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Experimental Study on Dimensional Variations of 3D Printed Objects Based on Printing Orientation, with Applications in Dentistry

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Abstract

This study investigates the accuracy and precision of 3D printing technology in dental applications, focusing on the dimensional outcomes of models printed at different angles. The work involved importing a dental model into slicing software, adjusting its orientation, and creating support structures for stability. The model was then 3D printed using proper equipment and underwent post-processing steps including cleaning, washing and curing the material. Subsequently, the printed models were scanned using a specialized desktop scanner and saved for further analysis. Accuracy evaluation was conducted using dedicated software, comparing the scanned files and employing an algorithm for precise alignment. Color deviation maps were utilized to visually represent variations, aiming to assess how the positioning during printing affects the trueness and precision of 3D-printed dental models. The study's analysis of trueness and precision involved statistical tests using IBM SPSS Statistics software. The color maps generated from the 3D comparison revealed positive and negative deviations, indicated by different colors. Comparing the results, the models positioned at 0° exhibited the least dimensional deviation, while those at 90° showed the highest. In terms of precision, the models printed at 0° demonstrated the highest reproducibility, while those at 15° exhibited the lowest. In accordance with the desired level of precision, it is recommended that printed models be produced at an inclination angle of 0°.

Keywords: 3D print; Dental model; Resin; Accuracy; Trueness; Software

Introduction

3D printing was developed in 1980 by Charles Hull, who introduced the first form of this technology known as Stereolithography (SLA-Stereolithography). Continuously evolving, this technology made significant progress, leading Charles Hull to establish his own company, 3D Systems, in 1986, marking a milestone in the scientific history of three-dimensional printing. This technology, specifically stereolithography, was patented in August 1984 and approved by the United States Patent and Trademark Office (USPTO) in 1986 [1]. Since then, stereolithography technology has been continuously evolving, becoming the most well-known form of three-dimensional printing [2]. In this technology, the platform is immersed in a photosensitive resin [3]. The laser draws cross-sections of the object to form each layer. Once a resin layer is fully polymerized, the platform moves vertically by a distance equivalent to the thickness of one layer, allowing the formation of the next layer. This process is repeated hundreds to thousands of times to complete the three-dimensional object [2]. The thickness of the polymerizable layer depends on the printer model's specifications and can range from 15 µm to 150 µm. The wavelength range of the UV laser used to polymerize the photosensitive material also depends on the printer type, typically starting at 200 nm and reaching up to 500 nm [3].

Thermoplastic Extrusion Modeling (FDM- Fused Deposition Modeling) is other printing method which is based on the extrusion of a thermoplastic material, involving the passage of a plastic filament through an extruder. The filament is heated to its melting point and deposited in layers. The extruder performs horizontal movements while the platform moves vertically after each new layer is deposited [3]. The deposited layers are thermally bonded or fused using chemical agents [4].

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Digital Light Processing (DLP) is a technology invented by Larry Hornbeck of Texas Instruments in 1987 [5]. It is similar to stereolithography and is classified by ASTM (American Society for Testing and Materials) under the same category of additive manufacturing technology, based on the use of UV light for the polymerization of photosensitive resins [3]. The difference between the two technologies lies in the light source. The light source in Digital Light Processing technology is a high-definition projector that can photopolymerize the resin layer in the x-y axis simultaneously [2,6]. Digital Light Processing technique is considered faster and more efficient compared to stereolithography [6], resulting in parts with a high degree of precision and a superior surface finish [7].

Technological advancements resulting from the implementation of three-dimensional printing technology have manifested in various fields, including medicine, automotive manufacturing, mechanical engineering, and art. In terms of dental applications, rapid prototyping represents one of the most efficient tools for three-dimensional printing complex anatomical structures [8]. In dental medicine, additive manufacturing technology is utilized in prosthodontics, surgery, orthodontics, endodontics, and tissue engineering [9,10].

One of the first applications of additive manufacturing technology in dental medicine was the visualization of digital impressions to obtain printed models for diagnostic purposes or to create functional models for fixed prosthodontic restorations [3]. Printed models can replace cast models, which are more susceptible to damage under normal environmental conditions or during storage [8]. 3D printed models demonstrate a clinically acceptable level of precision [11]. A comparative analysis of cast models and digital models regarding reproducibility and accuracy, conducted by Park et al. [12] demonstrated larger yet acceptable dimensional changes in digital models. Dental restorations utilizing crowns or bridges are among the most common clinical procedures in dental prosthodontics. Comparative studies evaluating various parameters of restorations obtained through milling and additive manufacturing techniques have shown better results in terms of marginal adaptation compared to conventional restoration techniques. Additionally, 3D-printed crowns have demonstrated superior internal and occlusal adaptation [13]. Different materials with varying mechanical properties are used in the additive manufacturing of dental crowns, including ceramic materials such as aluminum oxide, zirconium-based ceramics and three-dimensional printed resins [13,14]. Wang et al. [15] demonstrated the accuracy of printing zirconium-based ceramic crowns. The extensive use of digital technology in dental prosthodontics can primarily be attributed to its application in obtaining partial or complete dentures. The first step in the workflow is obtaining the prosthetic field impression. This can be achieved through direct intraoral scanning or indirect scanning of impressions made with alginate or gypsum models. Although intraoral scanning offers multiple benefits, there are several disadvantages that limit its application in the fabrication of partial or complete dentures. These include difficulties in obtaining precise scanning due to the presence of saliva or blood in the oral cavity, as well as challenges in capturing the static and dynamic morphology of soft oral tissues [3,13]. Another limitation in obtaining dentures through 3D printing technology is the lack of a try-in phase to evaluate the prosthesis before its finalization. However, there are several options to overcome this limitation, such as producing low-cost printed models or adopting a virtual approach that combines facial scanning and intraoral scanning, followed by necessary adjustments [13]. In a clinical report conducted by Takeda et al. [16] 3D-printed removable prostheses were obtained using the replication technique, which utilizes existing prostheses as a foundation. The successful 3D printing of complete dentures has been demonstrated. These dentures were printed using photosensitive methacrylic resin (Dentca, USA). The two components of the denture, the base and artificial teeth, were printed separately and then bonded using adhesive systems for photosensitive resins [17]. For obtaining dental restorations supported by implants, it is necessary to determine the exact relationships between the implant and the prosthetic components. Recording these relationships can be achieved through impression taking using individual trays. Conventional individual trays have the disadvantage of uncontrolled space for the impression material and the amount of acrylic material required for their fabrication, as well as the inability to preview the implant. The impression technique can be improved by using a 3D-printed individual tray, which, through assisted software design, allows for the reduction of limitations associated with conventionally fabricated individual trays [18].

In dental medicine, splints are used to alleviate symptoms of temporomandibular disorders or to protect teeth from excessive occlusal forces. With the introduction of CAD/CAM technology in dental medicine, the fabrication of occlusal splints can be approached digitally by acquiring imaging data using intraoral or extraoral scanners, based on which the splint can be designed and subsequently 3D printed [19]. A specific advantage of 3D printing compared to milling is the lower cost of stereolithography technology [20].

In surgery, 3D printing can be categorized into four areas: Printing models, printing surgical guides, printing surgical splints, and printing implants [13]. Initially, 3D printing technology was limited to obtaining study models. These models have proven their efficiency in surgical techniques, offering better preoperative documentation in terms of patient anatomy. 3D printed models are used as surgical guides for simulating various procedures such as bone augmentation and implant placement [21]. The use of 3D printed models helps optimize surgical time, reduce the risk of intraoperative complications, and minimize potential errors [22]. Ideal surgical placement of implants should be guided by the design and position of the final prosthetic component.

In endodontics, 3D-printed models can be used as educational tools or for simulating and evaluating the management of therapeutic procedures. Depending on the printing technology, 3D models can be obtained in different colors, textures, transparencies, and with various mechanical characteristics to aid in the differentiation of different types of tissues, facilitating the understanding of dental morphology, root canal anatomy, and the simulation of access cavity preparation and mechanical root canal treatment. 3D-printed inkjet models infiltrated with epoxy resin, with a texture similar to bone, are used for simulating osteotomies [23]. The ability to reproduce the external morphology of the teeth and internal morphology of root canals makes 3D-printed models highly valuable in determining the working length of the root canal [24]. 3D-printed endodontic guides are based on principles similar to those used in dental implant surgery guides. Endodontic guides can be used to overcome difficulties encountered when locating root canals in cases of obliterated canals. The utility of guides has been demonstrated by accurately determining the osteotomy site and the apical resection level in challenging situations related to anatomical proximity, position of adjacent teeth, and dental apex orientation [23]. To obtain endodontic guides, CBCT

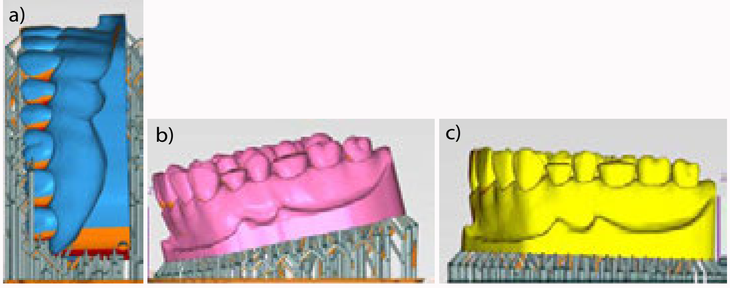

Figure 1: Model's orientation at: (a) 90° degrees; (b) 15° degrees; (c) 0° degrees.

imaging, intraoral scanning, and planning software are used [23]. Additively manufactured endodontic guides, which collect imaging data from cone beam Computed Tomography (CBCT), facilitate coordination of access cavity, coronal morphology, and root canal orifices. The treatment procedure is optimized in terms of preserving dental structures, providing predictable access, even in cases of severe developmental anomalies or calcified canals [25].

3D-printed models in orthodontics are used for diagnosis and treatment planning, demonstrating reproducibility and accuracy depending on the printing technology used. The accuracy of 3D-printed models has been demonstrated with DLP technology, while FDM technology has shown geometric imprecision [13]. Detailed records of dental arches are processed using software, which enables virtual simulation of orthodontic treatment. Subsequently, individualized dental appliances, aligners, brackets, and Archwires can be fabricated [13]. Aligners provide an esthetic option for orthodontic alignment treatment. 3D printing of aligners offers a time-efficient method for their design and final evaluation, overcoming the inaccuracies associated with conventional aligner fabrication through impression taking and thermoforming processes [8]. The viability of 3D-printed ceramic brackets has been demonstrated, meeting the requirements of the treatment plan and optimizing both aesthetic and mechanical aspects [13].

Given the necessity for precision in dental three-dimensional printing, the existing literature contains information highlighting the impact of printing methodologies on model accuracy. Consequently, a thesis has been posited, pro-posing an evident variance between the accuracy of the printed dental models and the spatial alignment of the model.

Materials and Methods

In order to conduct the experimental study, a 3D image of a dental didactic model (FrasacoGmbH, Germany) was used. The 3D file (.stl) was imported into the slicing software Phrozen 3D Slice Software (Phrozen, Taiwan). Before the slicing and exporting the project in (.ctb) format (Autocad Color-based Plot Style File), the model was positioned on the printer platform at 0°, 15°, and 90° degrees (Figure 1).

The support structures were automatically generated by the slicing software, and additional support structures were manually added in the high-risk areas of the model based on its orientation on the platform. The positioning of the support structures took into consideration the integrity of the clinically usable surfaces of the model, specifically the prosthetic area. The model was printed five times for each printing position using Phrozen Aqua 4K Resin Grey liquid resin material (Phrozen Technology, Hsinchu, Taiwan), which is recommended for dental practice due to its low contraction index. The 3D printer used was Phrozen Sonic Mini 4K (Phrozen Technology, Hsinchu, Taiwan), which is based on DLP printing technology with a printing resolution of 50 μm. The models were distributed on the printer platform considering the maximum printing volume of the printer: 135 mm × 75 mm × 130 mm. After completing the printing process and removing the support structures, each model was post-processed by washing and removing residues in two successive baths of Isopropyl Alcohol (IPA), with duration of 3 min for each washing step. The second washing step was performed using the "Wash" mode of the Anycubic Washing & Curing Machine (ANYCUBIC 3D Printing, Shenzhen, China) according to the manufacturer's instructions (Figure 2).

Figure 2: Anycubic washing & curing machine.

Figure 3: Scanning the 3D printed model.

The subsequent step after residue removal through washing is

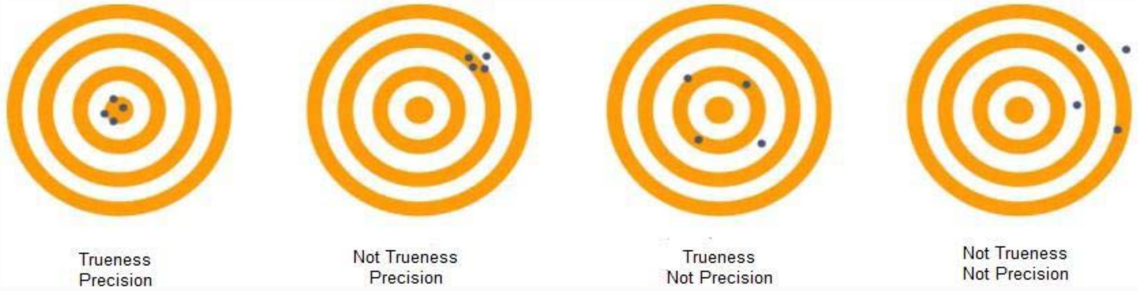

Figure 4: Schematic representation of trueness and precision.

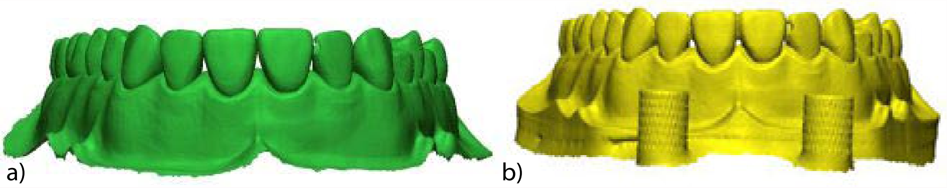

Figure 5: (a) segmented reference model; (b) scanned test model.

drying, followed by polymerization. The final step was carried out using the "Cure" mode of the Anycubic Washing & Curing Machine (ANYCUBIC 3D Printing, Shenzhen, China) for duration of 30 min. To obtain three-dimensional images of the models, a desktop scanner with a resolution of 0.01 mm, Thunk3D DT 300 (Thunk3D Inc., Beijing, China), specifically designed for dental applications, was used (Figure 3). The scanned models were then exported in (.stl) format and imported into the metrology software.

According to the International Organization for Standardization ISO 5725 [26], accuracy is defined in terms of trueness and precision [27]. Trueness refers to the minimum distance between the measured test object and the reference object, while precision refers to the reproducibility of the measured values through repeated measurements [28] (Figure 4).

Another ISO standard that is a relevant reference in the field of additive manufacturing is ISO/ASTM 52900, which provides a comprehensive classification of this technology into seven distinct process categories: Binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat polymerization (Figure 1). These categories encompass various methods used in additive manufacturing, each with its unique characteristics and applications. Among the most widely utilized technologies in this domain are Fused Deposition Modeling (FDM), Laminated Object Manufacturing (LOM), Stereolithography (SLA), Selective Laser Melting (SLM), and Selective Laser Sintering (SLS) [29].

For the analysis of trueness, each (.stl) scan file was indexed with the reference (.stl) file, while for the analysis of precision, each (.stl) scan file was indexed with each scan of the model in the same orientation category. For this purpose, Geomagic Control X software (3D Systems, Rock Hill, South Carolina, USA) was used. Geomagic Control X is software for inspection and quality control of three-dimensional objects, which allows processing of 3D scan data for measurement, comparison, and communication of results. The software utilizes the Iterative Closest Point (ICP) algorithm; one of the most commonly used algorithms for 3D file registration. The algorithm finds correspondences between two-point cloud areas, determining the minimum distance between them, and then compares the values from the test file with those from the reference model [30] (Figure 5).

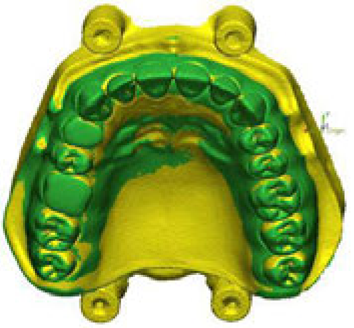

Figure 6: Best fit alignment.

The workflow protocol involves importing the scanned files in Stereolithography (.stl) format, with the first file being the reference data [31]. The initial processing of the reference file involves removing excess components to obtain minimal information requiring further processing, as the removed parts are no longer involved in the subsequent alignment. Prior to proceeding with the alignment step, the software has a re-segmentation function (Resegmenting Tool), which allows manual selection and division of parts of the model that present additional interest for comparison with the test model [27]. Using the Initial Alignment and Best Fit Alignment functions (Figure 6), the models are indexed with a standard software precision, and subsequently benefit from a superior final alignment compared to the initial alignment [32,33].

The software's 3D comparison function allows modifying the analysis limits and generating a color map, which can be used to analyze deviations from the reference model. Green color indicates adequate alignment or minimal deviations, dark blue areas indicate deviations below the reference model, and dark red areas indicate positive deviations [30,34]. To obtain the color maps, the limits of ± 300 μm were used. Areas that exhibited deviations beyond the

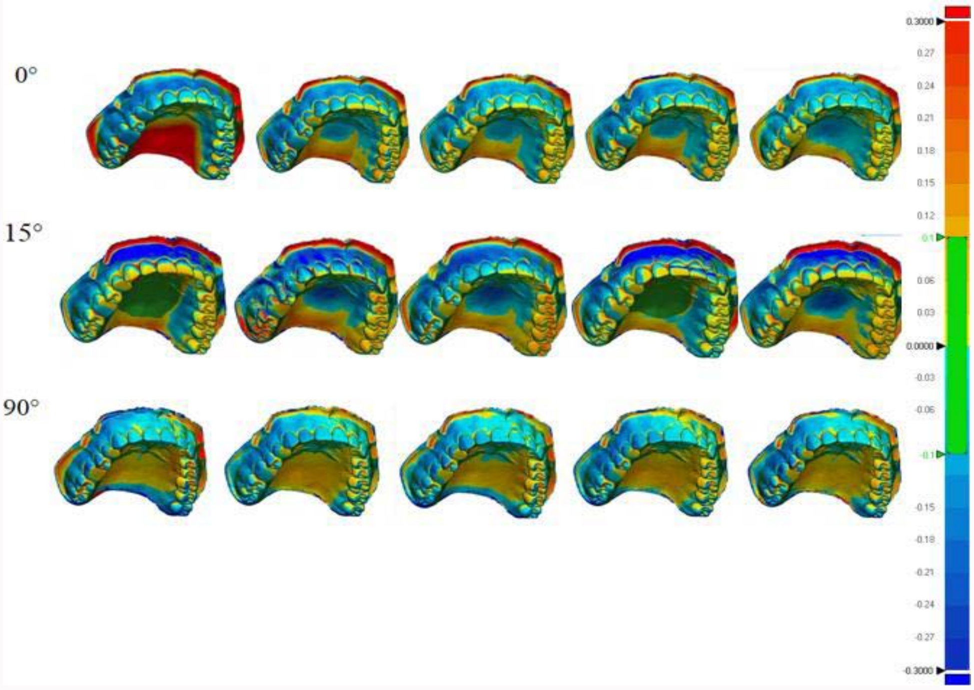

Figure 7: Three-dimensional analysis of models for accuracy.

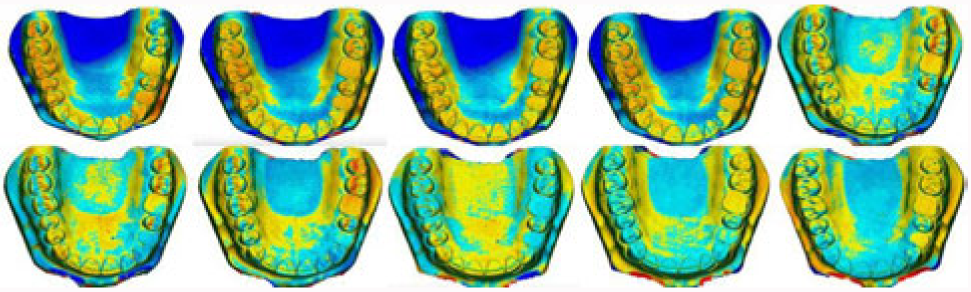

Figure 8: Three-dimensional analysis of models for precision at 0° position.

selected limits were colored accordingly, with dark red and dark blue, while areas between the limits generated variable colors between the two limits.

Results

The data regarding trueness and precision were presented in tables and tested for normality using the Shapiro-Wilk test in IBM SPSS Statistics software. The color map obtained from the 3D comparison for trueness and precision showed positive deviations represented by colors ranging from yellow to red, as well as negative deviations represented by colors ranging from cyan blue to dark blue (Figures 7-10) (Tables 1-6).

Regarding trueness, comparing the results based on the minimum and maximum values, the minimum deviation values from the reference model were obtained by models positioned at 0°, followed by those positioned at 15°, while the maximum dimensional deviation values from the reference model were obtained by models positioned at 90°.

Concerning precision, analyzing the minimum and maximum values, the models printed at a 0° angle exhibited the highest dimensional reproducibility, followed by those printed at a 90° angle. The lowest data reproducibility was obtained by models printed at a 15° angle.

Discussion

The results obtained provide evidence confirming the thesis, revealing minimal deviations in the printed models oriented at 0° compared to those at 15° and 90°. As a consequence, the study supports the validity of the thesis based on the observed accuracy analysis of the printed models. One key principle in the orientation of models on the printing platform is that angling them differently from 0° reduces the surface area of each layer, consequently decreasing the contact between the platform and the resin tank. This results in less force being exerted on the model during the layer-building process as the printer platform lifts [35]. The observed higher deviations in models oriented at 15° could be attributed to the manufacturing process. Multiple models (two or five) were placed on the platform, increasing the contact area with the resin tank and leading to larger printed layers per exposure. Support structures were initially auto-generated at 80% density and manually added in high-risk areas. Generating support structures is easier for models with flat surfaces compared to texture ones [36]. The comparative analysis using metrology software involved individual indexing of the test models

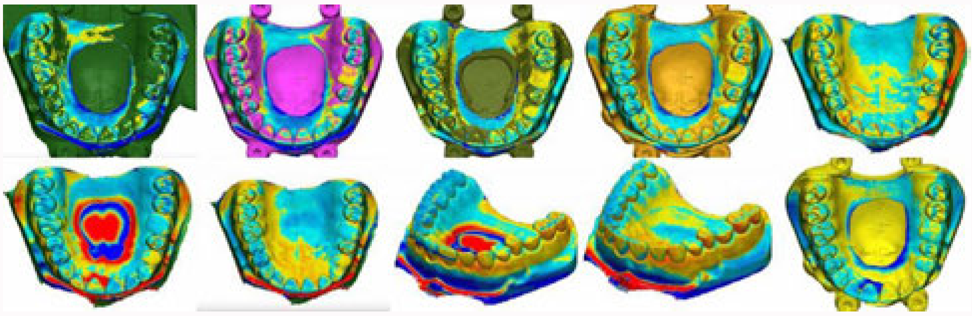

Figure 9: Three-dimensional analysis of models for precision at 15° position.

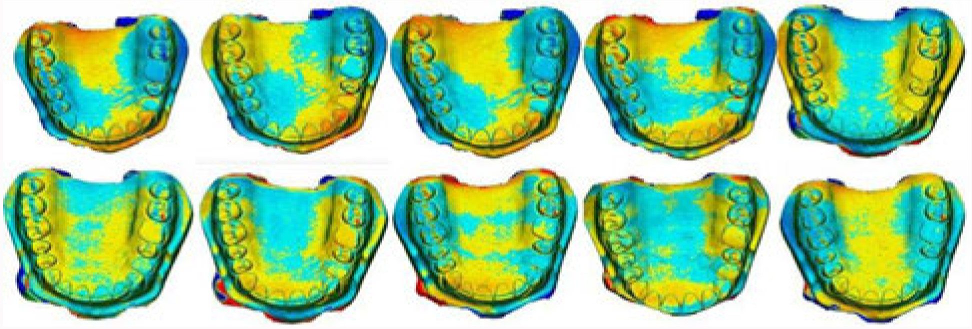

Figure 10: Three-dimensional analysis of models for precision at 90° position.

Table 1: Accuracy analysis values for 0° position, in millimeters.

Name	Min	Max	Avg	Root Mean Square	Standard deviation
1	-3.91	3.9102	-0.0444	0.8328	0.8316
2	-3.4056	3.4049	-0.0838	0.5818	0.5757
3	-3.0956	3.0953	-0.0688	0.4723	0.4673
4	-3.1471	3.1467	-0.0798	0.4779	0.4712
5	-3.4445	3.4441	-0.0643	0.5946	0.5946

Table 2: Accuracy analysis values for 15° position, in millimeters.

Name	Min	Max	Avg	Root Mean Square	Standard deviation
1	-3.9484	3.9479	-0.1495	0.8179	0.8042
2	-3.8327	3.8311	-0.1085	0.7626	0.7548
3	-3.3538	3.3539	-0.0993	0.5659	0.5571
4	-3.7139	3.7136	-0.158	0.7026	0.6846
5	-3.6501	3.65	-0.0862	0.7024	0.6971

Table 3: Accuracy analysis values for 90° position, in millimeters.

Name	Min	Max	Avg	RMS	Standard deviation
1	-4.2906	4.2899	-0.2158	0.9823	0.9583
2	-3.7173	3.7166	-0.1669	0.7081	0.6881
3	-3.4618	3.4611	-0.1217	0.5987	0.5862
4	-3.6061	3.6054	-0.1622	0.6727	0.6528
5	-3.7285	3.7276	-0.1439	0.7216	0.7071

Table 4: Values of precision analysis for 0° position, in millimeters.

Name	Min	Max	Avg	Root Mean Square	Standard deviation
1	-3.1419	3.1415	-0.0731	0.4659	0.4601
2	-3.0766	3.0753	-0.0701	0.4686	0.4634
3	-3.14	3.1398	-0.0797	0.4801	0.4734
4	-3.2896	3.2891	-0.0609	0.535	0.5315
5	-2.9041	2.9043	0.0172	0.3536	0.3532
6	-2.9881	2.9878	-0.0031	0.3714	0.3714
7	-3.0633	3.063	0.0223	0.4033	0.4027
8	-2.8349	2.8359	-0.0194	0.3384	0.3379
9	-2.9065	2.9068	-0.0152	0.3691	0.3691
10	-2.8966	2.8955	-0.0067	0.3632	0.3631

Table 5: Values of precision analysis for 15° position, in millimeters.

Name	Min	Max	Avg	Root Mean Square	Standard deviation
1	-4.137	4.1367	-0.147	0.8614	0.8487
2	-3.8771	3.8764	-0.1319	0.7336	0.7216
3	-4.0359	4.0359	-0.0859	0.8059	0.8013
4	-3.9272	3.9271	-0.0582	0.77	0.7678
5	-3.2769	3.2767	0.0241	0.4493	0.4486
6	-3.4863	3.4864	-0.0016	0.5355	0.5355
7	-3.5362	3.5361	0.0665	0.5638	0.5599
8	-2.9952	2.9951	-0.0246	0.3976	0.3968
9	-2.9755	2.9759	0.0161	0.4118	0.4115
10	-3.9046	3.9046	-0.0465	0.7784	0.777

to the reference model. However, the precision analysis did not utilize a pre-set option to index all models; instead, the indexing was done manually in pairs after manual segmentation of each model. Unfortunately, there was no standardized data reference considered for these processes.

The conclusion of this study aligns with other research papers that emphasize the significant influence of the presence or absence of a cross-arch plate and differences in the internal structure on the characteristics of 3D printed models produced using the DLP method.

Table 6: Values of precision analysis for 90° position, in millimeters.

Name	Min	Max	Avg	Root Mean Square	Standard deviation
1	-3.1628	3.1627	-0.0418	0.4655	0.4637
2	-3.0866	3.0863	-0.0438	0.4051	0.4027
3	-3.03	3.0301	-0.0541	0.4116	0.4081
4	-3.2039	3.2029	-0.0486	0.494	0.4916
5	-3.1032	3.1031	-0.0332	0.4185	0.4172
6	-3.0624	3.0621	-0.032	0.4064	0.4051
7	-3.1226	3.1229	-0.0148	0.4481	0.4479
8	-3.0798	3.0796	-0.0481	0.4157	0.4129
9	-3.1795	3.1782	-0.0391	0.478	0.4764
10	-2.955	2.9546	-0.0291	0.4004	0.3993

Group P, which featured a cross-arch support plate, exhibited superior stability compared to Group U, where deviations were observed in model contraction on both lingual sides in the posterior region [37].

Other study compared different 3D printer technologies for printing resin models chairside and demonstrated that these printers can produce accurate results within 30 microns in each XYZ dimension, making them suitable for clinical practice with overall errors within clinically acceptable levels of under 100 microns [38].

Morón-Conejo et al. [39] compared the accuracy, trueness, and precision of five different 3D printers used for full-arch models of patients, including both industrial and dental desktop printers. The results revealed statistically significant differences, with Multijet printing technology used in industrial 3D printers demonstrating better results compared to DLP and SLA technologies used in dental desktop printers. Standardizing the 3D printing protocol and parameters, material usage, postprocessing, and assessment time is crucial for accurate performance comparisons in the field of dental 3D printing.

Conclusion

Based on the limitations of this study, the following conclusions can be made: Firstly, the results indicate that printing models in the 0° position achieves superior levels of accuracy in comparison to models printed at both 15° and 90° angles. This suggests that the 0° position offers the optimal orientation for achieving precise dimensional outcomes.

Furthermore, the findings reveal that models printed in the 0° position demonstrate the highest degree of dimensional reproducibility. Successively, models printed at 90° exhibit a slightly lower level of reproducibility, followed by those printed at 15°.

These conclusions highlight the significance of print positioning in achieving accurate and reproducible 3D models. Further investigations are necessary to better understand the factors contributing to these differences and to refine the printing process, particularly in the context of its application in dental prosthetics.

References

1. Bandyopadhyay A, Bose S. Additive manufacturing. CRC press; 2019.
2. Zhang ZC, Li PL, Chu FT, Shen G. Influence of the three-dimensional printing technique and printing layer thickness on model accuracy. J Orofac Orthop. 2019;80(4):194-204.
3. Revilla-León M, Özcan M. Additive manufacturing technologies used for processing polymers: Current status and potential application in prosthetic dentistry. J Prosthodont. 2019;28(2):146-58.
4. Revilla-León M, Meyer MJ, Zandinejad A, Özcan M. Additive manufacturing technologies for processing zirconia in dental applications. Int J Comput Dent. 2020;23(1):27-37.
5. Jockusch J, Özcan M. Additive manufacturing of dental polymers: An overview on processes, materials and applications. Dent Mater J. 2020;39(3):345-54.
6. Sherman SL, Kadioglu O, Currier GF, Kierl JP, Li J. Accuracy of digital light processing printing of 3-dimensional dental models. Am J Orthod Dentofacial Orthop. 2020;157(3):422-8.
7. Alharbi N, Wismeijer D, Osman RB. Additive manufacturing techniques in prosthodontics: Where do we currently stand? A critical review. Int J Prosthodont. 2017;30(5):474-84.
8. Jindal P, Juneja M, Siena FL, Bajaj D, Breedon P. Mechanical and geometric properties of thermoformed and 3D printed clear dental aligners. Am J Orthod Dentofacial Orthop. 2019;156(5):694-701.
9. Bhargav A, Sanjairaj V, Rosa V, Feng LW, Yh JF. Applications of additive manufacturing in dentistry: A review. J Biomed Mater Res B Appl Biomater. 2018;106(5):2058-64.
10. Bukhari S, Goodacre BJ, AlHelal A, Kattadiyil MT, Richardson PM. Three-dimensional printing in contemporary fixed prosthodontics: A technique article. J Prosthet Dent. 2018;119(4):530-4.
11. Rungrojwittayakul O, Kan JY, Shiozaki K, Swamidass RS, Goodacre BJ, Goodacre CJ, et al. Accuracy of 3D printed models created by two technologies of printers with different designs of model base. J Prosthodont. 2020;29(2):124-8.
12. Park ME, Shin SY. Three-dimensional comparative study on the accuracy and reproducibility of dental casts fabricated by 3D printers. J Prosthet Dent. 2018;119(5):861.e1-7.
13. Pillai S, Upadhyay A, Khayambashi P, Farooq I, Sabri H, Tarar M, et al. Dental 3D-printing: Transferring art from the laboratories to the clinics. Polymers (Basel). 2021;13(1):157.
14. Raszewski Z, Chojnacka K, Mikulewicz M. Effects of surface preparation methods on the color stability of 3D-printed dental restorations. J Funct Biomater. 2023;14(5):257.
15. Wang W, Yu H, Liu Y, Jiang X, Gao B. Trueness analysis of zirconia crowns fabricated with 3-dimensional printing. J Prosthet Dent. 2019;121(2):285-91.
16. Takeda Y, Lau J, Nouh H, Hirayama H. A 3D printing replication technique for fabricating digital dentures. J Prosthet Dent. 2020;124(3):251-6.
17. Jurado CA, Tsujimoto A, Alhotan A, Villalobos-Tinoco J, AlShabib A. Digitally fabricated immediate complete dentures: Case reports of milled and printed dentures. Int J Prosthodont. 2020;33(2):232-41.
18. Kim JE, Kwon DH, Kim JH, Shim JS. A digital implant custom tray fabrication method using the design process for simulating the position of the impression copings and 3D printing technology. J Prosthet Dent. 2019;121(4):566-70.
19. Marcel R, Reinhard H, Andreas K. Andreas, accuracy of CAD/CAM-fabricated bite splints: Milling *vs.* 3D printing. Clin Oral Investig. 2020;24(12):4607-15.
20. Waldecker M, Leckel M, Rammelsberg P, Bömicke W. Fully digital fabrication of an occlusal device using an intraoral scanner and 3D printing: A dental technique. J Prosthet Dent. 2019;121(4):576-80.
21. Prasad TS, Sujatha G, Muruganandhan J, Patil S, Raj AT. Three-dimensional printing in reconstructive oral and maxillofacial surgery. J Contemp Dent Pract. 2018;19(1):1-2.
22. Somji SH, Valladares A, Kim SH, Yu YCP, Froum SJ. The use of 3D models

to improve sinus augmentation outcomes - A case report. Singapore Dent J. 2017;38:63-70.

23. Shah P, Chong BS. 3D imaging, 3D printing and 3D virtual planning in endodontics. Clin Oral Investig. 2018;22(2):641-54.
24. Liang X, Liao W, Cai H, Jiang S, Chen S. 3D-printed artificial teeth: Accuracy and application in root canal therapy. J Biomed Nanotechnol. 2018;14(8):1477-85.
25. Oberoi G, Agis H. 3D printing in endodontics, in guided endodontics. Kinariwala N, Samaranayake L, Editors. Springer International Publishing: Cham. 2021. p. 85-111.
26. Standardization, I.O.f. Accuracy (trueness and precision) of measurement methods and results.
27. Dutton E, Ludlow M, Mennito A, Kelly A, Evans Z, Culp A, et al. The effect different substrates have on the trueness and precision of eight different intraoral scanners. J Esthet Restor Dent. 2020;32(2):204-18.
28. Gurpinar B, Tak O. Effect of pulp chamber depth on the accuracy of Endocrown scans made with different intraoral scanners versus an industrial scanner: An *in vitro* study. J Prosthet Dent. 2022;127(3):430-7.
29. Pérez M, Carou D, Rubio EM, Teti R. Current advances in additive manufacturing. 2020;88:439-44.
30. Latham J, Ludlow M, Mennito A, Kelly A, Evans Z, Renne W. Effect of scan pattern on complete-arch scans with 4 digital scanners. J Prosthet Dent. 2020;123(1):85-95.
31. Chiu A, Chen YW, Hayashi J, Sadr A. Accuracy of CAD/CAM digital impressions with different intraoral scanner parameters. Sensors (Basel). 2020;20(4):1157.
32. Rotar RN, Jivanescu A, Ille C, Podariu AC, Jumanca DE, Matichescu AM, et al. Trueness and precision of two intraoral scanners: A comparative *in vitro* study. Scanning. 2019;2019:1289570.
33. Mădălina-Georgiana D. Studiu experimental privind variatiile dimensionale ale obiectelor printate 3D in functie de pozitia de printare cu aplicatie in protetica dentara. 2021.
34. Zarone F, Ruggiero G, Mauro MID, Spagnuolo G, Ferrari M, Sorrentino R. Accuracy of three impression materials on the totally edentulous maxilla: *In vitro/in silico* comparative analysis. Materials (Basel). 2020;13(3):515.
35. Formlabs. Model orientation best practices for SLA printing.
36. Alharbi N, Osman RB, Wismeijer D. Factors influencing the dimensional accuracy of 3D-printed full-coverage dental restorations using stereolithography technology. Int J Prosthodont. 2016;29(5):503-10.
37. Shin SH, Lim JH, Kang YJ, Kim JH, Shim JS, Kim JE. Evaluation of the 3D printing accuracy of a dental model according to its internal structure and cross-arch plate design: An *in vitro* study. Materials (Basel). 2020;13(23):5433.
38. Nulty A. A comparison of trueness and precision of 12 3D printers used in dentistry. BDJ Open. 2022;8(1):14.
39. Morón-Conejo B, López-Vilagran J, Cáceres D, Berrendero S, Pradíes G. Accuracy of five different 3D printing workflows for dental models comparing industrial and dental desktop printers. Clin Oral Investig. 2023;27(6):2521-32.