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Original Article

Assessment of Trueness and Precision of FDM 3D Printed Maxillary Arch Models Obtained from CBCT Scans

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Abstract

Aim: The aim of this study was to assess the trueness and precision of three dimensional (3D) printed maxillary arch models obtained by fused deposition modelling (FDM) based on CBCT scan data.
Subjects and methods: A human skull was scanned by cone beam computed tomography (CBCT) to obtain the Standard Tessellation Language (STL) file of maxillary bone, then three maxillary models were printed by FDM technique. For dimensional accuracy assessment, nine linear measurements were selected and measured using digital caliper on both the skull and the printed models. The recorded measurements were compared to their corresponding measurements on skull (trueness assessment), and the measurements in each one of the 3 models were compared together (precision assessment), then data were statistically analysed.
Results: In trueness assessment, FDM printed models shows no statistically significant differences in overall dimensions, the recorded mean absolute difference was 0.05 mm, and the mean relative difference was 0.15%. However, regarding the precision, the results revealed a significant difference in the overall dimensional error in the 3 models compared to each other.
Conclusion: FDM constructed maxillary models had minimal dimensional error, which was statistically and clinically insignificant, hence they can be used safely in the dental clinical with comparable accuracy to the models produced by more expensive 3D printing techniques

Keywords: CBCT, 3D printing, FDM, Maxillary models

Introduction

A During the last few decades, the dental field has witnessed revolutionary progress since the integration of digital technologies and the transition from a two-dimensional (2D) to a three-dimensional (3D) practice. 3D printing or additive manufacturing is the construction of 3D object from a computer aided design (CAD) model or a digital 3D model. It can be done in a variety of processes in which material is deposited, joined, or solidified under computer control, with material being added together, typically layer by layer. 3D printing technologies have the advantages of high material utilization and the ability to manufacture a single complex geometry. However, it is a relatively costly procedure, which is time consuming and needs post processing procedures.(1)

There are several types of 3D printers available at the market; each with its distinctive advantages. The most commonly used in dentistry are: Fused Deposition Modeling(FDM), Stereolithography (SLA) , Digital Light Processing (DLP), Selective Laser Sintering(SLS) and Polyjet printing.(2)

FDM was originally invented and patented by Stratasys founder Scott Crump in 1989. Fast forward to the present, FDM is now the most commonly used 3D printing process also known as FFF (fused filament fabrication.). It uses the melt extrusion process to deposit filaments of thermal polymers in a predetermined pattern. FDM printers eject a thermoplastic filament that has been heated to its melting point layer by layer.(3)

There are several advantages of FDM printing such as: budget friendly, less complex procedure, variety of material choice, compact design, and filament reusability. Unfortunately, the FDM models has as rough surface finishing, weak strength and need long printing time. Additional demerits of the FDM printing technique are the layer adhesion problem, wrapping and nozzle clogging.(2,3)

Patient-specific 3D printed models are known to be useful surgical and educational tools. Faced with the large diversity of software, printing technologies and materials, the clinical team should invest in a 3D printer specifically adapted to the final application (4)

Hence the uniqueness of the anatomy, morphology and treatment performed in each dental patient, the demand for customized production mode has greatly increased. The development of 3D printing technology is pushed by medical and dental applications, to help in many aspects such as the fabrication of operation aids, prosthetic parts, implants, medical teaching models, medical instruments, and more.(5)

There are many applications of 3D printing in dentistry like: anatomical replicas and models, crown and bridges , retainers, implants, surgical guides, dentures and more. In order to create custom parts that match the patient’s anatomy, images of a patient’s anatomy are required. CBCT, CT, MRI, and other modalities are used to scan and collect the 3D data of the patients. Afterwards, the data is reconstructed into 3D data by computer software. Finally, the 3D data is made into solid models by 3D printer.(6)

CBCT systems are a variation of traditional CT systems. It’s an imaging modality in which a cone- shaped x-ray beam rotates around the patient, capturing data on an image detector. This data is used to reconstruct a 3D image of the different regions of the patient’s anatomy in oral and maxillofacial region. (7)

CBCT has revolutionized the imaging of the maxillofacial region due to its wide range of applications across the fields of dentistry, ranging from diagnosis to treatment planning and digital scanning. It is also can be used in a variety of applications such as: evaluation of the jaw, sinuses , nerve canals and nasal cavity, determining bone structure and tooth orientation, detecting and measuring jaw tumors, surgical planning for impacted teeth, accurate placement of dental implants, diagnosis of TMJ, cephalometric analysis and reconstructive surgery.(7)

In conclusion, despite the advanced technology of the used 3D printer or the selected imaging modality, all of them are still prone to errors which can be attributed to different factors. Therefore, it is worthy to evaluate dimensional accuracy of printed objects. Accuracy can be expressed using trueness and precision. In this case, trueness refers to the closeness of a model to a true value, and precision refers to the closeness of the results of repeatedly printed models. The aim of this study is to determine the dimensional accuracy of 3D printed maxillary models generated from CBCT scan data. (8).

Subjects and Methods

Study design: This study is an in vitro diagnostic accuracy prospective study (data collection was planned before the index test and reference standard were performed)

Study Sample & Sample Preparation: Sample size was calculated by using t test (Matched pair), G. power 3.1.9.7, depending on a previous study ***Petropolis et al., 2015*** (9) **.** as reference. If mean ± standard deviation of dry skull regarding APW is 26.5 ± 0.065, and in FDM 100 is 26.23 ± 0.059, minimally the study needed sample size is 3, with effect size 4.33. When power was set at 80%, type I error was set at 5%.

After institutional ethical clearance from faculty of Dental Medicine, Ahram Canadian University, a dry skull of any gender or any age with good bone density was selected from The Dental Anatomy Department. Maxillary arch of the selected skull was carefully examined for defects. Anatomical landmarks needed as measurements landmarks were checked and proven detectable.

Reference Model Measurement: Nine linear measurements were agreed upon by the authors of the current study, the measurements were selected to reside in different directions (vertical, horizontal, oblique) and planes (anteroposterior, mediolateral) to ensure covering all possible dimensional errors. All the measurements were measured in (mm) using digital caliper (with 0-150 mm measuring range) by two oral radiologists with 10+ years of experience. The selected measurements were as follows (Table 1), to serve as the reference standard for all measurements later.

Data Acquisition (Sample scanning):

Scanning was performed using CBCT machine as follows: CBCT images were acquired by i-CAT machine (by KaVo dental, USA), with the following protocol: a peak voltage of 120 KVp, a current of 5 mA, a field of view: 4 cm height x 16 cm diameter. The skull was scanned to generate the DICOM file that was exported and transferred in DICOM format on a CD.

DICOM data processing: The DICOM data sets were then imported into a 3D image reformatting software, OnDemand3D software (by Cybermed Inc., South Korea), for data analysis and primary reconstruction.

Data Processing:

Standard tessellation language (STL) File Generation was done as following: Digital Imaging and Communications in Medicine (DICOM) images were imported to an open source “3D Slicer” software (by 3D Slicer Community) for thresholding, segmentation, and generation of the corresponding STL file. The scanned skull was saved as STL file.

Next, STL files were imported and manipulated on a 3D software “Meshmixer 3.5” (by Autodesk, USA) for optimizing, cleaning up, smoothening, solidification and finishing of the STL file. This file was used for fabrication of the models. (Figure 1a)

Model fabrication (3D printing): The STL files was sent to a private center (3D layers, Egypt) for fabrication. Printing was done using “Pursa mk3 S printer” (by Pursa Research, Czech Republic). Model preparation, slicing and printing were done using a built-in manufacturer software PursaSlicer software (by Pursa Research, Czech Republic). It was printed using white Z-PLA filament *(polylactic acid filament)* in 0.2 mm layer thickness with a 0.4 mm nozzle diameter, and an estimated period of 2 hours/model.

Later, the support structure was removed manually mechanically in the post-processing phase. The process was repeated 3 times for printing a total of 3 models using the FDM printer. (Figure 1b)

Printed Models Measurement : The same nine linear measurements (previously mentioned) were recorded in (mm) using the same digital caliper for all the printed models (3 FDM printed models). All the measurements were measured by 2 experienced oral radiologists with different experience levels to ensure the inter-observer reliability. Each assessor repeated the measurements 2 times per model within 2 weeks as a time interval to ensure the intra-observer reliability.

Data collection: All the recorded data was collected, documented, and sorted for statistical analysis.

Results

Statistical analysis was performed with SPSS 20, Statistical analysis was performed using SPSS 20®1, Graph Pad Prism®2 and Microsoft Excel 20163. Data was represented as mean and standard deviation for quantitative data.

Data were explored for normality by using Shapiro Wilk and Kolmogorov-Smirnov normality test which revealed that all data is parametric data (P-value > 0.05).

Accordingly, comparison between two groups was performed by independent t test, while comparison between more than two groups was performed by One Way ANOVA followed by Tukey`s Post hoc test for multiple comparisons.

Mean difference was calculated by the following equation (mean difference = tested group – original group), while Mean Relative difference % was calculated according to the following formula:

$$= \frac{(V_2 - V_1)}{|V_1|} \times 100$$

Were V1: Mean of tested group, V2; mean of original group.

Also, inter-observer and intra-observer reliability coefficient were calculated using (Kappa test) to evaluate the agreement between 2 radiologists (Inter-observer reliability) and 2 different readings of each radiologist separately.

<u>Results of the current study is presented as follows:</u>

1. Inter-observer and Intra-observer reliability
2. Trueness (comparison between original model and FDM group)
3. Precision (comparison between different models in FDM group)

1. Inter-observer and Intra-observer reliability:

Interobserver reliability coefficient (Kappa test) was used to evaluate the agreement between 2 assessors and revealed that there was almost perfect agreement (1.00) regarding the FDM model.

Intra-observer reliability coefficient (Kappa test) was used to evaluate the agreement between 2 readings of the same assessor and revealed that there was almost perfect agreement (1.00) regarding the FDM model.

2. Trueness (comparison between original model and FDM group)

Mean and standard deviation of original model and FDM group at different distances, and difference between them, relative difference % were presented in (Table 2) and (Figure 2a). Comparison between measurements on the skull and on FDM group was performed by using **independent t test** which revealed that:

FDM was significantly higher than the original skull in D1 (P=0.003), D4 (P=0.02), D5 (P=0.04), D7 (P=0.01), and D9 (P=0.005).

There was insignificant difference between them regarding D2 (P=0.51), D3 (0.72), D6 (P=0.11), D8 (P=0.027).

In overall, there was insignificant difference between them (P=0.99).

***3.* Precision (comparison between different models in FDM group):**

Mean and standard deviation of 3 different models in FDM group were presented in (Table 3) and (Figure 2b). Comparison between three different models was performed by using One Way ANOVA test which revealed significant difference regarding D1 (P=0.02), D3 (P=0.01), D8 (P=0.0001), followed by Tukey`s Post Hoc test for multiple comparisons which revealed that:

D1; Model 1 (19.8 ± 0.04) was significantly the highest, but model 2 (19.45 ± 0.08) was significantly the lowest, while model 3 (19.52 ± 0.19) revealed insignificant difference with other models.

D3; Model 1 (41.67 ± 0.11) was significantly the highest, but model 2 (41.28 ± 0.10) was significantly the lowest, while model 3 (41.41 ± 0.13) revealed insignificant difference with other models.

D8: Model 1 (26.23 ± 0.19) was significantly the lowest, but model 2 (29.23 ± 0.05) was significantly the lowest.

In overall, Model 1 (19.8 ± 0.04) was significantly the highest, but model 2 (19.45 ± 0.08) was significantly the lowest, while model 3 revealed insignificant difference with other models.

Table (1): Linear measurement to be measured on original and printed models.

D1: (From Tip of the anterior nasal spine to crest of the ridge at midline)
D2: (From left infra orbital foramen to crest of the ridge at midline)
D3: (From right infra orbital foramen to crest of the ridge at midline)
D4: (From left infra orbital foramen to crest of the ridge posteriorly)
D5: (From right infra orbital foramen to crest of the ridge posteriorly)
D6: (Nasal cavity widest dimension horizontally)
D7: (Crest of the ridge at midline to the posterior nasal spine)
D8: Inter-canine distance (From the left canine to right canine)
D9: Inter molar distance (from left 2^{nd} molar to right 2^{nd} molar)

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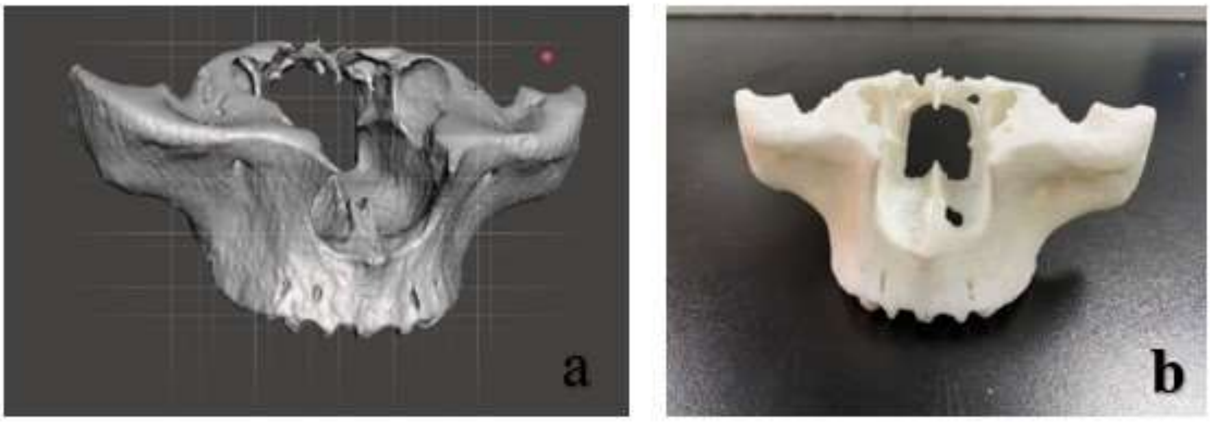

Figure (1): (a) STL file and (b) 3D printed models

Table (2): Statistical comparison between original model and FDM:

D	Original		FDM		Difference (Independent test)						
					MD	SD	SEM	Relative difference %	95% CI		P value
	M	SD	M	SD					L	U	
D1	18.45	0.25	19.59	0.19	1.14	0.06	0.18	6.18	0.63	1.64	0.003*
D2	41.28	0.05	41.40	0.29	0.12	0.24	0.16	0.29	-0.35	0.59	0.51
D3	41.62	0.12	41.45	0.20	0.17	0.08	0.13	0.41	-0.54	0.21	0.72
D4	28.15	0.24	28.92	0.28	0.77	0.04	0.21	2.74	0.17	1.36	0.02*
D5	28.39	0.27	28.98	0.21	0.59	0.06	0.19	2.08	0.04	1.13	0.04*
D6	27.74	0.31	27.20	0.35	0.54	0.04	0.26	1.95	-1.28	0.21	0.11
D7	53.45	0.11	54.04	0.22	0.59	0.11	0.14	1.10	0.19	0.98	0.01*
D8	28.35	0.06	27.29	1.44	1.06	1.38	0.83	3.74	-3.37	1.25	0.27
D9	41.23	0.35	39.24	0.51	1.99	0.16	0.35	4.83	-2.98	-0.99	0.005*
Overall	34.29	10.72	34.24	10.54	0.05	0.18	0.68	0.15	-24.15	20.04	0.99

Min: minimum *Max: maximum* *M: mean* *SD: standard deviation*
P: probability level which is significant at P ≤ 0.05
Means with the same superscript letters were insignificantly different as P > 0.05.
Means with different superscript letters were significantly different as P <0.05.

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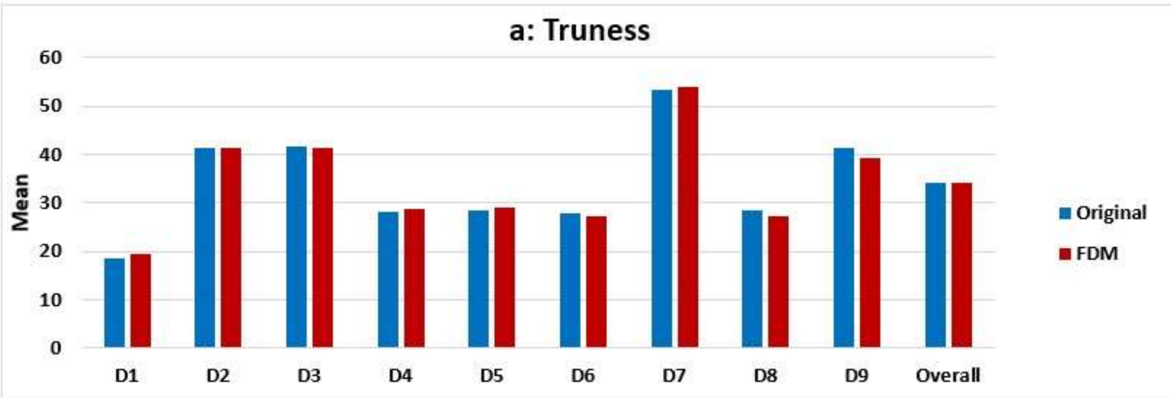

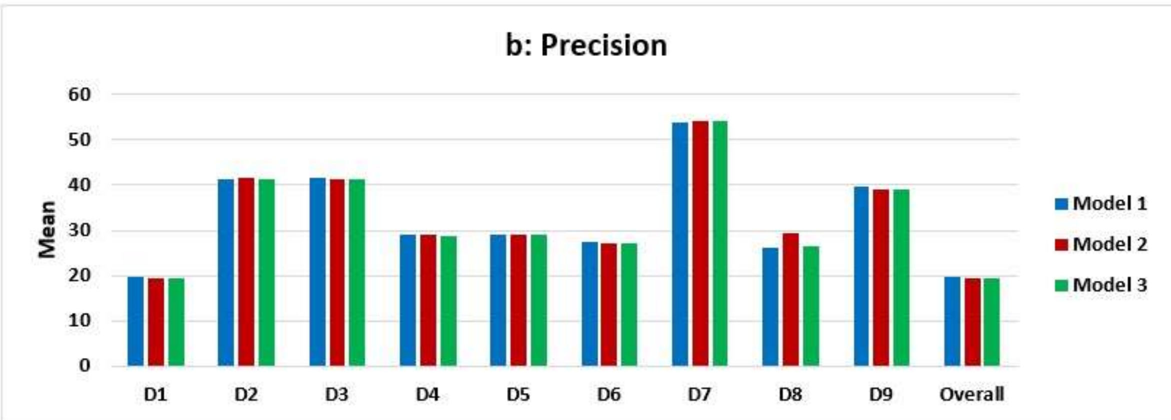

Figure (2): Bar chart showing three models FDM group (a) trueness (b) precision

Table (3): Statistical comparison between FDM models and each other:

D	Model 1		Model 2		Model 3		P value
	M	SD	M	SD	M	SD	
D1	19.80 a	0.04	19.45 b	0.08	19.52 ab	0.19	0.02*
D2	41.38 a	0.23	41.50 a	0.36	41.33 a	0.33	0.79
D3	41.67 a	0.11	41.28 b	0.10	41.41 ab	0.13	0.01*
D4	28.92	0.28	28.98	0.34	28.88	0.30	0.08
D5	28.99	0.19	28.98	0.32	28.97	0.14	0.91
D6	27.49	0.48	27.03	0.15	27.09	0.14	0.21
D7	53.78 a	0.10	54.15 b	0.06	54.21 b	0.13	0.003
D8	26.23 a	0.19	29.23 b	0.05	26.43 c	0.17	0.0001*
D9	39.55	0.75	38.98	0.19	39.18	0.36	0.41
Overall	19.80 a	0.04	19.45 b	0.08	19.52 ab	0.19	0.02

Min: minimum Max: maximum M: mean SD: standard deviation
P: probability level which is significant at $P \leq 0.05$, Counts with the same superscript letters were insignificantly different as $P > 0.05$, Counts with different superscript letters were significantly different as $P <0.05$

Discussion

The aim of the current study was to assess the dimensional accuracy of 3D printed maxillary arch models obtained by fused deposition modelling (FDM) and based on CBCT scan data. The comparison was done to determine and conclude the reliability of the FDM-printed maxillary models in the usage in different dental applications.

The parameters of "accuracy" used in this study described the **trueness** of printed models, suggesting their consistency with the refence model/skull. Also, it described the **precision** of the printed models which indicates their consistency with each other. (10)

The statistical analysis showed a non-statistically significant differences between the overall measurements of the 3D printed models and the skull (Trueness) with ***mean absolute difference of 0.05 mm*** and ***mean relative difference of 0.15%***. However, the results of the comparison between the 3 FDM models revealed a significant difference in the overall dimensional error in comparison to each other (precision).

Different studies defined the accepted clinical difference for the 3D printed models to be considered clinically accurate and reliable for usage in different applications. In ***Zhang et al., 2019*** study, the linear distance deviation within 0.2-0.5mm from a reference model was considered acceptable. (10) Also, ***Gottsauner et al., 2021*** study concluded that a tolerable deviation of 0.5 mm between reference and printed model, doesn't affect the accuracy and quality for the clinical demands of maxillofacial surgery. These conclusions indicated that the recorded error of the current study is considered clinically insignificant, and that FDM-3D printed maxillary model can be used safely in different dental clinical applications. (11)

In 2018, a study by ***Reddy et al., 2018*** studied the quality of an FDM-based 3D printer using nine different bones from different parts of the human body. The differences between the anatomical specimens and printed models ranged from 0.16 mm to 0.63 mm. These results can only be partially compared with those of our study because of the difference in the CT scanning, segmentation, and rendering process which can also affect the quality of 3D printed model. (12)

The result of the current study is in agreement with a study by ***Zhang et al., 2019*** who compared the scanned STL file of maxillary reference model to the scanned STL file of SLA 3D printed file using 3D superimposition analysis. The study recorded a dimensional error of 0.051 mm. This agreement in error resulted in SLA and FDM printed models suggests that FDM can be used as an affordable alternative to the expensive SLA printing technique. (10)

This suggestion was previously concluded by the findings of ***Kasparova et al., 2013*** comparing FDM to more expensive 3D printing technologies, there were no differences between the affordable FDM printer and professional printers in terms of clinical purpose. With these findings, there may be a potential to incorporate the more cost-effective FDM printing technology into dental use. More research should be conducted to evaluate the cost effectiveness and efficiency of various FDM printers compared to those of the professional printers used in dental labs. (13)

In another study ***Rebong et al., 2018***, A total of twelve FDM printed models were compared to the refence model using a digital caliper to obtain linear measurements. It was concluded that dental models reconstructed by FDM technology had minimal dimensional differences of 0.35 mm compared to reference models. Moreover, in this particular study the inter-canine distance and the inter-molar distance were recorded, and they both recorded a non-significant statistical difference. This comes in partial accordance with the current study where the inter-canine distance recorded a non-significant statistical difference, but the inter-molar distance recorded a statistically significant difference. This discrepancy could be owing to the difference in the sample size between the two studies. (14)

In 2015, CT scans of a dry skull were used to fabricate models using a consumer-grade FDM printer. Seven linear measurements were made on the models and compared with the corresponding dry skull measurements using an electronic caliper. A dimensional error of 0.21 mm and 0.44% was recorded. This study’s conclusion was that FDM printers can produce medical models with sufficient dimensional accuracy for use in maxillofacial surgery. These results and conclusion are in agreement with the current study findings which confirm the accuracy of the FDM 3D printed models. (9)

Earlier, ***El-Katatny et al., 2010*** assessed the errors generated during the fabrication process of human skull and mandible. A comparison between the linear measurements of eleven landmarks on the virtual model of a skull and nine for the mandible and its FDM printed replica was conducted. Studies on the skull showed an average of absolute mean differences of 0.108mm and relative mean difference of 0.24 %. While range of errors with regarded to the mandible replicas showing an average absolute mean difference of 0.079mm and relative mean difference of 0.22%. These recorded errors are higher than the current study which could be due to the difference in the advancement of the 3D printer itself in the last years, suggesting that in the future the resulted error is expected to keep on decreasing. (15)

Another important note is that the error resulted in mandible was less than the one in maxilla. This could be owing to the anatomical complexity of the maxilla and the difference in bone thickness in different areas which may affect the printing accuracy as well.

More recently, a comparison between FDM and DLP technique was conducted using twenty pairs of plaster models. Twenty-one reference points were placed on models, followed by scanning and printing of these models using FDM and DLP techniques. Measurements were made on these models using a digital calliper. The results showed that there was no significant difference in the measurements made between the FDM printed model and the original models, with an overall mean difference of -0.11 mm (range: from −0.49 to 0.17 mm). DLP printed models recorded an overall mean difference of 0 mm (range: from −0.42 to 0.50 mm). These results show that the FDM and DLP are both comparable and can be used interchangeably. Moreover, the FDM results come in accordance with the current study but with a difference in the dimensional change, while the current study recorded a positive error " indicating expansion", the ***Jaber et al., 2020*** study recorded a negative error "indicating shrinkage". This difference between the direction of the error could be justified by the difference in the image acquisition method (desktop scanning vs CBCT imaging). Therefore, this difference should be noted and considered when using FDM printed models in clinical use. (16)

Concerning the precision, the current study results may indicate inconsistency in the printed models with significant difference between the models. However, precision is highly related to the printing parameters and conditions. Different factors could affect the printing consistency like nozzle temperature , diameter , model wrapping, printing bed stability and more. So, it's highly recommended to reassess the precision using different FDM printers from different manufactures with larger sample size to fully assess the FDM printers' precision.

Regarding the study limitations, the ability of the researcher to repeatedly identify several landmarks on reference or printed models should be considered, as there would be an amount of identification error that could affect the evaluation procedure of the 3D printed models. Also, the lack of quantitative evaluation of the printing accuracy of maxilla was one of the major limitations of the studies included for results comparison.

Moreover, accuracy is related to the printer, the radiographic image, segmentation process, the size of the printed object and the printing material. Depending on the radiological data processing technique a 3D-printed model will always exhibit some discrepancies, so the operator has to keep it in mind acquisition and processing of the radiographically obtained image. ***Petropolis et al., 2015*** reported that medical models produced on a FDM printer from CT image data have sufficient dimensional accuracy to be useful in maxillofacial operations. (9)

Finally, from the current study and the previous studies results, it is important to highlight the importance of the 3D printed bone models used as training or simulation models for tumor removal, or bone reconstruction. These models were reported to have 43% share of the articles describing the use of AM models. Also, it was found that the functional and aesthetic results were superior in the patients where a 3DP models were applied. (4)

At the same time, A planning model needs to be accurate, yet cheap, as one patient cannot cover extensively all expenses. A training model essentially requires reproducing relevant haptic feedback and to be an inexpensive investment. These two qualities are also expected to simulate a surgical intervention, but also with a high level of accuracy. (4)

Since the affordable fused deposition modeling printers exhibited satisfactory results for creating training models, it could be recommended for usage as a 3D printing technique to produce the needed maxillary models.

Conclusion:

Maxillary dental models constructed by FDM technology had minimal dimensional error which was statistically and clinically insignificant. Maxillary FDM printed models can be used safely in the dental clinical use producing models with comparable accuracy to the models produced by more expensive 3D printing techniques.

Conflict of Interest:

The authors declare no conflict of interest.

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Ethics:

This study protocol was approved by the ethical committee of the faculty of Oral and Dental Medicine-Ahram Canadian University on: 13/8/2023,approval number:IRB00012891#74

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