# Accuracy of 3D-Printed Dental Models of Different Tooth Surfaces

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# Abstract

**Background:** Few studies have been reported regarding the accuracy of 3D-printed models for orthodontic applications. The aim of this study was to assess the accuracy of 3D-printed dental models of different tooth surfaces.

**Methods:** Thirty maxillary dental models were produced by means of a stereolithography-based 3D printer. Each printed model was digitally scanned and compared with the oral-scanned STL file via superimposition analysis, with a colour map used to assess the accuracy of different surfaces of anterior and posterior teeth.

**Results:** Statistically significant differences were found in the average deviations of different tooth surfaces. The mean average absolute deviations of the occlusal surfaces of posterior teeth were greater than those of other surfaces. Percentages of points beyond the upper and lower limits of different tooth surfaces displayed the same results.

**Conclusions:** The occlusal surfaces of posterior teeth on 3D-printed dental models show greater deviations than those of other regions, especially in pits and fissures.


# Background

Rapid prototyping (RP) technologies provide the possibility for a physical dental model to be generated from digital data economically and conveniently. These three-dimensionally printed dental models have saved dentists from the dilemma of storage space, risks of damage, and the inconvenience of miscommunication. The 3D-printed dental model is being increasingly used in orthodontic diagnosis and treatment. However, it is subject to deviations due to the accuracy of the 3D printer.

Currently, the most commonly used techniques for orthodontics applications are PolyJet and stereolithography (SLA). Due to its high printing resolution and fast forming speed, there has been an increase in the number and availability of SLA-based printers in recent years.[1] Digital light processing (DLP) is a subset technology of SLA printing that uses a projected planar image of light to photopolymerise resin.[2] During this process, the printing plate moves up in a given Z-axis distance (for example, 0.025 mm, 0.05 mm, 0.1 mm), and photopolymerising resin is projected to the light of a specific wavelength (405 nm) that cures a cross-section layer by layer. This printing process is repeated until the model is complete. It usually takes up to several hours for a dental model to be printed with this technology, depending on the Z-axis print layer thickness set by the printer.[3]

However, little research has been reported regarding the accuracy of 3D-printed models for orthodontic applications. Most of the literature compares linear measurements of 3D-printed models with those of stone models.[4-7] Zhang *et al*. compared the accuracies of 3D-printed dental models using three types of DLP and SLA printers at different thicknesses and found that the printing accuracy of all printers was higher at 50 μm.[8] Park and Shin[9] compared the accuracy and reproducibility of conventional dental casts and 3D-printed models fabricated by three types of printers. The results showed that the volumetric changes in casts made by the conventional method were significantly smaller than those of 3D-printed casts. Brown *et al.*[10] compared the tooth and arch measurements of three model types (digital, DLP, and PolyJet) with those of stone models Their results indicated high degrees of agreement among all types of models for all measurements, except the crown height measurements between the stone and DLP models. However, linear measurements indicate that the print model is consistent with the plaster model, but the results of linear measurements can demonstrate only that the 3D-printed model is suitable only for use in orthodontics study. More and more orthodontic appliances are being manufactured based on 3D-printed models; therefore, accuracy of tooth surfaces is critical. Models with inaccurate 3D-printed surfaces may lead to the poor fit of an orthodontics appliance. The purpose of this study was to assess the accuracy of 3D-printed dental models of different tooth surfaces.

# Methods

A sample of 30 maxillary dental models was included in this study. Thirty volunteers who met the criterion for inclusion (having a complete permanent dentition) and without the exclusion criteria (having obvious dental anomalies in size and shape and severe dental crown defects) were randomly selected from the hospital. First, digital dentition data were obtained by intraoral scan (iTero, Align Technology Inc., San Jose, CA). These scanned data were set as prime STL reference models. Thirty STL reference models were printed with DLP rapid prototyping technologies (DentLab One, SHINING 3D, Hangzhou, China), with a build layer thickness of 0.05 mm. [11] The 3D-printed models were then scanned with the same intraoral scan as the STL test models.

The digital models generated from both intraoral scan and 3D-printed models were exported to Geomagic Control software (3D Systems, Rock Hill, SC) as STL format files for model superimposition. Each tooth of the 3D-printed model was segmented separately into buccal, lingual, and occlusal surfaces and superimposed with the corresponding tooth of the STL reference model, then merged for calculation of the deviation of the STL reference model (Fig. 1). With 'canine to canine' as the anterior region and 'first premolar to second molar' as the posterior region, the superimposition was done separately for the buccal surfaces of anterior teeth (BA), lingual surfaces of anterior teeth (LA), occlusal surfaces of anterior teeth (OA), buccal surfaces of posterior teeth (BP), lingual surfaces of anterior teeth (LP), and occlusal surfaces of anterior teeth (OP). The segmenting procedure was done twice independently by two researchers. Observer consistency was calculated for reliability. Each 3D-printed model scanning file (labeled as the STL test model) was then individually superimposed on the oral-scanning file (labeled as the STL reference model) by means of an automated best-fit algorithm (Fig. 2). Geomagic software showed the means and standard deviations of different tooth surface distances between the STL reference models and the STL test models. A 0.10-mm threshold parameter was set as the critical value for the analysis of deviations between the STL reference model and the STL test model. Any points in the test file deviating from the reference file by more than 0.10 mm in the positive or negative direction were considered to be beyond the upper or lower limits, accordingly. Reports were generated for separate calculation of the total positive and negative deviations.

IBM SPSS Statistics 20.0 (IBM, Chicago, IL) was used for statistical analysis. The Tukey test was used to evaluate the differences between the superimposition of the STL test model and the STL reference model. P values less than 0.05 were considered to be significant.

# Results

The repeatability of the measurements in this study was high, with an intraclass correlation coefficient value of 0.878. The colour map showed the deviations of the STL test model and the STL reference model (Fig. 2). A 0.10-mm threshold parameter was set as the critical value for the analysis of deviations between the reference file and each test file. The darker the colour, the larger the variance, and the lighter the colour, the smaller the variance, i.e. red and blue showed greater deviations than yellow and green. It could be clearly seen from the colour map that the colours of occlusal surfaces of posterior teeth were much darker than those of other surfaces.

The average deviations of 3D-printed dental models of different tooth surfaces were then collected and compared (Table 1). The average deviation of the anterior region was generally smaller than that of the posterior region, which can be seen clearly from the box chart (Fig. 3). The means and standard deviations of the occlusal surfaces of posterior teeth were greater than those of other surfaces, with a statistically significant difference ($P < 0.05$).

Table 1
Average absolute deviations of different tooth surfaces.

| Surface | BP | LP | OP | BA | LA | OA |
|---|---|---|---|---|---|---|
| Mean (mm) | 0.03838 | 0.03707 | 0.04950* | 0.03377 | 0.03265 | 0.03526 |
| SD (mm) | 0.00718 | 0.00662 | 0.00962 | 0.00772 | 0.00769 | 0.00910 |

*$P < 0.05$.

Percentages of points beyond the upper and lower limits of different tooth surfaces were also compared (Table 2). The variance between the different tooth surfaces was more pronounced. The occlusal surfaces of posterior teeth appeared to have higher percentages of points beyond the upper and lower limits, which showed greater deviation from the reference models ($P < 0.05$) (Fig. 4).

Table 2
Percentages of points beyond the upper and lower bounds of different tooth surfaces.

| Surface | BP | LP | OP | BA | LA | OA |
|---|---|---|---|---|---|---|
| Mean | 1.029 | 1.124 | 4.460 | 1.160 | 1.920 | 1.509 |
| SD | 0.717 | 0.906 | 2.838 | 1.061 | 1.675 | 1.559 |

*$P<0.05$

# Discussion

Few investigations have focused on deviations of the different tooth regions (anterior and posterior teeth) and different tooth surfaces. This study compared deviations of 3D-printed models and reference models on buccal, lingual, and occlusal surfaces of anterior and posterior teeth. It could be seen that the average deviation of the posterior dentition of the 3D-printed model was more significant than that of the anterior region. Kim *et al*. evaluated 4 types of 3D-printed models (SLA, DLP, FFF, and the PolyJet techniques) for tooth, arch, and occlusal measurements.[12] They found that the difference was larger in the posterior region than in the anterior region in superimposed 3D digital models, which is consistent with the results of this study.

The results of our research clearly demonstrated that the occlusal surfaces of posterior teeth of 3D-printed models deviated primarily from those of the intraoral scan model. Both the average absolute deviations and percentages of points beyond the upper and lower limits of different tooth surfaces provided confirmatory evidence for this discovery. Although, in this study, the average difference between the 3D-printed model and the reference model appeared as a small inclusion occlusal surface, the deviation in the region of posterior pits and fissures was obvious. The dark red colour in this region showed the deviation here to be even more than 0.1 mm, which may have some significant clinical effects. For example, a 3D-printed template or tray cannot be fitted well onto this 3D-printed working model in the laboratory.

Printing errors in the 3D-printed model can arise from each link of the printing process and the parameters thereof. These include residual polymerisation of the resin, effects of support structures, print resolution (X and Y planes), layer thickness (Z plane), and surface finishing.[13] Favero *et al*. investigated the effect of print layer height on the accuracy of 3D-printed models using three layer heights (25, 50, and 100 μm) and found that the 25-μm and 100-μm layer height groups had the greatest and least deviations, respectively.[1] Keating *et al*. examined one SLA model and found statistically significant differences in the Z plane compared with its corresponding stone model and hypothesised that it may be due to the greater layer thickness of the investigated SLA model (0.15 mm).[14] The relatively significant deviations found in this research may result from the complex morphology of the occlusal surfaces of posterior teeth. Buccal and lingual surfaces are relatively flat and smooth compared with occlusal surfaces, whilst the morphology of the occlusal surfaces of posterior teeth is hilly, particularly in deep pits and fissures.

During the rapid prototyping process, the photosensitive resin, which is sticky and requires manual cleaning, will be cured by the ultraviolet laser.[15] The liquid adhesive can flow along the smooth surface but can easily remain on the pits and fissures of the occlusal surfaces of posterior teeth. If it is not cleaned completely or not cleaned in time, the material at the bottom of the groove will cure by itself, as occurs during pit and fissure sealing. The deeper the fissure, the greater the deviation (Fig. 5). To solve this problem, technicians can fill the deep grooves in the stone model or digital model in advance to minimise the 3D-printing error.

For the DLP system, only one type of printer was used in this research, which may have been a limitation in our study. Numerous studies have compared the measurements made on 3D-printed models and traditional casts and among different rapid prototyping techniques. Dietrich *et al*. investigated the accuracy of the SLA and PolyJet systems through surface superimposition.[16] They concluded that the PolyJet models showed greater accuracy than the SLA models, but the precision measurements favoured the SLA models. Both systems were suitable for clinical use. Brown *et al.* assessed the accuracy of 3D-printing techniques by tooth and arch measurements and concluded that both the DLP and PolyJet printers were clinically acceptable, due to high degrees of agreement between the printed and stone models. [10]

However, few investigations have focused on deviations of the different tooth regions (anterior and posterior teeth) and surfaces. This study compared deviations of 3D-printed models and reference models on buccal, lingual, and occlusal surfaces of anterior and posterior teeth. No study has drawn firm and reliable conclusions as to whether the deviations between 3D-printed models and a reference model are clinically acceptable. It remains controversial whether differences in dimensions between the reference model and the 3D-printed models affect the accuracy of orthodontic appliances. Kasparova *et al.* compared traditional plaster casts, digital models, and 3D-printed models and found 3D-printed models to have advantages over traditional plaster casts due to their accuracy and price.[6] Wan Hassan *et al*. compared the accuracy of measurements made on rapid prototyping and stone models with different degrees of crowding.[4] They found significant differences for all planes in all categories of crowding except for crown height in the moderate crowding group and arch dimensions in the mild and moderate crowding groups. They concluded that the rapid prototyping models were not clinically comparable with conventional stone models.

Intraoral or extraoral scanning is becoming more and more common and may even replace traditional models in the future, but there is no clear evidence as to whether digital models and 3D-printed models can take the place of stone models to produce some orthodontic appliances in the laboratory. Even designed and produced with digital models, those appliances still need to be tried on the 3D-printed models. Further, due to the relatively obvious print errors on the occlusal surfaces of posterior teeth, some appliances and templates made with digital models cannot be fully placed on 3D-printed models.[17] Some measurement differences that occur in these 3D-printed dental models will affect the accuracy of manufactured orthodontic appliances, especially the fit on occlusal surfaces. Deviations in the occlusal template for orthognathic surgery will affect the precision of the surgery. 3D-printing technology is also widely used in the design and manufacture of clear aligners. As is well-known, differences between sequential aligners are only 0.2-0.3 mm, so errors over 0.3 mm may influence the expression of tooth movement. Cole *et al.* examined the accuracy of 3D-printed retainers compared with conventional vacuum-formed and commercially available vacuum-formed retainers.[18] The results showed the least deviation from the original reference models in the conventional vacuum-formed retainers and the greatest deviation in the 3D-printed retainers. However, the deviation was clinically acceptable. Further research is needed to confirm the precision and clinical acceptability of 3D-printed models in orthodontics clinics.

# Conclusions

When the print errors of different surfaces of anterior and posterior teeth were compared with the DLP technique, the occlusal surfaces of posterior teeth displayed greater deviations than other regions, especially in pits and fissures. This should be taken into consideration in the implementation of digital orthodontics.

# List Of Abbreviations

RP: Rapid prototyping; SLA: stereolithography; DLP: Digital light processing; 3D: three-dimensional; BA: buccal surfaces of anterior teeth; LA: lingual surfaces of anterior teeth; OA: occlusal surfaces of anterior teeth; BP: buccal surfaces of posterior teeth; LP: lingual surfaces of anterior teeth; OP: occlusal surfaces of anterior teeth

# Declarations

## Ethics approval and consent to participate

This study obtained Ethical Committee approval from the Institutional Review Board of Shanghai Ninth People's Hospital affiliated to Shanghai Jiao Tong University, School of Medicine(2016-213-T126) and the written informed consent was obtained from all participants.

## Consent for publication

Not applicable.

## Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

## Competing interests

The authors declare that they have no competing interests.


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### Authors' contributions

DT performed the main study and drafted the manuscript. XLG and WXT helped to acquire data. YLJ analyzed and interpreted the data. YNS was a major contributor in designing the manuscript. FB designed the main scheme of the research and modified the manuscript. All authors read and approved the final manuscript.


### Acknowledgements

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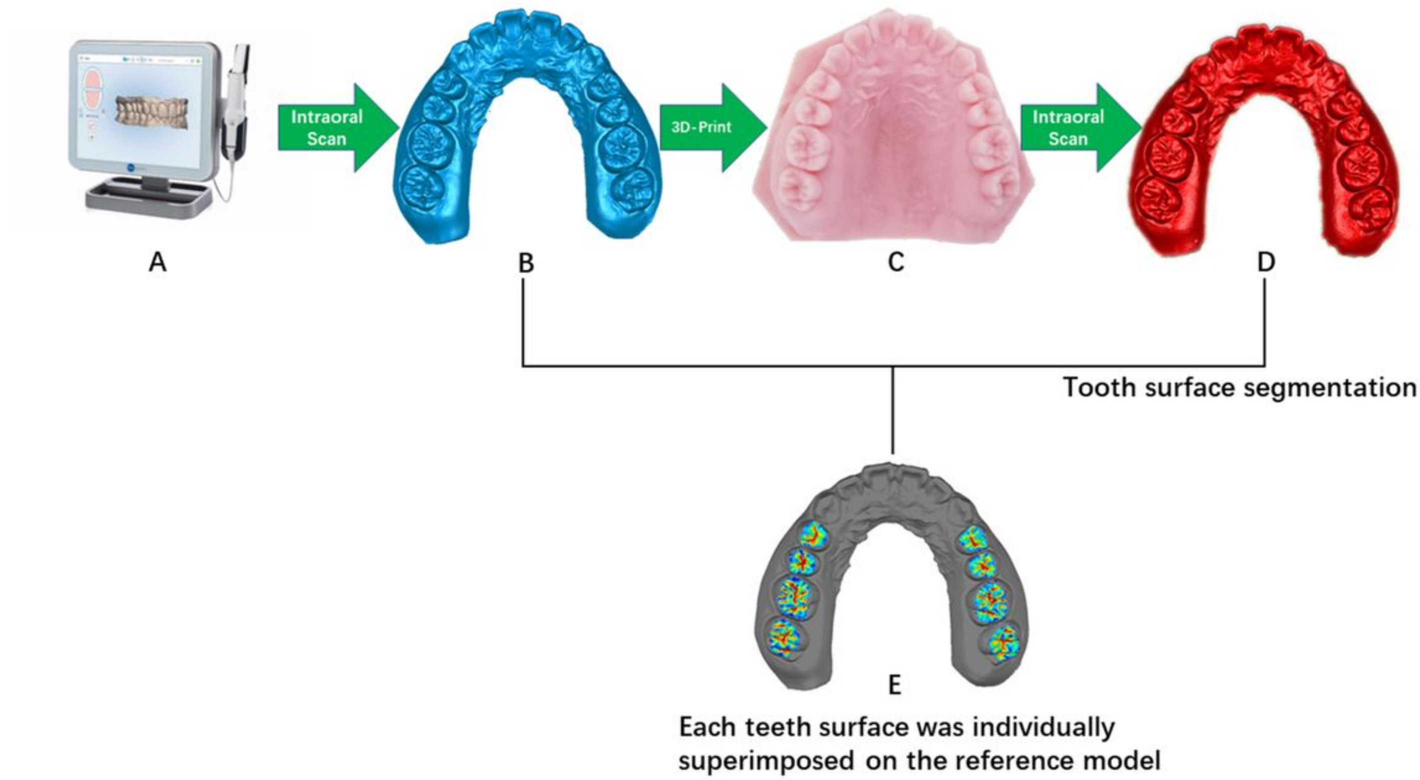
# Figures




## Figure 1

Schematic figure, illustrating the design of this study. Scanning models generated from intraoral scans and 3D-printed models were exported to Geomagic Control software. Tooth surface segmentation was performed on 3D-printed scanning models, and each tooth surface was individually superimposed on the reference model.

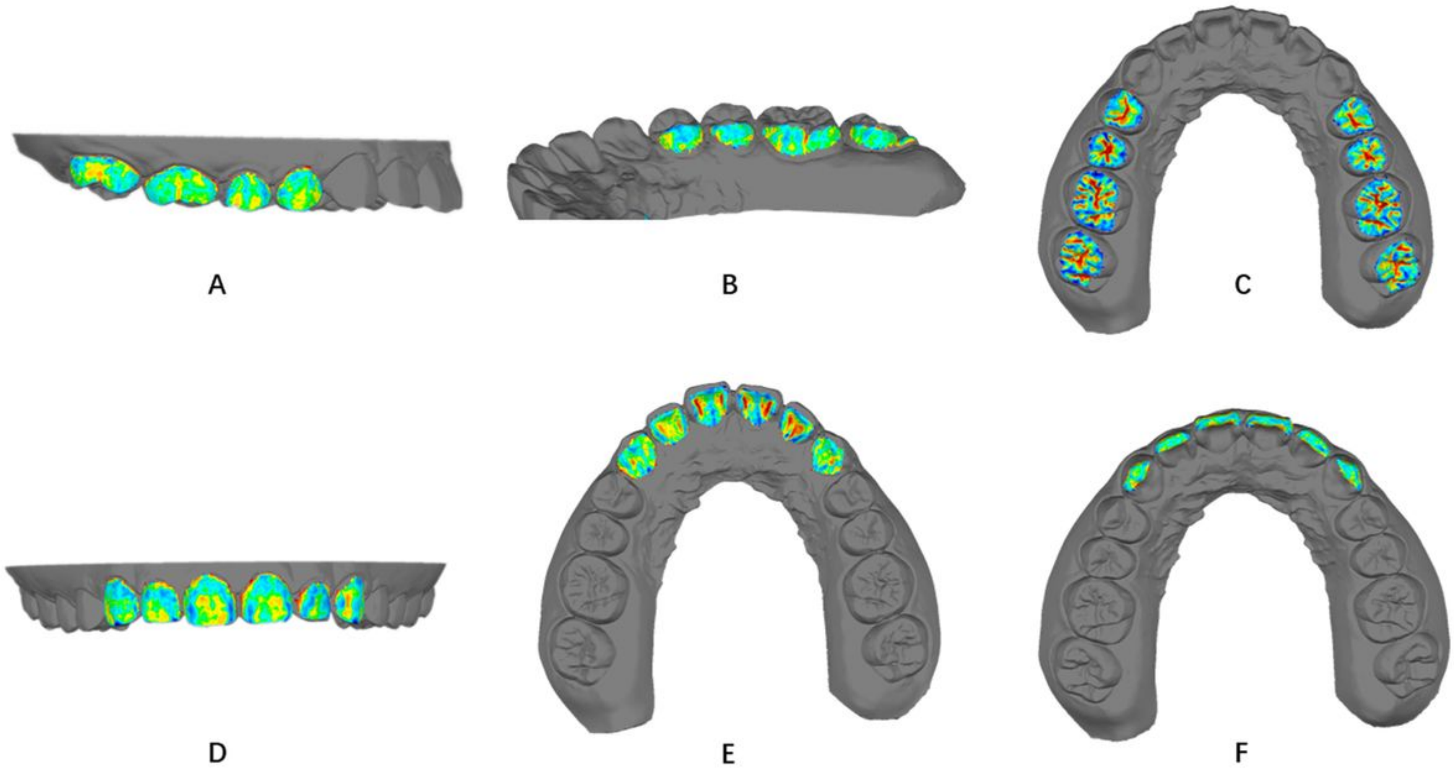
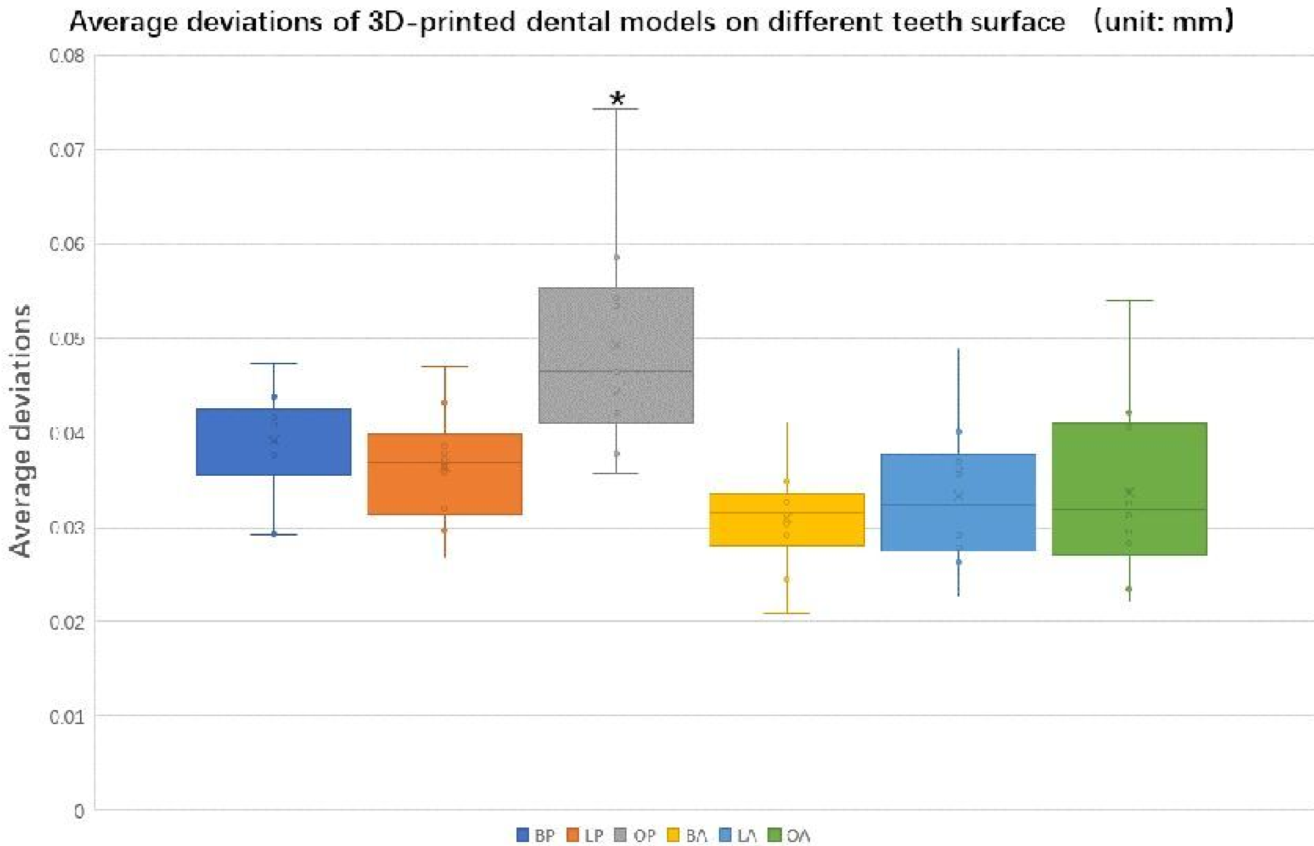


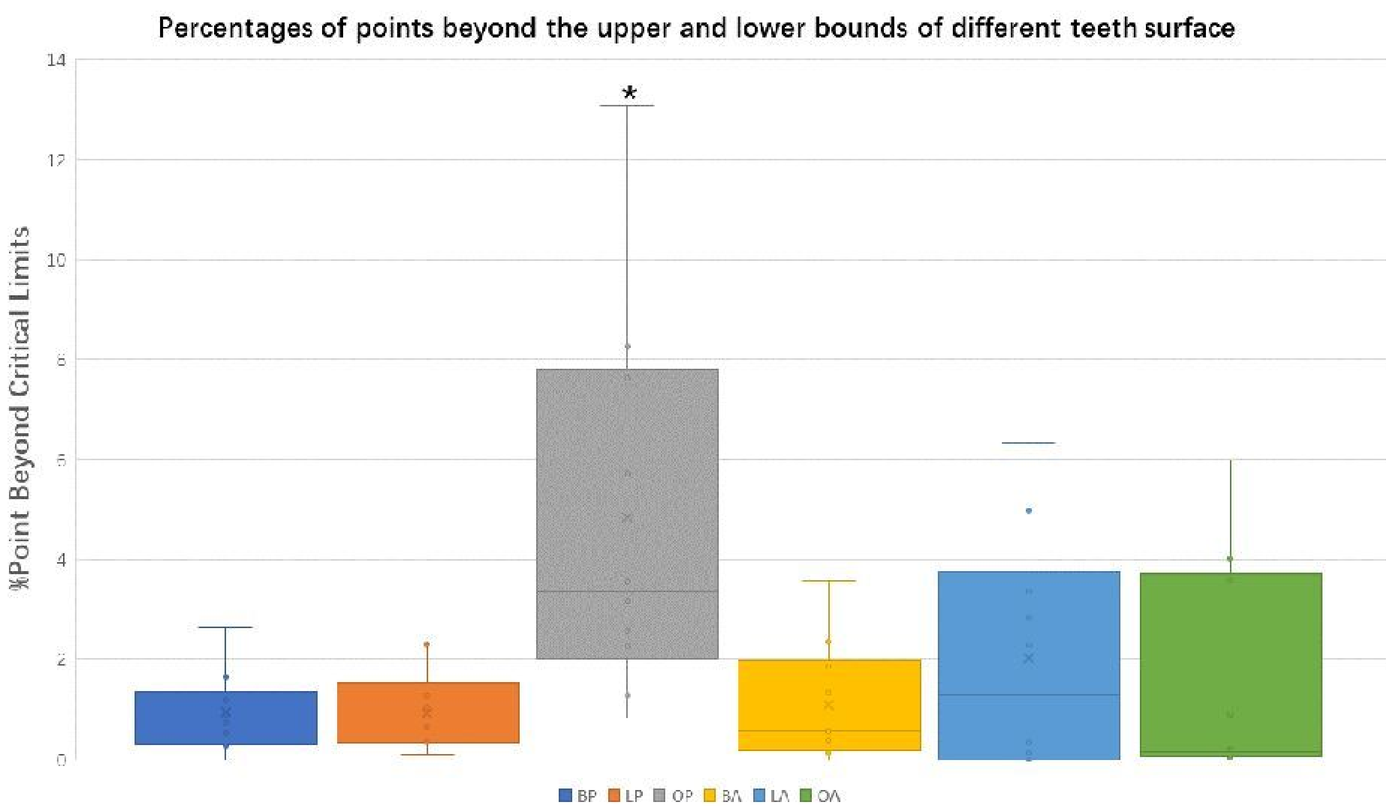
**Figure 2**

The colour map shows the differences on different tooth surfaces between the STL reference model and the STL test model. Each tooth surface was individually superimposed on the reference model. A, Buccal surfaces of posterior teeth (BP). B, Lingual surfaces of posterior teeth (LP). C, Occlusal surfaces of posterior teeth (OP). D, Buccal surfaces of anterior teeth (BA). E, Lingual surfaces of anterior teeth (LA). F, Occlusal surfaces of anterior teeth (OA). The darker the colour, the larger the variation; the lighter the colour, the smaller the variation. Red and blue showed greater deviations than yellow and green.



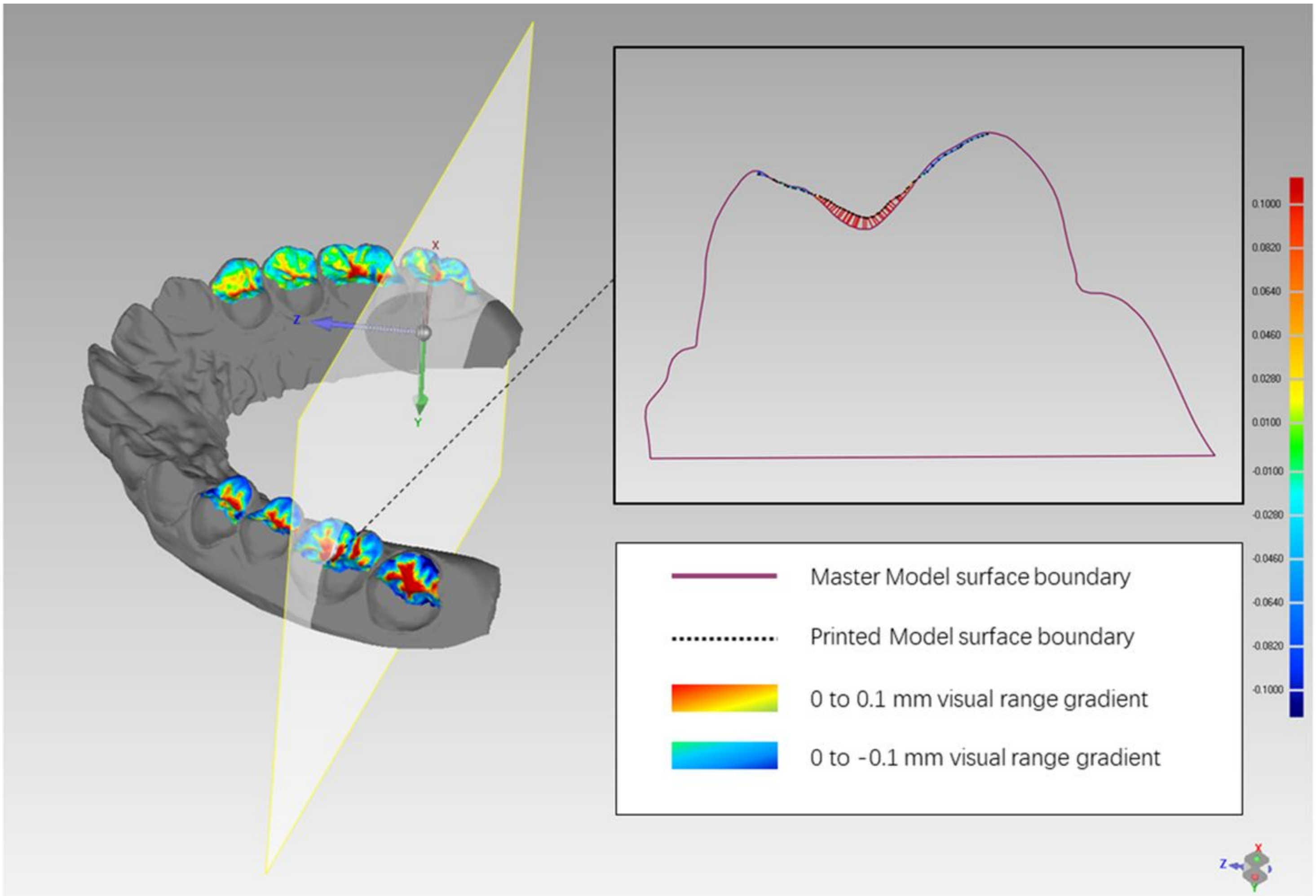

## Figure 3

Average deviations of 3D-printed dental models on different tooth surfaces. The average deviations of the occlusal surfaces of posterior teeth were significantly greater than those of other surfaces.



## Figure 4

Percentages of points beyond the upper and lower limits of different tooth surfaces. A 0.10-mm threshold parameter was set as the critical value for the analysis of deviations between the plastic model and the 3D-printed model. The occlusal surfaces of posterior teeth showed significantly higher percentages of points beyond the upper and lower limits.




## Figure 5

Cross-section of the superimposition. From a cross-section of the superimposed files, it can be clearly seen that there is an obvious difference between the surfaces of the STL reference model and the STL test model, especially in the groove region of the OP.