Original Article

Accuracy of three-dimensional dental resin models created by fused deposition modeling, stereolithography, and Polyjet prototype technologies: *A comparative study*

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ABSTRACT

Objectives: The aim of this study was to assess the dimensional accuracy of fused deposition modeling (FDM)–, Polyjet-, and stereolithography (SLA)–produced models by comparing them to traditional plaster casts.

Materials and Methods: A total of 12 maxillary and mandibular posttreatment orthodontic plaster casts were selected from the archives of the Orthodontic Department at the Indiana University School of Dentistry. Plaster models were scanned, saved as stereolithography files, and printed as physical models using three different three-dimensional (3D) printers: Makerbot Replicator (FDM), 3D Systems SLA 6000 (SLA), and Objet Eden500V (Polyjet). A digital caliper was used to obtain measurements on the original plaster models as well as on the printed resin models.

Results: Comparison between the 3D printed models and the plaster casts showed no statistically significant differences in most of the parameters. However, FDM was significantly higher on average than were plaster casts in maxillary left mixed plane (MxL-MP) and mandibular intermolar width (Md-IMW). Polyjet was significantly higher on average than were plaster casts in maxillary intercanine width (Mx-ICW), mandibular intercanine width (Md-ICW), and mandibular left mixed plane (MdL-MP). Polyjet was significantly lower on average than were plaster casts in maxillary right vertical plane (MxR-vertical), maxillary left vertical plane (MxL-vertical), mandibular right anteroposterior plane (MdR-AP), mandibular right vertical plane (MdR-vertical), and mandibular left vertical plane (MdL-vertical). SLA was significantly higher on average than were plaster casts in MxL-MP, Md-ICW, and overbite. SLA was significantly lower on average than were plaster casts in MdR-vertical and MdL-vertical.

Conclusions: Dental models reconstructed by FDM technology had the fewest dimensional measurement differences compared to plaster models. (*Angle Orthod.* 2018;88:363–369.)

KEY WORDS: Orthodontic models, 3D printing, Prototyping technology

INTRODUCTION

Integration of digital technologies in orthodontic practices has led to a logical transition from a two-dimensional to a three-dimensional (3D) practice approach. Offices are increasing the utilization of digital scanners, cone beam computed tomography, and 3D printers because of the numerous advantages they offer. Digital technology saves patients from unpleasant alginate impressions while also providing

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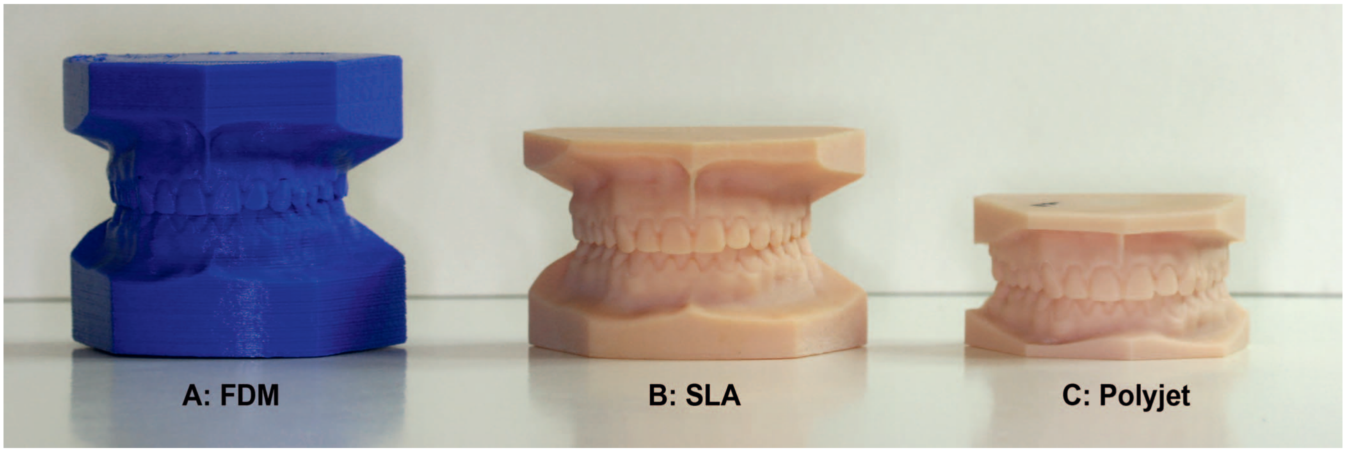

Figure 1. The 3D models printed by (A) FDM, (B) SLA, and (C) Polyjet technology.

the orthodontist with an efficient and convenient way to store patient data. Unlike traditional plaster casts, which have been considered the most commonly used orthodontic records for decades, digital models are not fragile and prone to degradation and can be easily retrieved and shared.[1–3]

Currently, there are a large selection of 3D printers available that utilize many different printing technologies. From these available printers, digital files can be printed using ceramic, metal, wax, and resin materials utilizing highly unique processes depending on which technology is utilized. The most commonly used printing technology in orthodontics is fused deposition modeling (FDM), whereby liquid resin is built up as a solid object. Stereolithography apparatus (SLA) is a rapid prototyping process that utilizes an ultraviolet (UV) laser to cure a liquid polymer into a solid resin. Polyjet modeling uses an array of ink-jet print heads to deposit liquid photopolymers onto a platform. The material is immediately cured by UV lamp and is subsequently built up in layers.[1,4–6]

The application of 3D printing in orthodontics is rapidly increasing, but the differences between the additive processes used for the printing need to be further explored. The purpose of this study was to compare the dimensional accuracy of FDM, Polyjet, and SLA printing technologies with that of orthodontic plaster models to elucidate which printing technology is most capable of replicating plaster models.

MATERIALS AND METHODS

This study was reviewed by the Indiana University Institutional Review Board (IRB) and was deemed exempt under IRB protocol 1702324542. A total of 12 maxillary and mandibular posttreatment plaster models were selected from the archives of the Orthodontic Department at Indiana University School of Dentistry. These models were selected based on the following inclusion criteria:

1) Casts must have been taken for final or 2-year posttreatment records and have matching maxillary and mandibular models;
2) A complete permanent dentition erupted from first molar to first molar, without any extractions; and
3) High-quality dental casts (meaning that the casts [a] had no broken teeth, air bubbles, or voids and [b] were trimmed and polished to the American Board of Orthodontics [ABO] standards).

Selected plaster models were scanned according to the manufacturers' directions with the Ortho Insight 3D Desktop Scanner (Motionview, Chattanooga, Tenn). Digital files generated by the desktop scanner were saved in stereolithography (STL) format, coded to remove any identifying information, and stored to an encrypted drive. STL files were converted into physical models using three rapid prototyping techniques: FDM (Makerbot Industries, Brooklyn, NY), SLA (3D Systems, Rock Hill, SC), and Polyjet printing (Stratasys, Eden Prairie, Minn). FDM models were printed at the Indiana University Library 3D Printing Studio on a Makerbot Replicator printer at a layer thickness of 100 μm. SLA models were fabricated by the Allesee Orthodontic Appliances Laboratory, which used the 3D Systems SLA 6000 printer and printed models at 50-μm layer thickness. Finally, Dynaflex Laboratory created the Polyjet models with a 16-μm layer thickness using the Stratysys Objet Eden500V printer. All models were printed on their base and contained a solid core (Figure 1). Measurements began 1 week after all models were printed.

Interrater reliability was assessed by comparing measurements performed by two investigators on five randomly selected plaster casts and their corresponding SLA resin models. All measurements (Table 1;

Table 1. Transverse, Anteroposterior, Vertical, Mixed Plane, and Articulated Model Measurements

Measurement	Definition
Transverse plane—intercanine width	Distance between the cusp tips of canines
Transverse plane—intermolar width	Distance between the mesiolingual cusp tips of the first molars
Anteroposterior plane	Distance from the canine tip to the buccal cusp tip of the first premolar on the ipsilateral side
Vertical plane	Distance from most apical concavity of the gingival margin to the cusp tip of the canine
Mixed plane	Distance between distoincisal edge of the central incisor to the cusp tip of the ipsilateral canine
Overjet	Distance of a perpendicular line from the center of the upper right central incisor incisal edge to the facial surface of the opposing lower central incisor in anteroposterior plane
Overbite	Distance of a straight line perpendicular from the center of the upper right central incisor incisal edge to the incisal edge of the opposing central incisor in the vertical plane

Figure 2) were obtained using a hand-held digital caliper (O4OO-EEP, Orthopli, Philadelphia, Pa). The co-investigator then repeated the same set of measurements. Measurements showing differences equal to or larger than 0.5 mm were repeated until differences of less than 0.5 mm were obtained.

Intrarater reliability testing was conducted to ensure that the measurements could be accurately replicated. Five plaster casts with their corresponding FDM, SLA, and Polyjet models were randomly selected for the reliability study. All measurements were recorded by the same investigator on two separate occasions 1 week apart. Any differences between the two sets of measurements greater than or equal to 0.5 mm were identified and repeated until acceptable reliability was achieved.

The 12 maxillary and 12 mandibular dental models were analyzed separately for transverse, anteroposterior, vertical, and mixed-plane measurements (Table 1; Figure 2). To address possible asymmetric distortions, both the right and left quadrants were measured. Using the method described by the ABO,[7] the 12 paired dental models were articulated to measure overjet and overbite.

No identifiable personal health information was recorded from the electronic medical records of the 12 models chosen. Any identification codes on the model were removed or covered, and a study identification code was given to the models. Measurements for the original model and the three subsequent printed models were recorded as 1A for the original model and as 1B, 1C, and 1D, respectively, for the subsequent models. Investigator blinding was not possible during the study, as the resin-printed models produced by each of the tested printers had unique colors and appearances. To combat any bias during measurement, the co-investigator measured all models from one printer at once before proceeding to measure models from a different printer.

Statistical Analysis

With a sample size of 12 patient plaster casts, the study had 80% power to detect differences from the plaster cast for each 3D printing technology and between the 3D printing technologies of 1.8 mm for mandibular transverse plane, 2.1 mm for maxillary transverse plane, 0.9 mm for mandibular mixed plane, and 1.5 mm for maxillary mixed plane, assuming two-sided paired *t*-tests, each conducted at a 5% significance level.

Repeatability of the measurements was evaluated using Bland-Altman plots and intraclass correlation coefficients (ICCs). Separate analyses were performed for the transverse, anteroposterior, vertical, and mixed-plane measurements for the upper and lower jaws. For each measurement, paired *t*-tests were used to test for significant differences between the 3D printing technologies and the original plaster models.

Bland-Altman plots, ICCs, and measurement error were used to evaluate the agreement of each 3D printing method with plaster, and paired *t*-tests were used to compare the 3D and plaster measurements. Repeated-measures analysis of variance was used to compare among the 3D printing methods, allowing each method to have a different variance and allowing correlations between methods to vary. A 5% significance level was used for all tests.

A clinically significant difference between the models was defined as a measurement discrepancy of greater than 0.5 mm. In other words, a difference in dimensions between model types equal to or less than 0.5 mm is unlikely to have a significant clinical impact.

RESULTS

Inter- and intrarater reliability testing of all measured parameters was within 0.5 mm. Table 2 displays the measurement differences between plaster and resin models.

FDM vs Plaster

ICCs for agreement between FDM and plaster were all at least greater than 0.80, and all except maxillary left mixed plane (MxL-MP), overjet, mandibular right mixed plane (MdR-MP), mandibular left MP (MdL-MP), and overbite were at least 0.90. FDM was significantly

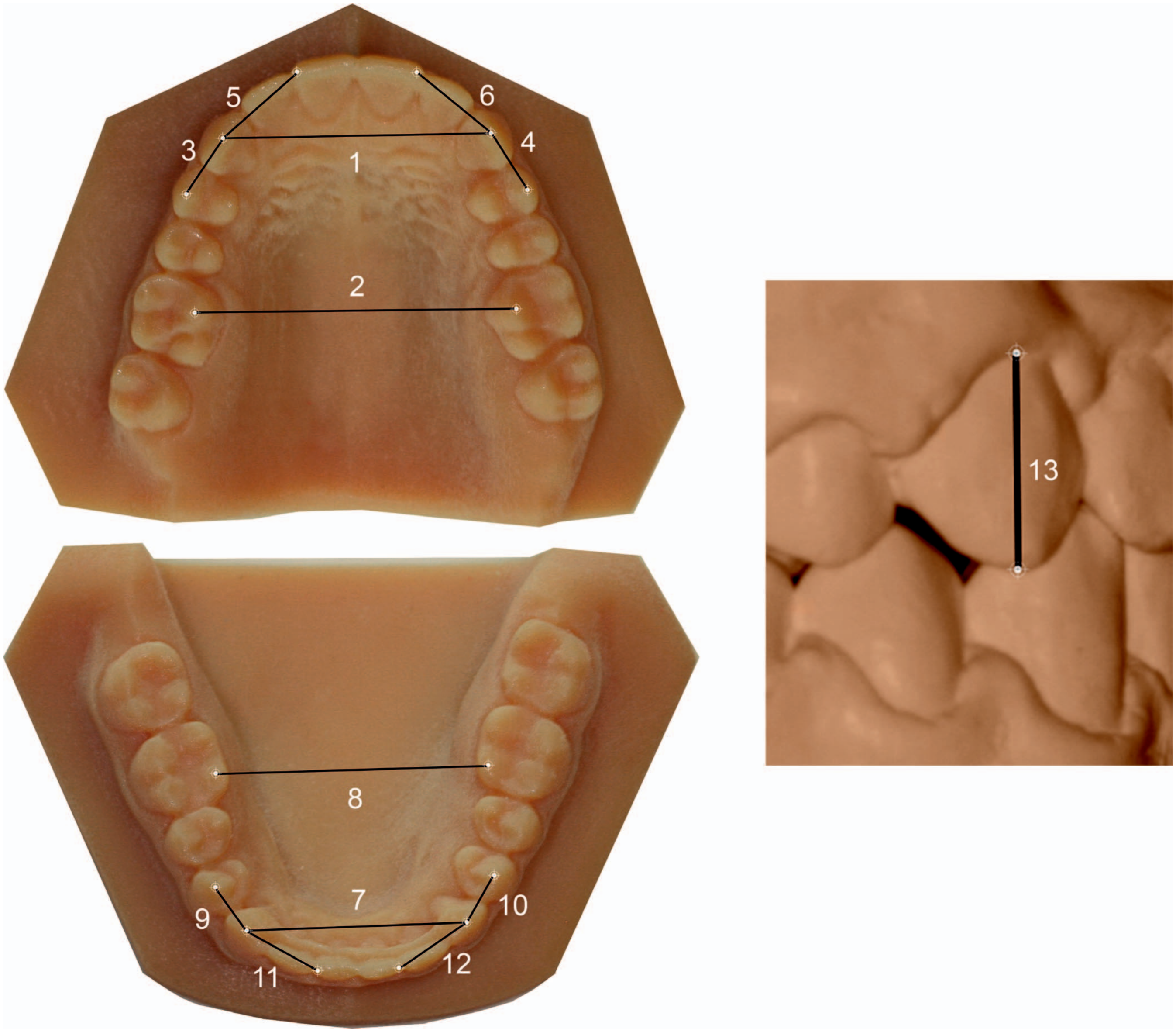

Figure 2. The selected parameters measured in transverse, anteroposterior, vertical, and mixed planes: 1, Mx-ICW; 2, Mx-IMW; 3, MxR-AP; 4, MxL-AP; 5, MxR-MP; 6, MxL-MP; 7. Md-ICW; 8. Md-IMW; 9. MdR-AP; 10. MdL-AP; 11. MdR-MP; 12, MdL-MP; 13, MxR-vertical.

higher on average than plaster for maxillary left MP (MxL-MP) and mandibular intermolar width (Md-IMW).

Polyjet vs Plaster

ICCs for agreement between Polyjet and plaster were all at least 0.80, and all except MxL anteroposterior plane (MxL-AP), overbite, overjet, MdL-AP, and MdL-MP were at least 0.90. Polyjet was significantly higher on average than Plaster for maxillary intercanine width (Mx-ICW), mandibular ICW (Md-ICW), and MdL-MP. Polyjet was significantly lower on average than plaster for MxR vertical plane (MxR-vertical), MxL-vertical, MdR-AP, MdR-vertical, and MdL-vertical.

SLA vs Plaster

ICCs for agreement between SLA and plaster were low (less than 0.80) for MdL-AP and overbite. ICCs for MxL-AP, MdR-MP, and MdL-MP were between 0.85 and 0.90, and all others were at least 0.90. SLA was significantly higher on average than was plaster for Md-ICW and overbite. SLA was significantly lower on average than was plaster for MdR-vertical and MdL-vertical.

Comparisons among Resin Models

FDM had a significantly smaller difference from plaster for Mx-ICW than did Polyjet ($P = .0203$) and

Table 2. Measurement Differences between Resin and Plaster Models[a]

Measurement	Type	N	Mean	SD	SE	Minimum	Maximum	*P*-Value	ICC (95% CI)	ME
Mx-ICW	FDM	12	−0.14	0.42	0.12	−0.69	0.60	.2570	0.99 (0.96–1.00)	0.29
	Polyjet	12	0.26	0.37	0.11	−0.19	1.04	.0339	0.99 (0.96–1.00)	0.26
	SLA	12	0.29	0.48	0.14	−0.43	1.10	.0612	0.98 (0.93–0.99)	0.34
Mx-IMW	FDM	12	0.11	0.42	0.12	−0.60	1.06	.4001	0.99 (0.96–1.00)	0.29
	Polyjet	12	−0.19	0.33	0.10	−0.77	0.21	.0685	0.99 (0.96–1.00)	0.23
	SLA	12	−0.02	0.37	0.11	−0.66	0.94	.8663	0.99 (0.96–1.00)	0.25
MxR-AP	FDM	12	−0.19	0.32	0.09	−0.86	0.51	.0697	0.90 (0.67–0.97)	0.23
	Polyjet	12	−0.06	0.32	0.09	−0.62	0.54	.5293	0.93 (0.76–0.98)	0.22
	SLA	12	−0.13	0.35	0.10	−0.55	0.41	.2115	0.91 (0.70–0.97)	0.25
MxL-AP	FDM	12	−0.12	0.29	0.08	−0.73	0.35	.1757	0.92 (0.73–0.98)	0.20
	Polyjet	12	−0.19	0.49	0.14	−1.12	0.51	.2102	0.81 (0.44–0.94)	0.35
	SLA	12	−0.23	0.39	0.11	−1.02	0.45	.0650	0.86 (0.56–0.96)	0.27
MxR-vertical	FDM	12	−0.07	0.21	0.06	−0.34	0.30	.2491	0.98 (0.93–0.99)	0.15
	Polyjet	12	−0.21	0.22	0.06	−0.55	0.19	.0088	0.97 (0.89–0.99)	0.16
	SLA	12	−0.07	0.18	0.05	−0.41	0.21	.2439	0.99 (0.96–1.00)	0.13
MxL-vertical	FDM	12	−0.01	0.31	0.09	−0.46	0.61	.8836	0.97 (0.89–0.99)	0.21
	Polyjet	12	−0.20	0.13	0.04	−0.35	0.04	.0004	0.98 (0.93–0.99)	0.10
	SLA	12	−0.12	0.20	0.06	−0.39	0.32	.0515	0.98 (0.93–0.99)	0.14
MxR-MP	FDM	12	0.34	0.60	0.17	−0.95	1.24	.0772	0.92 (0.73–0.98)	0.42
	Polyjet	12	0.09	0.59	0.17	−1.52	0.73	.5924	0.95 (0.83–0.99)	0.40
	SLA	12	0.12	0.62	0.18	−1.39	0.73	.5087	0.94 (0.79–0.98)	0.43
MxL-MP	FDM	12	0.60	0.50	0.14	−0.07	1.65	.0016	0.82 (0.46–0.95)	0.35
	Polyjet	12	0.18	0.54	0.15	−0.68	0.85	.2778	0.90 (0.67–0.97)	0.38
	SLA	12	0.26	0.39	0.11	−0.29	0.79	.0386	0.94 (0.79–0.98)	0.27
Md-ICW	FDM	12	−0.22	0.41	0.12	−1.22	0.36	.0911	0.97 (0.89–0.99)	0.29
	Polyjet	12	0.34	0.37	0.11	−0.40	0.84	.0091	0.97 (0.89–0.99)	0.26
	SLA	12	0.34	0.40	0.11	−0.28	1.09	.0133	0.97 (0.89–0.99)	0.28
Md-IMW	FDM	12	0.30	0.36	0.10	−0.32	0.83	.0148	0.99 (0.96–1.00)	0.25
	Polyjet	12	−0.25	0.44	0.13	−1.03	0.27	.0781	0.98 (0.93–0.99)	0.31
	SLA	12	−0.12	0.47	0.14	−0.86	0.71	.4107	0.99 (0.96–1.00)	0.33
MdR-AP	FDM	12	−0.13	0.29	0.08	−0.62	0.29	.1364	0.94 (0.79–0.98)	0.20
	Polyjet	12	−0.19	0.27	0.08	−0.55	0.26	.0361	0.95 (0.83–0.99)	0.19
	SLA	12	−0.09	0.38	0.11	−0.81	0.47	.4379	0.91 (0.70–0.97)	0.26
MdL-AP	FDM	12	−0.11	0.30	0.09	−0.49	0.33	.2332	0.93 (0.76–0.98)	0.21
	Polyjet	12	−0.20	0.41	0.12	−0.90	0.65	.1241	0.87 (0.59–0.96)	0.29
	SLA	12	−0.24	0.54	0.16	−1.33	0.62	.1550	0.73 (0.27–0.92)	0.38
MdR-vertical	FDM	12	−0.11	0.19	0.05	−0.45	0.17	.0675	0.99 (0.96–1.00)	0.13
	Polyjet	12	−0.20	0.21	0.06	−0.59	0.24	.0057	0.98 (0.93–0.99)	0.15
	SLA	12	−0.16	0.24	0.07	−0.61	0.22	.0383	0.98 (0.93–0.99)	0.17
MdL-vertical	FDM	12	−0.07	0.19	0.06	−0.24	0.32	.2598	0.98 (0.93–0.99)	0.14
	Polyjet	12	−0.16	0.17	0.05	−0.52	0.16	.0087	0.98 (0.93–0.99)	0.12
	SLA	12	−0.17	0.11	0.03	−0.35	0.03	.0002	0.99 (0.96–1.00)	0.08
MdR-MP	FDM	12	0.08	0.51	0.15	−1.21	0.92	.5963	0.85 (0.54–0.96)	0.35
	Polyjet	12	0.04	0.39	0.11	−0.55	0.72	.6994	0.91 (0.70–0.97)	0.26
	SLA	12	0.16	0.44	0.13	−0.78	1.03	.2347	0.87 (0.59–0.96)	0.31
MdL-MP	FDM	12	0.14	0.48	0.14	−0.70	0.63	.3262	0.88 (0.62–0.97)	0.34
	Polyjet	12	0.29	0.43	0.13	−0.42	1.15	.0436	0.88 (0.62–0.97)	0.31
	SLA	12	0.28	0.44	0.13	−0.40	0.97	.0529	0.89 (0.65–0.97)	0.31
Overjet	FDM	12	0.00	0.38	0.11	−0.83	0.38	.9880	0.84 (0.51–0.95)	0.26
	Polyjet	12	−0.08	0.32	0.09	−0.69	0.31	.3967	0.87 (0.59–0.96)	0.22
	SLA	12	−0.05	0.29	0.09	−0.80	0.36	.5749	0.91 (0.70–0.97)	0.20
Overbite	FDM	12	−0.06	0.23	0.07	−0.48	0.23	.3666	0.89 (0.65–0.97)	0.16
	Polyjet	12	0.13	0.29	0.08	−0.42	0.56	.1540	0.84 (0.51–0.95)	0.21
	SLA	12	0.32	0.27	0.08	−0.07	0.86	.0018	0.76 (0.33–0.93)	0.19

[a] Mx-ICW indicates maxillary intercanine width; Mx-IMW, maxillary intermolar width; MxR-AP, maxillary right anteroposterior plane; MxL-AP, maxillary left anteroposterior plane; MxR-Vertical, maxillary right vertical plane; MxL-vertical, maxillary left vertical plane; MxR-MP, maxillary right mixed plane; MxL-MP, maxillary left mixed plane; Md-ICW, mandibular intercanine width; Md-IMW, mandibular intermolar width; MdR-AP, mandibular right anteroposterior plane; MdL-AP, mandibular right anteroposterior plane; MdR-vertical, mandibular right vertical plane; MdL-vertical, mandibular left vertical plane; MdR-MP, mandibular right MP; MdL-MP, mandibular left mixed plane; FDM, fused depositional modeling; SLA, stereolithography; SD, standard deviation; SE, standard error; ICC, intraclass correlation coefficient; CI, confidence interval; and ME, margin of error.

SLA ($P = .0139$), where FDM measured lower than plaster while Polyjet and SLA measured higher than plaster, but Polyjet and SLA were not different from each other ($P = .83$).

FDM had a significantly smaller difference from plaster for Md-ICW than did Polyjet ($P = .0025$) and SLA ($P = .0017$), where FDM measured lower than plaster while Polyjet and SLA measured higher than plaster, but Polyjet and SLA were not different from each other ($P = .98$).

FDM had a significantly larger difference from plaster for Md-IMW than did Polyjet ($P = .0007$) and SLA ($P = .0011$), where FDM measured higher than plaster while Polyjet and SLA measured lower than plaster, but Polyjet and SLA were not different from each other ($P = .20$).

SLA had significantly a larger difference from plaster for overbite than did FDM ($P = .0003$) and Polyjet ($P = .0137$), where SLA measured higher than plaster while FDM and Polyjet measured slightly lower and slightly higher than plaster, respectively, but FDM and Polyjet were not different from each other ($P = .055$).

FDM, Polyjet, and SLA were not significantly different from each other for the remaining measurements (Mx-IMW: $P = .07$; MxR-AP: $P = .38$; MxL-AP: $P = .35$; MxR-vertical: $P = .07$; MxL-vertical: $P = .21$; MxR-MP: $P = .07$; MxL-MP: $P = .07$; MdR-AP: $P = .58$; MdL-AP: $P = .39$; MdR-vertical: $P = .18$; MdL-vertical: $P = .27$; MdR-MP: $P = .36$; MdL-MP: $P = .46$; and overjet: $P = .64$).

DISCUSSION

As 3D printing becomes more commonplace in the orthodontic landscape, the development of various printing technologies needs to be examined. Currently there are numerous 3D printers available on the market, with many using a unique rapid prototyping technology. With the acceptance of digital scanning as an accurate replacement to impressions, orthodontists have logically looked toward 3D printing as the next step toward a digital practice.[8–10] Out of the numerous different rapid prototyping technologies used in orthodontics, three of the most common are FDM, SLA, and Polyjet printing. This study compared these three technologies not only to each other but also to the more commonly used plaster casts.

Keating et al.[11] compared plaster, digital, and SLA printed models and indicated that the transparent color of the SLA models made landmark identification difficult, leading to errors in dimension measurements. The SLA models in this study were peach colored and lent themselves more easily to landmark identification. It can therefore be suggested that for accurate measurements on resin models, utilization of a solid color is preferable to a clear or transparent color.

Santoro et al.[2] compared plaster and digital models and defined the clinically acceptable range of differences as 0.50 mm; other studies[6,12–15] have used 0.20–0.50mm. In the present study, the statistically significantly different measurements of Mx-ICW, Md-ICW, Md-IMW, and overbite had mean measurements that were within 0.35 mm compared to the mean measurements of the original plaster casts. Future studies are needed to define the limit of measurement differences in dental models, as this has great implications for determining rapid prototyping accuracy and which resin types are appropriate for appliance fabrication.

The results of this study demonstrated numerous patterns with respect to the accuracy between the three different rapid prototyping techniques. FDM models had the least amount of variation compared to the SLA and Polyjet models. When comparing each technology to plaster, FDM models only had two statistically significant differences: FDM was higher on average than plaster in two intra-arch measurements, MxL-MP and Md-IMW. SLA models were found to have four statistically significantly different measurements compared to plaster casts, and Polyjet models had eight statistically significantly different measurements. These findings suggest that, at least with regard to dimensional accuracy, FDM models are not inferior compared to newer printing technologies and can be useful within the orthodontic profession. Similar to the findings of Kasparova et al.[5] comparing FDM to more expensive 3D printing technologies, there were no differences between the recreational FDM printer and commercial printers in terms of clinical purpose. With these findings, there may be a potential to incorporate the more cost-effective FDM printing technology into orthodontics. 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 orthodontic labs.

Both SLA and Polyjet models displayed similar variations from the original plaster casts, depending on the defined parameter. SLA and Polyjet models were higher on average than plaster casts for intra- and interarch measurements. SLA models were higher on average in Md-ICW (intra-arch) and overbite (interarch) measurements, while Polyjet models were higher on average for Mx-ICW, Md-ICW, and MdL-MP, all intra-arch measurements. In addition, both SLA and Polyjet models displayed a decreasing tendency for vertical dimensions compared to plaster models. SLA was significantly lower on average for MdR-vertical and MdL-vertical, while Polyjet was significantly lower for all vertical measurements in both the maxillary and mandibular arch (Mx/Md right and left vertical). This finding shows the similar variance of both SLA and Polyjet model measurements depending on the parameter measured. With intra- and interarch measurements, both SLA and Polyjet models were prone to increasing tendencies, while for vertical measurements they were prone to decreasing tendencies. These findings support the claims of previous studies[4,6,11] that rapid prototyping technology faces difficulties in the vertical dimension. It is important to note that in this study, vertical discrepancies were shown to have an increasing tendency, while previous studies have shown a decreasing tendency. The difficulty of SLA and Polyjet printers in replicating intra-arch, interarch, and vertical dimensions is difficult to explain completely and may have numerous causes. In the process of printing, the resin materials may experience expansion and/or shrinking, explaining the increasing and decreasing tendencies. Future studies should aim to resolve the conflicting expansion and shrinkage experienced in SLA and Polyjet models and look for patterns in dimensional errors in all three planes.

CONCLUSIONS

- Statistically significant differences within 0.35 mm were found between plaster, FDM, SLA, and Polyjet models.
- FDM models had the fewest differences and were best able to replicate plaster models.
- SLA and Polyjet models showed a tendency toward expansion for intra- and interarch measurements and a tendency toward shrinkage in the vertical plane.

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