W	−0.01100	0.09591	0.02145	−0.05589	0.03389	−0.513	19	0.614
Intercanine distance		0.20500	0.47404	0.10600	−0.01686	0.42686	1.934	19	0.068
Intermolar distance		0.21000	0.52305	0.11696	−0.03479	0.45479	1.796	19	0.088

Note: * H is height, ** W is width, t is t-test statistic [31], df is degree of freedom = n – 1, and p-value is probability value.

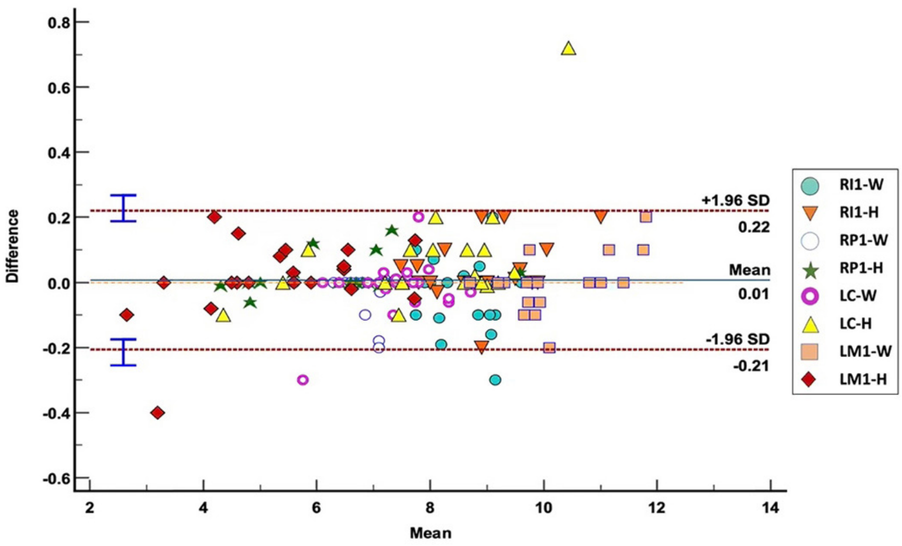


Fig. 9. The Bland–Altman plots of the four teeth width (W) and height (H) (right 1st premolars: RP1, right central incisors: RI1, left canines LC, and left 1st molars: LM1). The upper and lower limits of agreement (LoA), 95%, are given

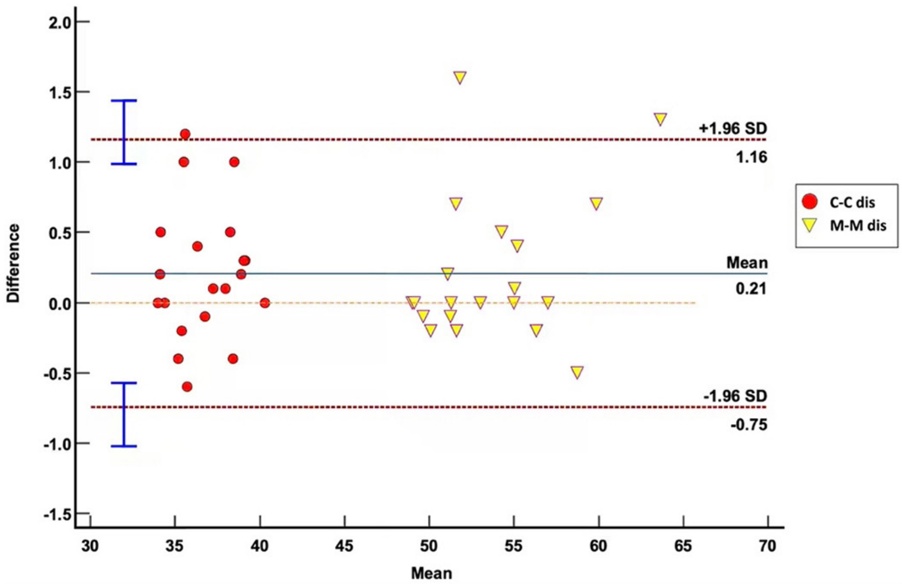


Fig. 10. The Bland–Altman plots of the intercanine (C-C dis), and intermolar distance (M-M dis). The upper and lower limits of agreement (LoA), 95%, are given

4 Discussion

In SfM Photogrammetry technique, the accuracy of the resulting digital 3D models mainly depends on the quality of the photos, which in turn counts on the photo studio setup and the camera resolution, which is considered a key factor in specifying the number of point density of the resulting models. This study uses the camera of the iPhone 6s plus smartphone to collect photos with a resolution equal to 12 MP. This smartphone has a shallow depth of field, which means only one part of the image is in focus. Some factors that affect the depth of field are aperture, focal length, and distance from the object. This smartphone has fixed aperture and fixed focal length, so shortening the space between the phone camera and the model (objective distance) in the photo studio setup leads to an increase the focus on model during photography and makes it occupy most of the photo. The photo studio is designed to do the most efficiently photograph using the phone camera, by using black fabric as a background to the studio, the printed pattern as flooring to the sample, and also good distribution of light source with no shadows, all these setups to increase the focusing on the model during photography, also help in distinguishing the models from their background which speeds up the construction process of the 3D models.

The quality and accuracy of the SfM results are also affected by the surface texture of the dental cast. Photographing a dental cast with many surface features results in a high acceptance ratio of input images, in contrast, a transparent surface or a reflective surface is interpreted wrongly, which results in a high rejection ratio of input photos and wrong meshes. Additionally, the use of printed markers around the model works as an additional feature and plays an important role in photo alignment and acceptance of input images. The dental plaster cast has a textureless surface due to its material nature, these surface features are diminished by the effects of the light source, thus; usually causing poor construction quality. For this reason, applying dry painting on the model surface effectively improves the extraction of features and increases the number of 3D points during the processing, yielding better results. The dental cast includes many details such as elevations and depressions, therefore; choosing a suitable shooting angle to cover the entire topography of the model is necessary. Additionally, a high overlap ratio between sequence images effectively improves the accuracy of the resulting 3D models. The total image collected for each dental cast was uploaded to photogrammetry software. As the images are processed, they must pass through various stages of quality testing, aligning, and detecting targets (markers). If any set of images can't pass any of these stages, they must be reconsidered, either in terms of the protocols or the photo studio setup and dental cast preparation before photographing, in order to increase the efficiency and accuracy of the resulting model until it is accepted medically (when comparing the resultant digital dental cast with the actual dental cast, the difference must be less than 0.5 mm). As a result, images can have a significant impact on both the final differences in producing a cast and its clinical acceptability. In summary, with careful preparation of the sample and the photo studio setup, the production of digital dental 3D models with high quality is easily replicated.

5 Conclusion

This study showed the success of using smartphones to digitize dental plaster casts using the SfM Photogrammetry technique. The same result with each scan is achieved by using a constant methodology of workflow, photo studio setup, and special preparation of casts. The dissimilarities between measurements made on the resulting digital 3D models and reference dental plaster casts are not statistically significant, also they are considered as having no clinical significance. With smartphones and simple hardware, the SfM Photogrammetry technique serves as an alternative way for dentists to convert dental casts to digital 3D models.

6 Acknowledgment

We would like to thank Hamza Medical Center for Rehabilitation team for providing us the required data used in this article.

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Article submitted 2022-10-21. Resubmitted 2022-12-19. Final acceptance 2022-12-27. Final version published as submitted by the authors.