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Accuracy of 3D printed polymers intended for models and surgical guides printed with two different 3D printers

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The purpose of the study was to evaluate the accuracy: trueness and precision of photopolymers used for dental models and surgical guides printed with two different digital light processing (DLP) printers. Forty specimens of four materials; E-dentstone®, E-shell®, NextDent™ Model, NextDent™ SG, and two designs; models A and B (*n*=5), were manufactured (DDDP, EvoDent). Trueness was evaluated by comparing values for 26 parameters with the CAD models' reference values and precision through standard deviation. The trueness and precision were higher for linear than for angle parameters. X- and Y-axes showed higher trueness than Z-axis and model B higher trueness than model A. The conclusions are; the accuracy is dependent on the design of the object. The linear precision appears to be high. The highest trueness was observed for a surgical guide polymer (NextDent™ SG). The definition of clinically relevant accuracy and acceptable production tolerance should be evaluated in future studies.

Keywords: Additive manufacturing, 3D printing, Digital light processing, Dental models, Surgical guides

INTRODUCTION

Additive manufacturing (AM) technologies such as rapid prototyping, more commonly known as three-dimensional (3D) printing, is an increasingly used technology for dental applications. Two of the most common applications for 3D printing using polymeric materials are dental models and biocompatible surgical guides, which facilitate the planning and manufacturing of dental restorations[1-5]. Since high accuracy of implant placement and fit of a dental restoration are crucial for the patient treatment and outcome, surgical guides and models manufactured by printing needs to be investigated to ensure that they are comparable to those manufactured by traditional technologies[3,6-8].

According to The American Section of the International Association for Testing Materials (ASTM), AM technologies can be divided into seven categories where stereolithography (SLA), including digital light processing (DLP), represents one[9]. SLA and DLP are technologies commonly used for printing 3D objects of polymeric materials, and the technologies have several similarities[2,10-13]. The 3D object is built layer by layer by immersing a build platform in a resin tank consisting of liquid light-cured resin, *i.e.*, photopolymers. The key difference between the technologies is the type of light source: SLA using an ultraviolet (UV) laser light to draw a pattern of a cross-section of the 3D object, and DLP using a digital light projector screen to project the entire cross-section of the 3D object at once. DLP is based on micro-electro-mechanical technology using a chip containing microscopic mirrors moveable in two directions, a so-called digital micromirror device (DMD)[10]. The number of pixels defines the resolution of the polymerized mask[10,12]. Resolution is the finest feature a 3D printer can produce and should not be confused with accuracy when evaluating the results of 3D printed objects. According to ISO[14,15] accuracy consists of trueness and precision. Trueness is defined as the closeness of agreement between measurements (arithmetic mean) and the true value and precision as the closeness of agreement between repeated measurements. In terms of dental models and surgical guides, the trueness can be described as how close the measurements of the printed object are to the CAD model's dimensions and the precision how close the measurements of repeatedly printed similar objects are to each other.

The accuracy of dental models and surgical guides can be influenced by different factors such as the type of AM technology and manufacturer[2,6,8,16-19] as well as the type of material, layer thickness[2,16,17,20] depth of cure[2,11,12], build orientation *i.e.* build direction and angle[7,10,21-23], platform position[7,10] amount of support structures[7,10,23] and the post-processing procedure[2,7,10-12,24]. In the literature, and in addition to these factors, the test set-up tend to differ, making a comparison between results of studies and general conclusions difficult. In comparison to traditional stone and milled models, studies[4,18,19,25,26] have shown that 3D printed models using different types of AM technologies might have sufficient accuracy for selected orthodontic applications, although not always having higher accuracy than stone models[4,8,19]. However, for prosthodontic applications the accuracy might not be clinically acceptable, and further research is needed[4,18]. Zhang *et al.*[16] compared the accuracy of 3D printed dental models using DLP and SLA technologies and different layer thicknesses, and generally, the accuracy increased with decreasing layer thickness. The DLP technology showed higher accuracy than SLA at a layer thickness of 100 µm, and the optimal layer thickness for DLP technology was 50 µm. The absolute average deviations

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for most groups were smaller than 0.05 mm, assessed as clinical acceptable for orthodontic applications[16].

Previous reviews[27,28] have indicated smaller deviations between the planned and postoperative implant position when using surgical guides, *i.e.*, guided implant surgery, which is consistent with the recommendations from the European Association of Osseointegration (EAO) consensus conference[29]. However, it is also emphasized that only limited data is available, and the evidence is scarce. Hence, further studies are needed. Accordingly, the number of studies analyzing the accuracy of the actual 3D printed surgical guides is also limited. Gjelvold *et al.*[24] evaluated the accuracy of 3D printed surgical guides manufactured with SLA and DLP technologies and concluded that the final implant position deviations were similar for both technologies.

Most studies have made comparisons of the accuracy of materials for the same application with different printers or printing techniques. However, there can be differences in the accuracy between materials with different applications manufactured in the same printer since layer thickness, activation range wavelength, shrinkage, and translucency differ between materials[11,12].

The purpose of the study was to evaluate the accuracy: trueness and precision of photopolymers used for dental models and surgical guides printed with two different DLP printers.

The null hypothesis was that there are no differences in accuracy between the different materials because the DLP technology produces a high accuracy regardless of material.

MATERIALS AND METHODS

A total of 40 specimens were manufactured in two different DLP 3D printers; 20 were printed in DDDP (EnvisionTEC, Gladbeck, Germany) and 20 in EvoDent (UnionTech, Frankfurt am Main, Germany) (Tables 1 and 2). The respective 20 specimens were divided into four groups (n=10) depending on the material and subsequently divided into subgroups (n=5) depending on the type of model. The specimens were as a die for an inlay (model A) and a model with two abutments for a four-unit fixed dental prosthesis, FDP (model B), according to ISO 12836:2015 Annex A and B[15] and modified by Braian *et al.*[17] (Figs. 1 and 2).

Two CAD models representing model A and B[17] with an edge radius of 0.01 mm were used (Solidworks educational edition 2013, Dassault Systèmes SE, Vélizy-Villacoublay, France). The dimensions of the CAD models were used as reference values for the upcoming measurements to evaluate the accuracy of the printed specimens (Table 3). The dimensions of the CAD models were controlled using Magics print DLP 21.22 (Materialise, Leuven, Belgium) and 3Shape Dental System (3Shape, Copenhagen, Denmark). Standard tessellation language (STL) files with the solid CAD models were exported to the printers. The mesh of model A consisted of 60 triangles and 32 vertices and model B of 5,800 triangles and 2,902 vertices with mesh density 128 and cell size 0.112 mm. Each CAD model was centrally placed directly onto the build platform without support structures using the software Perfactory® Software Suite 3.0 (EnvisionTEC, Marl, Germany) for DDDP and Magics print DLP 21.22 (Materialise) for EvoDent. The specimens were printed at room temperature of 23±1°C and post-processed one at the time according to the manufacturers' recommendations. The surgical guide materials used in the study are biocompatible. NextDent™ SG is a CE-certified Class I material and E-shell® a CE-certified Class IIa material and USP Plastic Class VI.

Manufacturing of specimens of E-Dentstone® and E-Shell® in DDDP

Build styles corresponding to the respective material, E-Dentstone® and E-Shell® were chosen in Perfactory® Software Suite 3.0. The layer thickness for E-Dentstone® was 50 µm and 100 µm for E-Shell®. The light source of the 3D printer was calibrated, and when changing material, the mask was regenerated according to the manufacturer's instructions. The projector brightness was set to 180 mW/dm^2 for E-Dentstone® and 230 mW/dm^2 for E-Shell®. The specimen was removed from the build platform with a chisel blade (UnionTech) and cleaned with isopropyl alcohol (IPA) 99.5% (Isopropanol Pro Analysis, Solveco AB, Rosersberg, Sweden, Lot 6091549) in three steps. The specimens made of E-Dentstone® were cleaned in a cleaning device (Form Wash, Formlabs, Somerville, MA, USA) for four minutes in two steps and air blasted for 10 s between the steps. The specimens made of E-Shell® were cleaned in the same way for two minutes in the respective step. As the last step, the specimens made of E-Dentstone® and E-Shell® were cleaned with fresh IPA in an ultrasonic bath (BioSonic UC100XD, Coltene Whaledent, Altstätten, Switzerland) for two minutes and one minute respectively according to the manufacturer's recommendations, followed by air blasting for 10 s. The specimens made of E-Dentstone® were subjected to a drying process in an incubator at 37°C for 30 min. Final polymerization of the specimens was carried out in a post-curing unit (Otoflash G171, EnvisionTEC) with 2×300 flashes for E-Dentstone® and 2×1,000 flashes for E-Shell® according to the manufacturer's instructions.

Manufacturing of specimens of NextDent™ Model and NextDent™ SG in EvoDent

The layer thickness for NextDent™ Model was set to 50 µm and 100 µm for NextDent™ SG according to the manufacturer's instructions. The STL file of each CAD model was prepared in Magics print DLP 21.22 and uploaded as a .utk file (building file format) to the printer (EvoDent). The specimen was removed and cleaned (Form Wash) as previously mentioned in one step for 10 min, followed by air blasting for 10 s. Each specimen was placed in a water-filled glass container in a post-curing unit (EvoDent Post Curing Unit, UnionTech) for 10 min,

Table 1 Overview of the groups and materials used

3D printer	Material	Material composition	Indication	Model A (n)	Model B (n)	Abbreviation of the group	Material manufacturer, Lot No.
DDDP[a]	E-Dentstone® Peach	Acrylated monomer 30–70%, Acrylated oligomer 10–20%, 1,6-hexandioldiakrylat 1–3%, Titanium Dioxide 0.1–0.2%	Models	5		EMA	EnvisionTEC, Gladbeck, Germany, 020718
DDDP[a]	E-Dentstone® Peach	Acrylated monomer 30–70%, Acrylated oligomer 10–20%, 1,6-hexandioldiakrylat 1–3%, Titanium Dioxide 0.1–0.2%	Models		5	EMB	EnvisionTEC, 020718
DDDP[a]	E-Shell® 600[c]	Tetrahydrofurfuryl methacrylate 10–25%, 7,7,9-Trimethyl-4,13-dioxo-3,14-dioxa-5,12-diaza-hexadecan-1,16-diol dimethacrylate 5–20%, Diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide <1%	Surgical Guides	5		ESA	EnvisionTEC, 180415
DDDP[a]	E-Shell® 600[c]	Tetrahydrofurfuryl methacrylate 10–25%, 7,7,9-Trimethyl-4,13-dioxo-3,14-dioxa-5,12-diaza-hexadecan-1,16-diol dimethacrylate 5–20%, Diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide <1%	Surgical Guides		5	ESB	EnvisionTEC, 180415
EvoDent[b]	NextDent™ Model	Monomer based on methacrylic ester: methacrylic oligomers >90%, Phosphine oxides <3%, colorants and pigments	Models	5		NMA	Vertex-Dental, Soesterberg, The Netherlands, n.a.
EvoDent[b]	NextDent™ Model	Monomer based on methacrylic ester: methacrylic oligomers >90%, Phosphine oxides <3%, colorants and pigments	Models		5	NMB	Vertex-Dental, n.a.
EvoDent[b]	NextDent™ SG[d]	Monomer based on methacrylic ester: methacrylic oligomers >90%, Phosphine oxides <3%, colorants and pigments	Surgical Guides	5		NSA	Vertex-Dental, n.a.
EvoDent[b]	NextDent™ SG[d]	Monomer based on methacrylic ester: methacrylic oligomers >90%, Phosphine oxides <3%, colorants and pigments	Surgical Guides		5	NSB	Vertex-Dental, n.a.

EMA: E-Dentstone Model Model A, EMB: E-Dentstone Model Model B, ESA: E-Shell Surgical Guide Model A, ESB: E-Shell Surgical Guide Model B, NMA: NextDent Model Model A, NMB: NextDent Model Model B, NSA: NextDent Surgical Guide Model A, NSB: NextDent Surgical Guide Model B, [a]Manufacturer: EnvisionTEC, Gladbeck, Germany, [b]Manufacturer: UnionTech, Frankfurt am Main, Germany, [c]CE-certified Class IIa material, [d]CE-certified Class I material

Table 2 Specifications of the 3D printers used

3D printer	Manufacturer	Build volume (W×L×H)	XY resolution	Layer thickness	Projector resolution	Light source	Software	Firmware
Desktop Digital Dental Printer (DDDP)	EnvisionTEC, Gladbeck, Germany	100×75×100 mm	71 µm	25–150 µm	1,400×1,050 pixels	Visible or UV LED	Perfactory® Software Suite 3.0	Perfactory® 4.5.5
EvoDent	UnionTech, Frankfurt am Main, Germany	111×62×85 mm	58 µm	50–100 µm	1,920×1,080 pixels	UV LED	Magics print DLP Software 21.22	DSCON Software

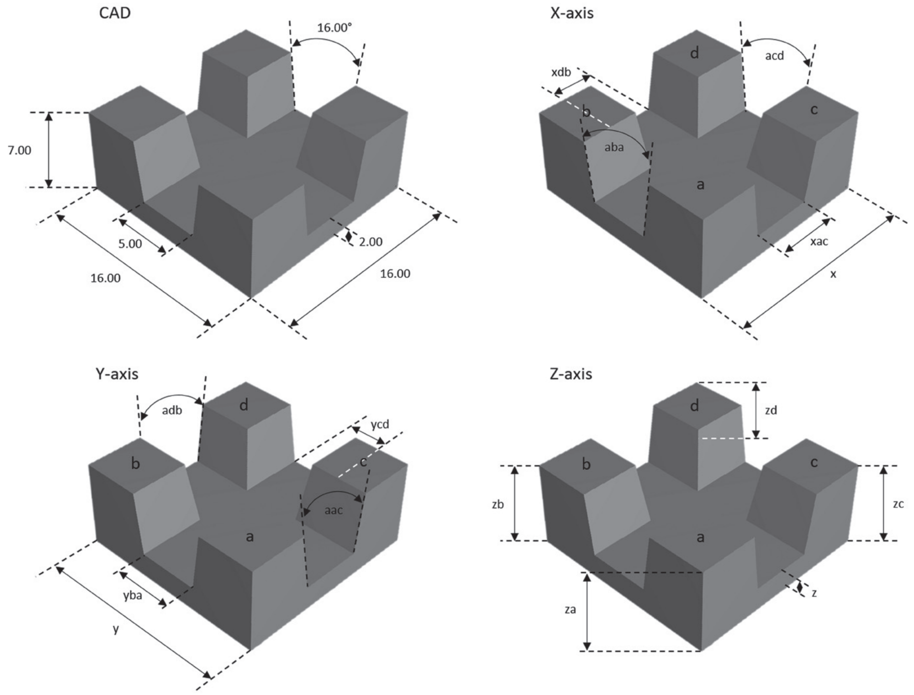

Fig. 1 Model A designed as a die for an inlay.
The CAD figure shows the dimensions (mm/degrees) of the parameters evaluated and X-, Y- and Z-axes the different parameters.

followed by air blasting according to the manufacturer's instructions. All specimens were stored in a sealed container at room temperature until the measurements were performed.

Measurements of trueness and precision

The measurements of each printed specimen were performed 30 min after completed post-curing by one operator. The parameters evaluated were divided into two horizontal axes; X and Y, one vertical axis; Z and angles; a (Figs. 1 and 2, Table 3). For model A, 15 parameters were evaluated, and for model B, 11 parameters were evaluated. The linear parameters were measured with a digital caliper (DIGI-MET 2212216, HOREX®, Preisser, Gammertingen, Germany) with a precision of 0.01 mm. The measurements were standardized by placing the caliper at the edges of the specimens, as indicated by the arrows in Figs. 1 and 2. The angle parameters (aac, aba, acd, adb, al and ar) were measured and processed with a digital light microscope (WILD M7A, Wild Heerbrugg/WILD MZ6, Leica Application Suite, Version 4.1.0 Build: 1264/Camera Leica DFC 420, Leica Microsystems, Heerbrugg, Switzerland). A putty mold for each model was used to standardize the position and the measurements of the specimens.

Each parameter was measured five times, and the

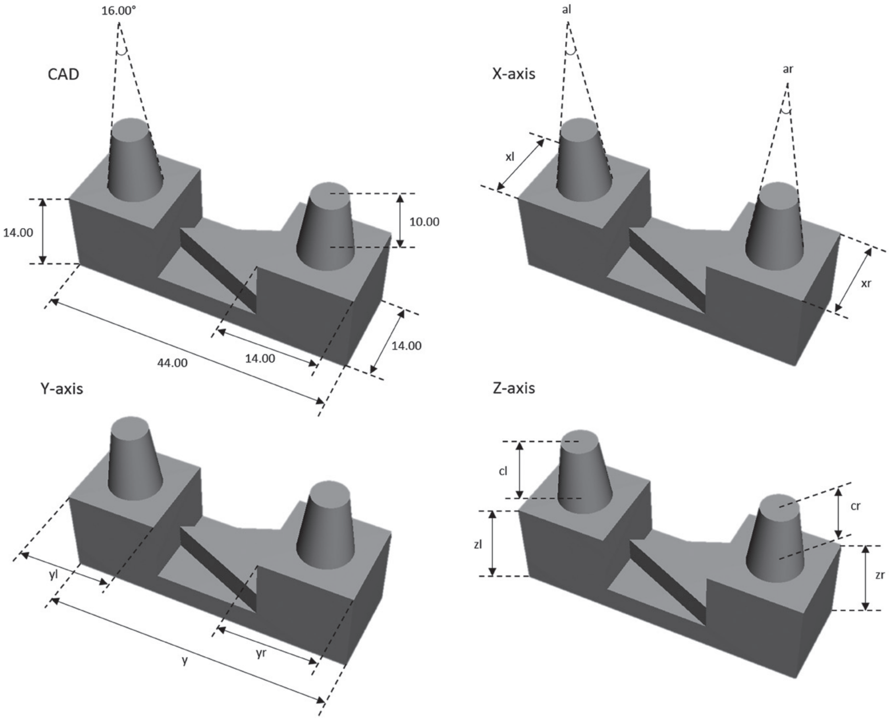

Fig. 2 Model B designed as a model for a four-unit FDP.
The CAD figure shows the dimensions (mm/degrees) of the parameters evaluated and X-, Y- and Z-axes the different parameters. l: left, r: right

Table 3 Parameters and dimensions (mm/degrees) of model A and B

	Model A		Model B	
Axis/angle	Parameter	Dimension (mm)/angle (degrees)	Parameter	Dimension (mm)/angle (degrees)
X-axis (horizontal/width)	x	16.00	xl	14.00
	xac	5.00	xr	14.00
	xdb	5.00		
Y-axis (horizontal/depth)	y	16.00	y	44.00
	yba	5.00	yl	14.00
	ycd	5.00	yr	14.00
Z-axis (vertical/height)	z	2.00	zl	14.00
	za	7.00	zr	14.00
	zb	7.00	cl	10.00
	zc	7.00	cr	10.00
	zd	7.00		
Angle	aac	16.00°	al	16.00°
	aba	16.00°	ar	16.00°
	acd	16.00°		
	adb	16.00°		

l: left, r: right, c: cone

arithmetic mean and standard deviation of each group of the respective parameter were calculated. The trueness was evaluated by comparing the values of the groups for the respective parameter with the CAD models' reference values. The precision was evaluated through the standard deviation of the groups of the respective parameter.

Statistical analysis

One-way ANOVA, Tukey's test was used to determine differences in trueness between the groups and the reference values (IBM SPSS Statistics 25, SPSS, Chicago, IL, USA). The level of significance was set to α=0.05.

RESULTS

The results of the measurements of the groups, along with the reference values for each parameter for models A and B are shown in Tables 4 and 5. The precision is shown through the standard deviation of the groups of the respective parameter. The trueness and precision were generally higher for the linear parameters than for the angle parameters.

The trueness is displayed through the differences between the values of the groups for the respective parameter and the CAD models' reference values, Tables 6 and 7. The X- and Y-axes showed higher trueness than the Z-axis and model B higher trueness in comparison to model A. The trueness of the groups significantly differed from the reference values for a majority of the parameters. Based on the statistical analysis NSA and NSB showed the highest trueness.

Table 4 The results of the trueness and precision (mm/degrees): arithmetic mean and standard deviation (±SD) of the groups and the reference values for each parameter for model A

Group		Parameters														
		x	xac	xdb	y	yba	ycd	z	za	zb	zc	zd	aac	aba	acd	adb
	Ref.	16.00	5.00	5.00	16.00	5.00	5.00	2.00	7.00	7.00	7.00	7.00	16.00	16.00	16.00	16.00
EMA	Mean	15.95	5.04	5.03	15.97	5.00	5.03	2.48	7.43	7.45	7.44	7.43	15.22	15.09	15.06	15.57
	SD	(0.02)	(0.03)	(0.05)	(0.03)	(0.03)	(0.04)	(0.01)	(0.02)	(0.01)	(0.02)	(0.02)	(0.36)	(0.55)	(0.36)	(0.32)
ESA	Mean	15.92	5.03	5.03	15.91	5.04	5.02	1.82	6.77	6.76	6.78	6.80	15.06	14.83	15.07	14.47
	SD	(0.02)	(0.03)	(0.02)	(0.01)	(0.06)	(0.05)	(0.06)	(0.07)	(0.07)	(0.05)	(0.06)	(0.48)	(0.54)	(0.56)	(0.62)
NMA	Mean	15.93	5.02	5.00	15.95	5.05	5.04	1.65	6.66	6.59	6.62	6.61	15.22	15.29	15.21	15.27
	SD	(0.04)	(0.04)	(0.07)	(0.03)	(0.04)	(0.02)	(0.25)	(0.19)	(0.27)	(0.22)	(0.26)	(0.48)	(0.44)	(0.48)	(0.36)
NSA	Mean	15.99	5.01	5.01	15.96	4.95	5.01	1.89	6.95	6.94	6.95	6.95	15.14	14.74	15.41	15.42
	SD	(0.01)	(0.05)	(0.03)	(0.01)	(0.10)	(0.03)	(0.05)	(0.01)	(0.02)	(0.03)	(0.03)	(0.55)	(0.64)	(0.44)	(0.53)

Ref.: The reference value of the CAD model for the parameter, SD: Standard deviation

Table 5 The results of the trueness and precision (mm/degrees): arithmetic mean and standard deviation (±SD) of the groups and the reference values for each parameter for model B

Group		Parameters										
		xl	xr	y	yl	yr	zl	zr	cl	cr	al	ar
	Ref.	14.00	14.00	44.00	14.00	14.00	14.00	14.00	10.00	10.00	16.00	16.00
EMB	Mean	14.03	14.00	43.90	14.05	14.00	14.41	14.40	10.03	10.01	15.88	16.06
	SD	(0.04)	(0.03)	(0.08)	(0.04)	(0.03)	(0.03)	(0.02)	(0.03)	(0.02)	(0.18)	(0.16)
ESB	Mean	14.05	14.05	44.01	14.06	14.07	13.56	13.84	10.09	9.98	16.14	16.44
	SD	(0.02)	(0.02)	(0.04)	(0.07)	(0.06)	(0.09)	(0.06)	(0.06)	(0.02)	(0.33)	(1.98)
NMB	Mean	14.01	14.04	43.95	14.00	13.99	13.83	13.78	9.95	9.96	15.22	16.25
	SD	(0.01)	(0.01)	(0.05)	(0.01)	(0.01)	(0.21)	(0.19)	(0.08)	(0.07)	(0.17)	(0.15)
NSB	Mean	14.03	14.02	44.00	14.02	14.01	13.88	13.87	9.95	9.95	16.03	16.06
	SD	(0.02)	(0.02)	(0.02)	(0.01)	(0.02)	(0.06)	(0.05)	(0.07)	(0.06)	(0.25)	(0.18)

Ref.: The reference value of the CAD model for the parameter, SD: Standard deviation

Table 6 Trueness (mm/degrees) for model A of the groups for each parameter

Group	Parameters														
	x	xac	xdb	y	yba	ycd	z	za	zb	zc	zd	aac	aba	acd	adb
EMA	−0.05*	0.04*	0.03	−0.03*	0.00	0.03*	0.48*	0.43*	0.44*	0.44*	0.43*	−0.78*	−0.91*	−0.94*	−0.43*
ESA	0.08*	0.03*	0.03*	−0.09*	0.04	0.02*	−0.18*	−0.23*	−0.24*	−0.22*	−0.20*	−0.94*	−1.17*	−0.93*	−1.26*
NMA	−0.07*	0.02	0.00	−0.05*	0.05*	0.04*	−0.35*	−0.34*	−0.41*	−0.38*	−0.39*	−0.78*	−0.71*	−0.79*	−0.73*
NSA	−0.01	0.01	0.01	−0.04*	−0.05*	0.01	−0.11*	−0.05	−0.06	−0.05	−0.05	−0.86*	−1.26*	−0.59*	−0.58*

Values denoted by * indicate a significant difference ($p \leq 0.05$) from the reference value.

Table 7 Trueness (mm/degrees) for model B of the groups for each parameter

Group	Parameters										
	xl	xr	y	yl	yr	zl	zr	cl	cr	al	ar
EMB	0.03*	0.00	−0.10*	0.05*	0.00	0.41*	0.40*	0.03	0.01	−0.12	0.06
ESB	0.05*	0.05*	0.01	0.06*	0.07*	−0.04*	−0.16*	0.09*	−0.02	0.14	0.44
NMB	0.01	0.04*	−0.05*	0.00	−0.01	−0.17*	−0.22*	−0.05*	−0.04*	−0.78*	0.25
NSB	0.03*	0.02*	0.00	0.02	0.01	−0.12*	−0.13*	−0.05*	−0.05	0.03	0.06

Values denoted by * indicate a significant difference ($p \leq 0.05$) from the reference value.

DISCUSSION

Providing surgical guides for implant placement positioning and dental models with a high accuracy are prerequisites for successful patient treatment. When implementing new technologies and materials in the treatment process, it is crucial to have knowledge about the trueness and precision of the products manufactured. In the absence of an ISO standard for assessing the accuracy of 3D printed objects, the study was based on the ISO standard 12836:2015, aiming to assess the accuracy of digitizing devices for CAD/CAM systems[15].

It is recommended to use at least two of the three specimens described[15]. Hence, following a previous study[17], the two dental geometries (model A and model B) were included in the study since considered more clinically relevant than the technical sphere-shaped specimen. Using ISO definitions of accuracy and standardized digital specimens can increase the likelihood of repeating the measurements with high reliability and facilitate comparisons of results. When the accuracy of standardized specimens has been validated, more complex geometries can subsequently be investigated.

The number of specimens for the respective material was based on previous studies[6,17]. Because the light intensity can vary across the build platform, thus possibly affecting the accuracy, the objects were printed one at the time centrally placed on the platform. This approach is supported by Unkovskiy *et al.*[7] that showed that the accuracy was higher in the central part of the platform, consequently emphasizing a central placement of specimens in further research, allowing accurate comparisons. Generally, the entire platform is utilized, and further research should address how the accuracy is affected by the placement on the platform. To adhere the object to the platform the initial layer might require higher exposure time or layer thickness depending on the technology and manufacturer[2,7,10]. The manufacturers' recommendations for the initial layer settings were consequently followed to avoid detachment or distortion of the specimens due to inadequate adhesion. For DDDP, the layer thickness was 0.4 mm, and for EvoDent, approximately 0.7–1.2 mm, depending on the tightening of the platform. Because the thickness varied and higher exposure time of the initial layer might cause compression, it could not be taken into account in the calculations in the Z-dimensions. Moreover, when removing objects printed directly on the platform, there is an imminent risk of dimensionally affecting the object in the Z-axis due to strong adhesion. Hence, the accuracy is not correctly represented. This assumption is evident in the results, which show lower trueness in the Z-axis, and in accordance with previous studies[7,20]. In the clinical situation, the additional initial layer thickness is though not crucial for the accuracy of the coronal part of a model or for surgical guides that are printed either with support structures or with an additional horizontal part towards the platform. Furthermore, the values of the Z-axis parameters were similar within the respective group in the present study, enabling modifications of the software settings to compensate for the deviations and increase the trueness.

The trueness of the groups significantly differed from the reference values for a majority of the parameters; hence, the null hypothesis can be rejected. Regarding the linear parameters, all trueness values were <0.5 mm and in the X- and Y-axes, the majority were <0.05 mm. Previous studies have shown similar results with a trueness of <0.1 mm[17] and <0.06 mm[16], although the results are not directly comparable due to different study designs, technologies, materials, and settings. Previous studies have also not made statistical comparisons between groups[16,17]. The trueness and precision were generally higher for the linear parameters than for the angle parameters, especially for model A, following the results from Braian *et al.*[17] where lower trueness was displayed for model A for the angle parameters. These results may be partly because the method used for the angle measurements is more complex, thus it is more difficult to achieve high reliability and that the geometry is negative. Furthermore, model B overall showed higher trueness compared to model A, possibly caused by the different geometries and complexity degrees.

There is no consensus concerning clinically relevant and acceptable values for the accuracy of models and surgical guides[30]. According to the ISO standard 6873, the acceptable discrepancy of type IV stone models is 0.05 mm[31]. An accuracy of 0.2–0.5 mm has been proposed as clinically acceptable in some studies[6,16,18,19], and others have proposed an accuracy of <0.2 mm because it is consistent with the reliability of the manual measurement itself[18]. Consequently, the results of the study concerning the linear parameters for trueness are in the range of what can be considered as a clinically acceptable accuracy for models.

Overall, the material NextDent™ SG (NSA, NSB) showed the highest trueness. One reason might be that the translucency of the material favors the depth of cure since pigments and dyes can inhibit the light from passing through the material[2,10]. Pixilation, *i.e.*, small areas with a lower degree of polymerization due to shadows between each pixel, associated with the DLP technology, might enhance the effect. Following the results of the present study, Zhang *et al.*[16] also achieved the highest accuracy with the EvoDent printer, although the groups were not compared statistically. Because the platform is moving in the Z-direction, potentially increasing the risk of repositioning biases, finer layer thicknesses can result in reduced accuracy. Accordingly, a layer thickness of 50 µm, as for the model materials, implies twice as many repositionings of the platform as the surgical guide materials of 100 µm. NextDent™ SG is in comparison to E-Shell® translucent but dyed, partly explaining the differences between the groups. Zhang *et al.*[16] contradictory concluded that the accuracy was slightly higher with a layer thickness of 50 µm compared to 100 µm, when using similar printers (UnionTec EvoDent and EnvisionTec Vida HD) and model materials (Model Ortho and E-Dentstone).

CONCLUSIONS

Within the limitations of this *in-vitro* study, the following conclusions regarding 3D printed polymers indicated for dental models and surgical guides can be drawn:

- The accuracy is dependent on the design of the object.
- The linear precision appears to be high.
- The highest trueness was observed for a surgical guide polymer (NextDent™ SG).
- The definition of clinically relevant accuracy and acceptable production tolerance should be evaluated in future studies.

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