Assessment of the accuracy of 3D printed teeth by various 3D printers in forensic odontology

Abstract:

Additive manufacturing technology has benefited many sectors, and its use in forensic sciences has opened up a variety of new opportunities for analysing and exhibiting forensic materials. However, to perform analytical procedures on 3D printed bones and teeth in forensic odontology, the metric and morphological precision of the printed replicas must first be validated. To address this, the present study was undertaken using 12 extracted human teeth that were 3D printed using five different techniques. Manual measurements and a digital mesh comparison were used to evaluate the metric precision of all samples. The findings showed that the printed replicas were accurate to within 0.5 mm of the actual teeth. It was suggested that Digital Light Processing (DLP) prints be used for potential forensic odontology applications based on measurements, digital comparison, and ease of use.

Keywords: *3D printing, 3D scanning, forensic science, forensic odontology, metric analysis, qualitative congruency analysis*

Introduction

Three-dimensional (3D) printing, also known as additive manufacturing, is the process of layering material sequentially to create a physical three-dimensional object from a digital model.[1,2] The process of making a 3D printed model from a digital model consists of four major steps: acquisition of 3D image data or designing a 3D model, segmentation and cleaning of acquired data, mesh conversion to a 3D model, and final data transfer to a 3D printer.[3] With the advent of 3D scanning and printing technology, their applications have been developed across industries such as medicine, dentistry, entertainment, forensic sciences, archaeology, etc.[4,5] 3D printing is being used in various forensic science sub-disciplines such as anthropology, nursing, crime scene analysis, ballistics, and odontology to produce 3D physical injury models,[6,7] reconstruction of fragmented specimens,[8,9] evidence reconstructions[10] and for demonstration in courts of law.[11,12]

Applications of 3D printing in Forensic Odontology

In the last 10 years, 3D printing has dramatically improved clinical dentistry with the advent of cone beam computed tomography and intraoral scanning technologies. These scanning and printing methods have been used for the preparation of surgical guides, restorations, orthodontic appliances and physical models in clinical dentistry.[13-15] However, the utilization of 3D printing in forensic odontology has been limited. 3D scanning and printing have been used to reconstruct missing teeth from empty dental sockets (forensic tooth reconstruction) [16] and to restore fragmented teeth[17], where reconstructed teeth were checked for odontometric precision. Previously, 3D scanning and printing were used for bitemark analysis.[18] *Ebert et al*[7] scanned a bitemark from the victim's skin and then printed it for improved visualisation, enabling them to successfully compare the bitemark injuries on the surface with the dental cast of the alleged offender.

Accurate 3D printed models could be used to estimate a person's age based on the sequence of dental eruptions. Accurate models may also be used for average grading of attrition (Li and Ji method), where direct inspection can be difficult due to poor visualisation, in sex determination and population identification studies [19-21] Bitemark analysis, can be difficult due to photo distortion or a progressive reduction in injury intensity.[22] 3D scanning and printing of bitemark injuries can be useful for visualization[7] but also for metric assessment[18], 3D superimposition[23] and also for the presentation of evidence. Recreation of bitemarks using 3D printing could lead to the full preservation and replication of tooth forms, lesions and abnormalities[24], as well as the 3D reconstruction of bitemarks from food products.[25] 3D scanning and printing technology can also be useful for analysis of cheiloscopy, rugoscopy and tongue prints.[26] 3D technology has also been proven to be effective in the demonstration of trauma and accident reconstructions.[11,27,28] In fact, 3D printing fracture demonstrations can be used to illustrate the injury process[29,30] as well as aid in restoration of fragmented specimens, that can be more useful in craniofacial identification [8,9] 3D digitisation techniques can play an important role in the identification of a cranium through facial reconstruction.[31,32] Forensic artists have produced facial reconstructions of victims using 3D printed skulls from computed tomography (CT) scan data.[33] Digital imaging techniques can be particularly useful in forensic analysis, where religious beliefs do not allow maceration of the deceased.[34]

Additive manufacturing processes

The American Society for Research and Materials in the United States (ISO/ASTM 52900) has categorised 3D printing technologies based on manufacturing methods into the following categories:

- **Material Extrusion**: Fused Deposition Modeling (FDM) or Fused Filament Manufacturing (FFF) employs thermoplastic filaments made of polymers such as acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) that are extruded via the printer bed's nozzle.[36]

- **Vat Polymerization**: Most of the printers using this method is a stereolithography (SLA) printer. In these printers, a thin film of light curable resin is mounted on the printer bed, which is then cured using a UV laser.[37] The other type of printer using this method is Digital Light Processing (DLP) where UV polymerized resins are cured by flash operation.[20]
- **Powder bed fusion**: The method adds thin layers of powder to the printing bed, which are melted using thermal energy from the laser. Selective laser melting (SLM) printers use metals or ceramics as powder.[38,39] Selective laser sintering (SLS) heats and fuses the powder. The powder of glass, metal or ceramic is used for this procedure.[38]

Other printing techniques include **polyjet** which utilises liquid photopolymer, which is cured to create a 3D object.[39] whereas **binder jetting (BJ)** utilises a jet of liquid bonding agent is utilised fuse successive layers of powder of bed of gypsum, metal or acrylic.[35] Adhesive is utilised to bond layers of paper, plastic or metal composite in sheet lamination technique.[35] **Electron beam melting (EBM)** printers are similar except they use a high voltage electron laser beam to melt metal powders.[40]

Model Accuracy

The accuracy of a 3D printed model depends on a variety of factors, such as imaging and scanning resolution, modelling parameters and type of printer, object to be printed and post-processing.[35,42,43] In order to maintain scientific standards, evidential integrity, and provide unbiased evidence, it may be important to check the accuracy of 3D printed models for forensic analysis and admissibility of 3D printed artefacts in a court of law.[10] Research has begun to investigate the metric accuracy of 3D printed skeletal models[10] using both manual and digital comparison methods. In recent study conducted using 3D printed dry human mandibles, the accuracy of reconstructions of anatomical landmarks, bone defects, and intra-socket dimensions were assessed; where FDM and DLP technique showed no significant difference, however deviations were observed when compared to gold standard.[44]In another study conducted for fabrication of dental prostheses it was found DLP technique gave accurate results with less deviation.[45] The present study investigates five different 3D printers and printing materials to determine the accuracy of the printed models and to work towards validation of 3D printed teeth for use as demonstrative evidence in a courtroom. The objective of this study was to quantitatively determine the accuracy of the 3D printed teeth using both manual and digital comparison techniques.

Materials and Methods

Data Collection

The study was conducted using a total of 12 extracted human teeth, comprising of single rooted (n=8) (maxillary and mandibular incisors, premolars) and multi rooted (n=4) (maxillary and mandibular molars) teeth obtained from the archives of Laboratory of Forensic Odontology, National Forensic Sciences University (NFSU), Gujarat, India. For this study, only teeth with intact morphology were selected; consciously teeth with complex anatomy were selected to test the accuracy of printing. A direct measuring method, using digital vernier callipers (Aerospace Digimatic, New Delhi, India) based on the conventional odontometrics was utilized to collect the linear measurements of the extracted teeth. Nine odontometric measurements were obtained by two observers (each with >5years of experience in odontology): crown length (CL), root length (RL), total tooth length (TTL), mesio-distal crown diameter at the cervix (MDCV), bucco-lingual crown diameter at the cervix (BLCV), mesio-distal diameter at the incisal edge (MDI), mesio-distal diameter at the occlusion (MDO), bucco-lingual crown diameter at the incisal edge (MDI) and bucco-lingual crown diameter at the occlusion (BLO).

3D Scanning, model preparation, 3D printing and post processing of the printed models

Each tooth was scanned using a Medit i500 Intra-oral handheld laser scanner (Seoul, South Korea). The scan data were processed in the Medit software where post-processing (such as base removal and cleaning) of the acquired 3D model and conversion of the model to the stereolithography (.stl) file format was carried out.[46]The resultant .stl files were printed on independent printers using five different 3D printing technologies detailed below.

Sr. No.	Type of 3D Printing	Printer Model	Specification for printing
1	**Fused deposition modelling technique (FDM)**	Flashforge™ Guider 2 3D printer (Zhejiang Flashforge3D Technology Inc., Zhejiang, China)	Material used was Polylactic acid (PLA) with a single nozzle, nozzle diameter 0.4 mm, precision ± 0.1-0.2 mm, thickness is 0.05-0.4 mm, speed 10-200 mm/.
2	**Stereolithography (SLA)**	Z Rapid (China)3D printers	Material used was ZR680 with a layer thickness of 0.1mm.The support structures were manually removed post-printing using tweezers
3	**Selective Laser Sintering (SLS)**	3DSYSTEM (USA)	The material used was duraform prox pa plastic with a layer thickness of 0.1mm
4	**Multijet fusion technology (MJF)**	HP (India) printers	Material used was HP MJF PA12 with a layer thickness of 0.1mm.
5	**Digital Light Processing (DLP)**	ENVISIONTEC (GERMANY) printer	Material used was ABS TOUGH M. The layer thickness was 0.1mm and the support structures were removed using tweezers.

Table 1: Different types of printing techniques use.

Subsequently, the 3D printed tooth models were scanned for digital comparison using the same hand-held laser scanner that obtained the original scans.

Digital Comparison

Mesh to mesh comparison was utilised to perform digital quantitative analysis using an open-source free software, CloudCompare (v2.11.2, (Anoia) Stereo [64-bit], for windows), as used by Robles *et al.*[47] The scanned specimens were individually considered as the “reference model” and the scanned 3D printed models the “test model”. The scanned 3D printed teeth were registered in respect to the “reference model” using the registration tool to align the models. Using the cloud-to-mesh distance tool[48], the difference between the reference model and the test model was calculated, which provided the mean distance (root mean square, RMS) with standard deviations for each comparison. Colour scalar maps were also generated for graphical visualisation of any metric differences.

Cross-sectional Model analysis

Geomagic qualify (3D systems, Morrisville, North Carolina) was used to perform cross-sectional model (CSM) analysis, as similarly performed by Elisova 2020[49]. Reference models and test models were registered with each other using 'Best-fit alignment'.[50]Longitudinal cross-section and the occlusal cross-section were generated using 2D comparison tool. Using the 2D comparison tool, the plane was aligned along the long axis of the tooth, resulting in a longitudinal cross-section after which 2D deviations were measured. Similar steps were employed for generating occlusal cross-sections by aligning the plane along the occlusal table and 2D deviations were computed. These steps resulted in 2D representations of the sections that demonstrated the difference between the two compared models.

Statistical Analyses

Manual and digital odontometric data were analysed using Microsoft Excel version 16.42 for Mac (Microsoft, Redmond, WA, US). Interobserver distance values were analysed using within-subject standard deviations (wSD; square root of average standard deviation) and 95 per cent repeatability (as previously used in [Carew 2018; Brough 2013]).[10,51] Using the mean manual comparison data of the two observers, the accuracy of the printed teeth were determined by subtracting the mean value measured from the printed tooth from the mean value measured from the initial tooth (as previously performed in [Carew 2018]). The absolute mean of differences across both measurements was then compared per printer and per sample to determine the accuracy across the printed teeth.

For the digital comparison data, the RMS, mean distance, and standard deviation values obtained from CloudCompare were assessed by calculating mean values per printer and per sample (as above).

Results

All twelve different tooth samples were created using the five different 3D printers (n=60 printed teeth). Figure 1 illustrates the printed maxillary first premolars from each printer.

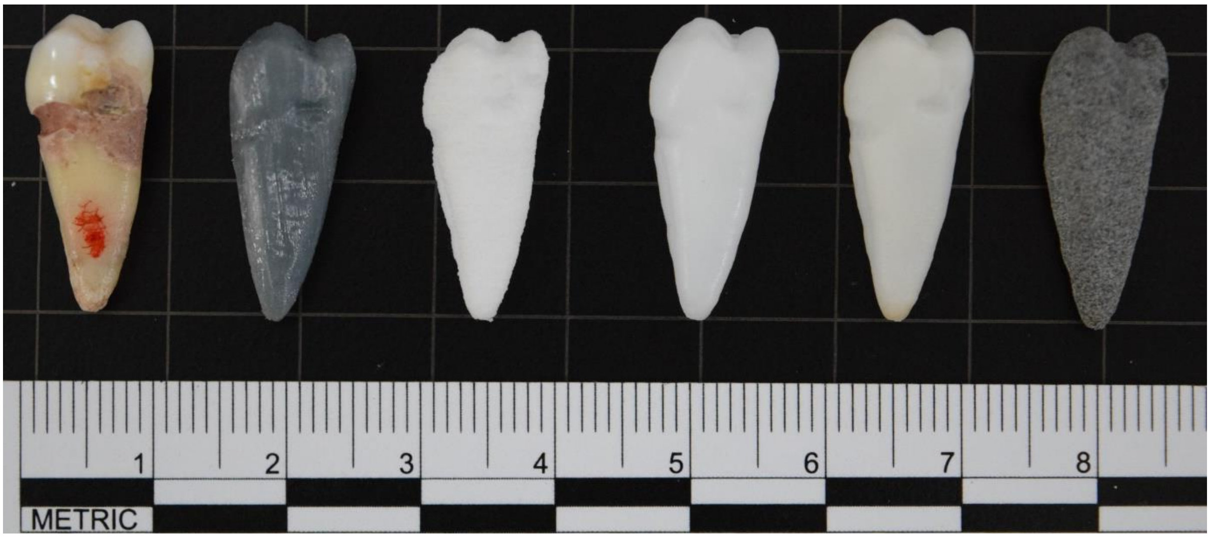

Figure 1. 3D printed teeth and original tooth from left to right: Natural tooth, FDM printed tooth, SLS printed tooth, DLP printed tooth, SLA printed tooth and MJF printed tooth.

Inter-observer Error

Odontometric measurements taken by the two observers from the printed and original teeth were analysed to assess inter-observer reliability. The inter-observer comparison demonstrated low difference values (<0.05 mm) and thus good reliability. Absolute mean differences and standard deviations per sample, between Observer 1 and Observer 2 data ranged from 0.01 mm to 0.05 mm (Table 2), wSD ranged from 0.10 mm to 0.26 mm, and 95 percent repeatability ranged from 0.26 to 0.47 mm. Absolute mean differences and standard deviations per measurement between Observer 1 and Observer 2 data ranged from 0.01 mm to 0.04 mm (Table 3), wSD ranged from 0.08 mm to 0.20 mm, and 95 percent repeatability ranged from 0.22 to 0.55 mm. A paired t-test of absolute mean differences resulted in p-values > 0.05, indicating that there were no statistically significant differences observed between the data obtained by the two observers.

Table 2 Interobserver data per sample: Absolute mean of observer differences, mean standard deviation (SD), within-subject standard deviations (wSD) and 95% repeatability (mm)

Sample	Abs mean difference	Mean SDs	wSD	95 % repeatability
1	0.01	0.01	0.10	0.28
2	0.01	0.01	0.12	0.33
3	0.05	0.04	0.23	0.63
4	0.01	0.01	0.10	0.27
5	0.01	0.01	0.09	0.24
6	0.03	0.02	0.17	0.47
7	0.02	0.01	0.13	0.36
8	0.02	0.01	0.13	0.35
9	0.01	0.01	0.10	0.26
10	0.01	0.01	0.10	0.29
11	0.02	0.01	0.15	0.40
12	0.07	0.05	0.26	0.73

Table 3 Interobserver data per measurement: Absolute mean of observer differences, mean standard deviation (SD), within-subject standard deviations (wSD) and 95% repeatability (mm)

Measurement	Abs mean difference	Mean SD	wSD	95 % repeatability
Crown Length	0.03	0.02	0.18	0.49
Root Length	0.04	0.03	0.20	0.55
Total Tooth Length	0.02	0.01	0.13	0.37
MD at cervix	0.04	0.03	0.20	0.54
MD at occlusion	0.01	0.00	0.08	0.23
MD at incisal edge	0.01	0.00	0.08	0.22

BL at cervix	0.01	0.01	0.12	0.32
BL at occlusion	0.01	0.01	0.09	0.26
BL at incisal edge	0.01	0.01	0.09	0.24

Manual comparison

The difference between the manual odontometric measurement data taken from the printed teeth and the measurement data taken from the original teeth were used to determine the accuracy of the printed teeth.

Absolute mean differences for all tooth measurements per printer are seen in Table 4 and for each sample in Table 5. All mean difference values were less than 0.5 mm showing the precision when compared to the dimensions of the original tooth, except for one sample (FDM sample 10). The prints with the highest trueness (lowest absolute mean differences)[52]were sample 4 from printer MJF and sample 8 from DLP, both with absolute mean differences of 0.07 mm. The FDM prints showed the lowest trueness (maximum absolute mean difference) with an absolute mean difference of 0.78 mm for sample 10 from the FDM printer

*Table 4 Manual comparison difference (printed tooth value minus original tooth value) results per printer (mm), (absolute, abs), (standard deviation, SD) (*lowest difference,)*

Printer	Mean Abs Mean	Min Abs Mean	Max Abs Mean	Mean SD
FDM	0.30	0.08	0.78	0.25
MJF	0.24	0.07*	0.43	0.21
DLP	0.21	0.07*	0.40	0.20
SLA	0.26	0.09	0.46	0.25

SLS	0.24	0.12	0.49	0.22

*Table 51 Manual comparison difference (printed tooth value minus original tooth value) results per sample (mm), (absolute, abs), (standard deviation, SD) (*lowest value,)*

Sample	Mean Abs Mean	Min Abs Mean	Max Abs Mean	Mean SD
1	0.33	0.17	0.45	0.32
2	0.26	0.17	0.33	0.28
3	0.24	0.14	0.34	0.21
4	0.20	0.07*	0.36	0.16
5	0.19	0.13	0.26	0.13
6	0.22	0.18	0.30	0.21
7	0.13	0.08	0.22	0.12
8	0.12	0.07*	0.22	0.11
9	0.30	0.25	0.42	0.24
10	0.51	0.38	0.78	0.48
11	0.26	0.16	0.33	0.23
12	0.24	0.14	0.40	0.20

Digital comparison

The digital comparison performed using CloudCompare provided distance values (RMS) of the difference between the printed tooth and the original tooth. Figures 2 and 3 show distance maps and graphs between the natural and printed tooth of Sample 10 (sample 10 showed maximum difference between the printed and original specimen). Mean RMS values are presented by printer (Table 6) and by sample (Table 7). The mean RMS values ranged from 0.04 to 0.19 mm, which were less than 0.5 mm and thus within the accuracy threshold demonstrating the accuracy of the original tooth.

The highest trueness observed [52] was for sample 6 from the DLP printer (RMS 0.04 mm), and the lowest trueness observed was for sample 9 from the FDM printer (RMS 0.19 mm).

Table 6 Digital comparison results per printer (mm)

Printer	Mean RMS	Min RMS	Max RMS	Mean SD
FDM	0.12	0.04	0.19	0.18
DLP	0.07	0.04	0.13	0.13
MJF	0.07	0.04	0.11	0.11
SLA	0.08	0.05	0.14	0.11
SLS	0.10	0.06	0.14	0.12

Table 7 Digital comparison results per sample (mm)

Sample	Mean RMS	Min RMS	Max RMS	Mean SD
1	0.07	0.05	0.09	0.06
2	0.08	0.07	0.10	0.07
3	0.08	0.05	0.11	0.07
4	0.08	0.05	0.14	0.07
5	0.08	0.05	0.10	0.08
6	0.09	0.04	0.16	0.06
7	0.07	0.05	0.09	0.05
8	0.05	0.04	0.06	0.05
9	0.14	0.11	0.19	0.12
10	0.09	0.07	0.14	0.08
11	0.12	0.09	0.19	0.11
12	0.10	0.08	0.13	0.09

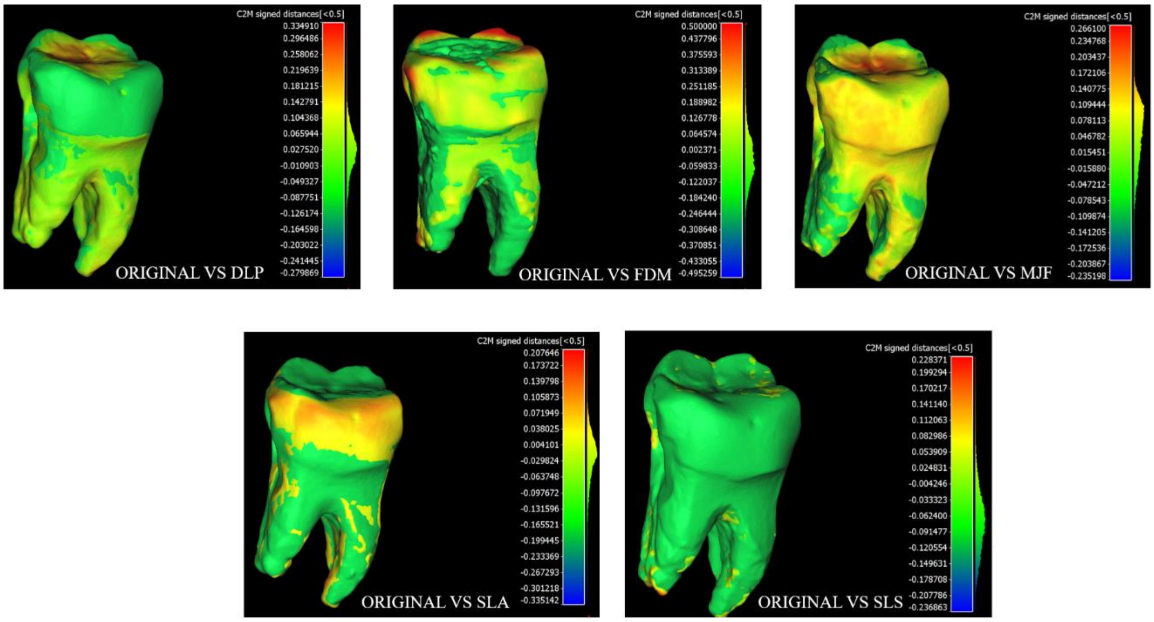

Figure 2: Colour scales showing cloud to mesh distances between Original and different 3D printed teeth for Sample 10

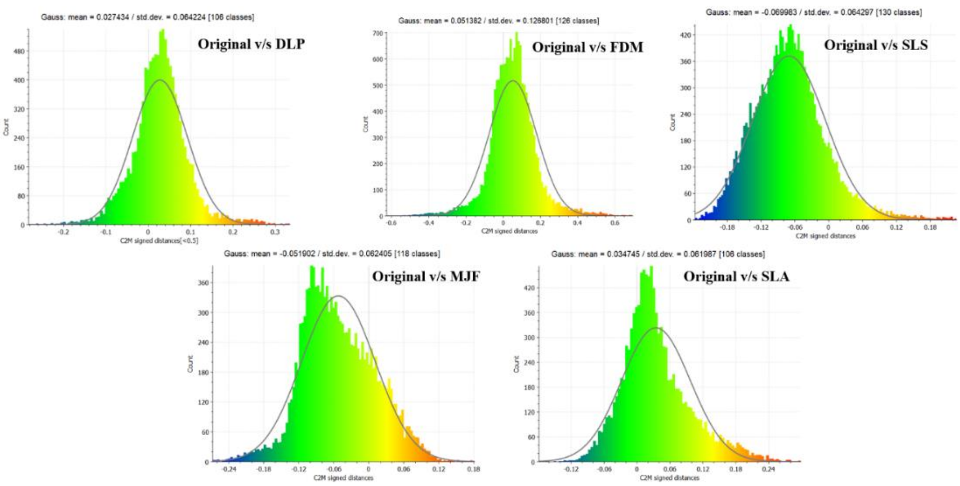

Figure 3: Colour graphs showing Cloud to mesh distances differences between Original and different 3D printed teeth for Sample 10

Cross-sectional Model analysis

CSM analysis was performed in occlusal and longitudinal cross-section for tooth sample 6 (a premolar). The results (shown in Figure 4) demonstrated the areas of differences between a DLP printed tooth and the original tooth, and an FDM printed tooth with the original tooth using a colour scale. All differences observed were less than the accuracy threshold of 0.5 mm, with higher distance values seen on the CSM for the FDM sample (RMS 0.0917 mm occlusal, RMS 0.1119 mm longitudinal) compared with the DLP sample (RMS 0.0463 mm occlusal, RMS 0.0561 longitudinal).

2D distance deviations between the printed and original teeth were visualised along the tooth surface. Figure 5 illustrates the morphological differences between the longitudinal cross sections of original (purple outline) and 3D Printed (black outline) teeth.

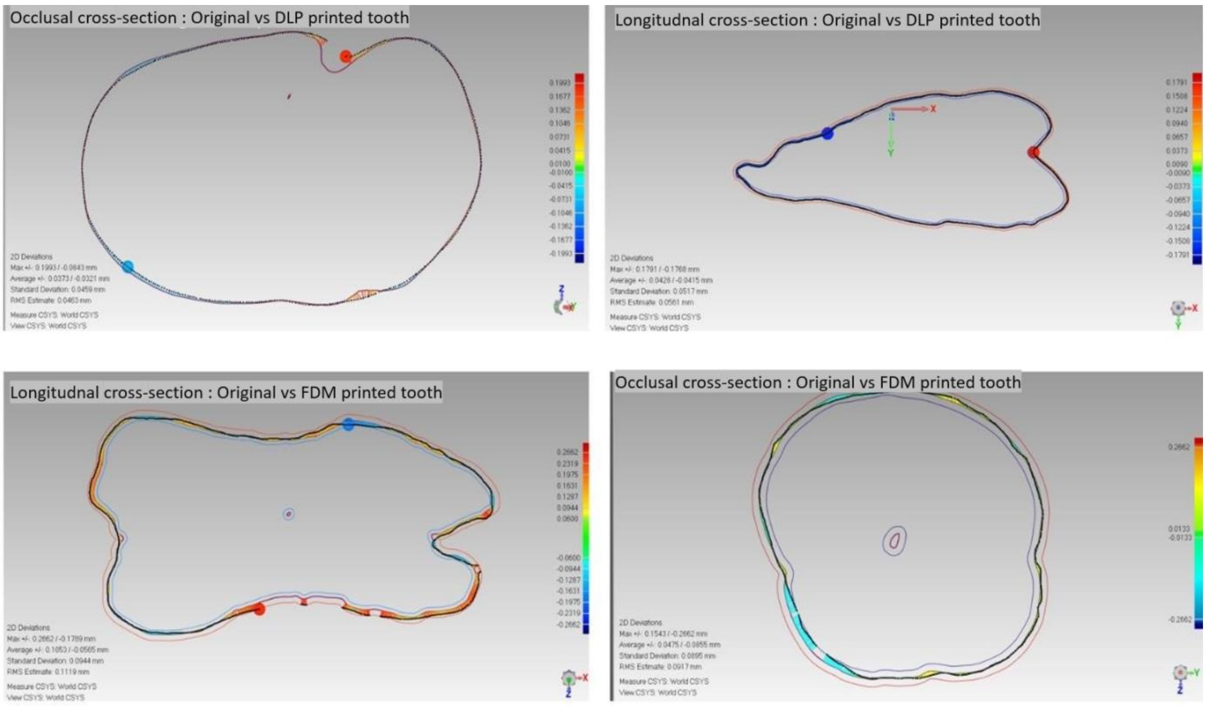

Figure 4 Cross-sectional Model (CSM) analysis for tooth sample 6 in occlusal view (left images) and longitudinal view (right images) for re-scanned printed teeth DLP (upper images) and FDM (lower images) compared with the reference model (scanned original tooth). 2D deviation data and scale indicating differences between printed teeth and original teeth are shown (red being positive differences, and blue being negative differences). Scale bar values differ per image.

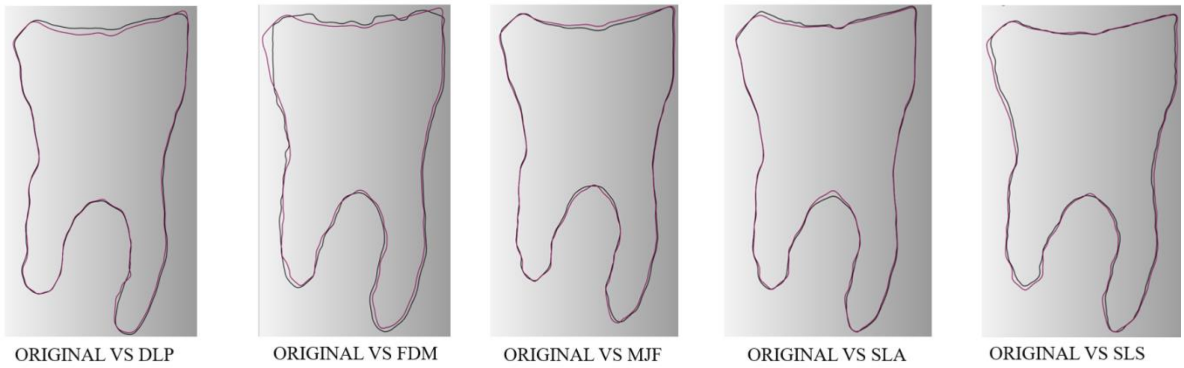

Figure 5 Morphological differences between the longitudinal cross sections of original (purple outline) and different 3D Printed (black outline) teeth to visualise discrepancies between them (Sample 10)

Discussion

Metric analysis is required for numerous analytical procedures conducted for dental age estimation, bitemark analysis, sex and ancestry identification.[18,19] In order to conduct forensic analysis using 3D printed models, it is important to determine the dimensional accuracy of the 3D printed dental models and to determine which technology generates the model with the highest accuracy. There are studies that illustrate the accuracy of 3D printing models, but to the best of our understanding, the vast majority[10,20,21] use a comparison of linear dimensions rather than a comparison of deviation levels. The present study explored the dimensional accuracy of 3D printed dental models developed using five separate 3D printers. This preliminary study is one of the few studies investigating the accuracy of 3D printed teeth using manual metrics and digital analysis.

Rebong et al.[53] revealed that 3D printed dental models produced with stereolithography, polyjet and fused deposition modelling (FDM) varied statistically from plaster models. Hazevald and co-workers carried out another study of multiple rapid prototyping techniques such as digital light processing, Polyjet printing, and 3D printing utilizing stone powder and highlighted that rapid prototyping techniques could replace stone models in the manufacture of orthodontic instruments.[21] The statistics performed to calculate interobserver reliability in the present study showed no apparent error and presented values <0.05mm. Statistics conducted to perform a comparison of models produced using various printers indicated that absolute mean difference values (less than 0.5 mm) were accurate, except for one incidence in that of sample 10, printed using FDM technology. The prints with the highest trueness observed were for sample 4 from MJF printer and sample 8 from DLP, both with absolute mean differences of 0.07 mm. The FDM prints showed the lowest trueness (maximum absolute mean difference) with an absolute mean difference of 0.78 mm for sample 10 from the FDM printer.

The colour maps produced for the digital analysis revealed that the dimensions of the STL file of the original tooth were similar to those of the STL of the dental models printed with DLP and MJF (mean RMS 0.07 mm), whereas the maximum discrepancy was observed with the FDM prints (mean RMS 0.12 mm). The colour maps demonstrated that the variance was usually found in the furcation region of the base (for multirooted) , the occlusal groove, and the root apex, which are confluent with the results of Lee et al.[54] This is most likely due to difficulties in scanning complex structures such as furcation and overlapping of the scans. The post processing of the scans also contributes to this distortion. According to Bibb et al.[55], surfaces that are obscured or obtuse from the line of light cannot be scanned, resulting in the development of "void." This disparity in scanning and processing of scanned data may have an effect on the efficiency of 3D printing, as reported by Carew et al[10] that 3D scanning and modelling parameters are more important than printing resolution. Nevertheless, the variances observed were minimal and (with the exception of one comparison) within the threshold for accuracy in this study.

In addition to scanning criteria, basic knowledge of printing techniques is important to understand dimensional errors. FDM printers use poly lactic acid (PLA), a thermoplastic material that melts at a certain temperature to create a print with a very low resolution.[50] The thickness of the layer also influences the resolution of the printing process. However, the prints produced from the various printers tested in this study were accurate, but more factors about the aesthetics of printing, the cost of selecting a printer, the time taken to print should be acknowledged as contributing to the final product.[10] The FDM printers used in this study were cheaper when compared to the costlier SLS and MJF (INR 2000/- to 3000/- for 12 prints) produced the prints that showed maximum dimensional error, were unesthetic owing to the visible layer lines and had longer post-processing time. FDM technology exhibited a significant variation in metrics, since the thermoplastic material melts at higher temperatures and is then laid down on the previously defined path. The layer lines are formed by the deposition of successive layers over the previous layer, that exerts force on the underlying areas. The constant variation in the temperature may result in warping and dimensional instability. Based on the practicality of usage and parameters mentioned above DLP technology is preferred, for its aesthetics, economical when compared to MJF and SLS printers (INR 800/- to 1000/- for 12 prints).. Further studies are indicated using incisors, canines, premolars and molars (with and without anomalies) to evaluate the printing accuracy in respect to complex anatomy and reproducibility owing to smaller size. Based on reviewers comments teeth were reprinted using DLP technique with layer thickness of 0.1mm which showed minimal difference of 0.20 mm, which showed accuracy when compared to other techniques.

Conclusion

This preliminary study, undertaken to quantitatively compare the metric accuracy of 3D prints from a forensic odontology point of view is the first of its kind in India which demonstrated that:

- Though the differences were observed between all the 3D printed and original teeth. However it was observed that the minimal deviation from the original was observed in DLP printed teeth at 0.05mm and 0.1mm.
- The manual odontometric data obtained were reliable between observers
- 3D printed teeth were accurate to within 0.5 mm (with one exception) following a manual comparison
- The 3D prints obtained from all five printers were accurate to within 0.5 mm following a digital comparison
- Cross-sectional Model (CSM) analysis demonstrated minimal discrepancies, thus showing morphological accuracy.
- A final consideration of all parameters indicated that DLP prints were preferable overall within the limitations of the study.

Accurate scanning and modelling are important for effective and accurate 3D printed teeth models, and digital comparison studies can be performed straightforwardly accessibly using open-source software. Further work is required to explore 3D printing capabilities in cases representing burnt remains and traumatic events. This study adds to the growing body of literature discussing and addressing the validity and reliability of 3D printed replicas as demonstrative evidence in the forensic sciences, and specifically in forensic odontology.

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