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Accuracy of 6 Desktop 3D Printers in Dentistry: A Comparative *In Vitro* Study

Keywords

Accuracy
3D Printing
Trueness
Digital Dentistry
Dental Models

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Received: 29.02.2020
Accepted: 08.04.2020

doi: 10.1922/EJPRD_2050Mangano11

ABSTRACT

Purpose: To compare the accuracy of 6 desktop 3D printers in dentistry. Methods: A parallelepiped (PP) with known geometry and holes of different diameters was designed and printed with 6 desktop 3D printers (Sheraprint 40®; Solflex 350®; Form 2®; MoonRay D75®; Vida HD®; XFAB 2000®). For each printer, 9 PPs were printed with proprietary materials; these PPs were not cured and underwent dimensional analysis by optical microscopy and precision probing. A file representative of a dentate model (DM) was also printed with the aforementioned printers. For each printer, 3 DMs were printed with the proprietary materials. These DMs were cured and after 1 month, scanned with a desktop scanner and superimposed on the virtual reference model, to investigate trueness. Results: Dimensional analysis by optical microscopy and precision probing highlighted the reliability of the 3D printed models; errors were compatible with clinical use. However, both linear and diameter measurements revealed statistically significant differences between the machines. The trueness of the DMs 1 month after printing was low, suggesting that they underwent dimensional contraction over time, albeit with differences between the printers. Conclusions: The 3D printed models showed acceptable accuracy, although statistically significant differences were found among them.

INTRODUCTION

The digital revolution has now hit the world of dentistry, which is undergoing rapid transformation. Intraoral,[1,2] desktop[3] and face scanners,[4] along with cone beam computed tomography (CBCT), [5,6] allow acquiring a range of three-dimensional (3D) information useful to the dentist for formulating and planning treatment in surgical, prosthetic or orthodontic computer-assisted design (CAD) software. The transition from the real to the virtual makes possible "virtualising" the patient.[7] With the various CAD software and supported by the dental technician, the dentist plans treatment and designs a range of devices (surgical guides,[8] prosthetic structures such as crowns[9] and bridges,[10] and dentate models [DMs][11]) that are useful in practice. These devices must then be manufactured through conventional (moulding or casting), subtractive (milling)[12,13] or additive (3D printing) procedures.[13,14]

Additive manufacturing or layered production is a process for the fabrication, layer by layer, of 3D objects from computer models.[14] A 3D printer works by using a computer file to make a series of layers in cross section.[14] Each portion is printed on top of another to produce the 3D object[14]. The advantages of additive manufacturing techniques (3D printing) compared to milling and conventional moulding and casting are well-known in the industrial world: 3D printing allows the production of extremely complex objects (for example, generative geometries, fractal curves or hollow objects) without the limits of conventional techniques (such as the need to use cutters and drills or moulds).[15] The production of prototypes is faster and at lower cost, since there is no waste of material; the production process becomes more sustainable, with benefits for the environment.[15]

Today, dentists can print various devices for surgical,[16] prosthodontic[17] and orthodontic[18] applications. In surgery, dentists can 3D print resin guides for the placement of dental implants in the proper position, depth and inclination;[8,16,19] custom titanium meshes[20] for use in regenerative bone procedures; and custom-made implants.[21] In prosthesis, it is possible to print study and precision models for the restoration of natural teeth and implants;[22] prosthetic restorations such as crowns and bridges, both in resin[23] and more recently in zirconia;[24] and frameworks and test structures for different applications. In orthodontics, the future includes 3D printing of aligners.[25]

Despite all these possible applications, the knowledge of 3D printing in dentistry is still poor, as is the scientific literature supporting these applications. Further evidence is needed, because the different manufacturers of 3D printers propose various solutions, and for the dentist it is difficult to choose correctly.[14,15]

A first and necessary distinction should be made based on production technology and the materials used, because the world of 3D printing is extremely varied. Leaving aside the industrial applications (such as laser sintering)[21] that work with metals, the most important technologies of desktop 3D printers, using resins, are stereolithography (SLA) and digital light processing (DLP).[14,15,26,27] These production techniques were devised respectively in 1986 by Charles "Chuck" Hull and in 1987 by Larry Hornbeck.[27] In SLA, a laser beam is projected onto the tray containing the resin to be cured; it is guided by mirrors and lenses to the coordinates required.[27] The mechanism is simple: the laser spot treats the resin only where it is needed, leaving liquid that does not have to solidify, according to the printing project.[27] In DLP, on the other hand, a projector emits light towards the resin tank; in this case, the light is directed onto the resin through a digital micromirror device (DMD).[27] The DMD is a complex system of micro-mirrors in aluminium, each of which can direct a pixel of polymerising light onto the resin to cure it. In practice, the DMD is a precise system that directs the light where necessary, and away from the points that should not be treated.[27] In fact, the movement of these tiny mirrors (maximum 10–12°) determines their ability to "switch on" or "off" the light, according to a binary code.[27] Thus, if the mirror is in the on position, the light pixel will be projected onto the tank and cure the resin in it; if "off", it will be diverted onto an absorbent surface.[15,27]

DLP (including its liquid crystal display- LCD variant, in which a monitor projects an entire image directly onto the resin tank) is potentially faster than SLA, because it shoots enough light to create one layer at a time; the laser spot instead has to move horizontally to complete a layer.[15,27] Speed is important, especially for a large dental laboratory that needs to produce several models per day; however, it has nothing to do with accuracy.[27,28] The resolution of acquisition (on the Z and XY axes) should also not be confused with accuracy. For both SLA and DLP, the resolution of acquisition on the Z axis could be defined as the minimum possible translation or advancement in Z; in reality, this does not coincide with the minimum layer thickness, because the material used is an important variable that affects the final accuracy.[27,28] With regard to the XY resolution of acquisition, for both SLA and DLP printers, it is appropriate to address the minimum size of the light source. In SLA printers, the minimum size of the light source is the laser spot; in DLP printers, it is given by the size of the micro-mirrors.[27,28] Ideally, the smallest size of the light source should match the minimum printable size; once again, however, it is necessary to consider the variable given by the materials in use.[27,28] Ultimately, considering the "accuracy" of a 3D printer can be a mistake: the term "accurate" better refers to the printed objects (models, crowns, bridges or surgical guides). The material used plays an important role: 3D printers use several resins, and there are differences between the different materials. In addition, a multitude of other factors can affect the accuracy of the printed objects. These include the physics of light and its propagation, the chemistry of resins and their polymerisation, the electronics of the panels (DLP and LCD) or laser (SLA), the lenses and mirrors, the mechanical advancement and/or rotation of the system, and the software – the true "harmoniser" of processes.[14,15,27,28] This explains why determining the accuracy of printing processes is difficult.

To date, little is known about the accuracy of the different SLA and DLP 3D printers that are currently available in the dental market.[15,26-32] Therefore, the purpose of this *in vitro* study was to compare the accuracy of 6 different desktop 3D printers that use these two technologies, and which are now available on the dental market.

MATERIALS AND METHODS

STUDY DESIGN

A parallelepiped (PP) of known shape, geometry and dimensions (L1 = 30 mm, L2 = 40 mm, L3 = 10 mm), with 3 holes of different diameters (D1 = 1.998 mm, D2 = 2.998 mm, D3 = 3.998 mm) in the centre (*Figure 1*), was designed in 3D-modelling software (Rhinoceros®) then printed with 6 different desktop 3D printers (Sheraprint 40®; Solflex 350®; Form 2®; MoonRay D75®; Vida HD®; XFAB 2000®; *Table 1*). For each printer, 9 PPs were printed in three different printing processes, using the proprietary material and with the layer thickness indicated by the manufacturer for the fabrication of DMs. The models

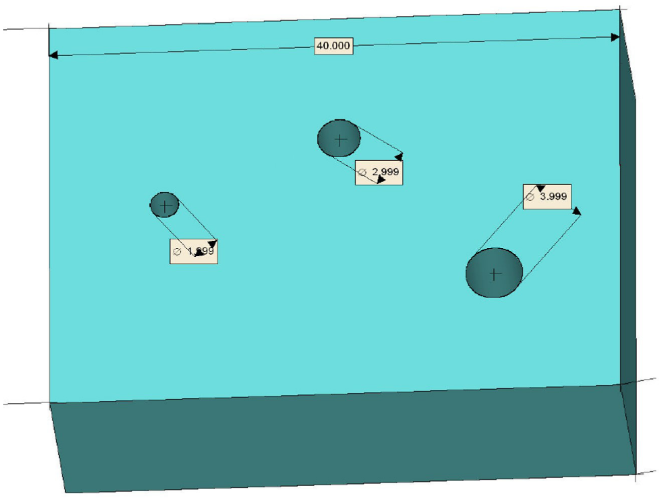

Figure 1: Reference file of a parallelepiped (PP), as designed in a computer-assisted-design (CAD) software (Rhinoceros®). The linear dimensions (L1 = 30 mm, L2 = 40 mm, L3 = 10 mm) of the PP walls were known, as well as the diameters of the three different holes (D1 = 1.998 mm; D2 = 2.998 mm; D3 = 3.998 mm, respectively) that were designed inside the solid.

were printed adhering to the printing area, without supports of any kind, and placed in three different positions of the printing plate (left, right and centre). Once the models were printed, no curing (polymerisation) was done: they were washed, placed in a dark box away from heat or light, and immediately delivered to the measuring centre (CAD4D srl®) to undergo dimensional analysis with optical microscopy and precision probing. The measurement system used was optical and tactile, using a microscope (QVI Smartscope Flash 200®) for 33x optical measurement and a precision probing system (Renishaw R 0.25®) with certified calibration tolerance of 0.0013 mm.

Measurements were made in two sessions. The first session included volumetric analysis of the side–side distance (30 nominal X and 40 nominal Y) and measurement of the 3 hole diameters (performed through optical sampling at 33x). Detection was performed using a repeated analysis program for all 54 samples provided: operations were performed several times and the best data of the repeated readings were collected, in order to discard the poorest data. The second session included analysis to evaluate the distortion in X and Y of each hole (performed using a Renishaw R. 0.25® mm tip). Again, detection was performed using a repeated analysis program for all 54 samples provided. The data collected during these two different measurement sessions were collected in two different Excel® spreadsheets and sent to the statistician for analysis.

To complete the study, a generic stereolithographic (STL) file was selected from a library of clinical cases, representative of a model of a maxilla after orthodontic treatment. This virtual model, as a reference, was printed with all 6 desktop 3D printers. For each of the printers, 3 models were printed with the proprietary material and the layer thickness indicated by the manufacturer for printing DMs, in one single printing process (*Figure 2*). Once again, the models were printed adhering to the printing area, without any kind of support, and placed in 3 different printing area positions (left, right and centre). The models were removed from the printer, washed as prescribed by the manufacturer, and then cured or polymerised. Then,

Table 1. Main characteristics of the 6 desktop 3D printers compared in the study.

3D printer	Technology	Footprint	Weight	Build envelope	Layer thickness	Specification
Sheraprint 40®, Shera, Lemforde, Germany	DLP (UV LED 385 nm)	480 x 690 x 410 mm	42 kg	2 x 130 x 75 mm (double construction area)	50- 100 µm	Projector resolution 1920 x 1080 pixels
Solflex 350®, Voco, Cuxhaven, Germany	DLP (UV LED 385 nm)	400 x 400 x 545 mm	20 kg	64 x 120 x 130 mm	25- 200 µm	Projector resolution 1280 x 2400 pixels
Form2®, Formlabs, Sommerville, MA, USA	SLA (UV laser 405 nm, 250 mW)	350 x 330 x 520 mm	13 kg	145 x 145 x 175 mm	25- 50- 100 µm	Laser spot 140 µm
Vida HD®, Envisiontec, Gladbeck, Germany	DLP (industrial UV light)	395 x 350 x 787 mm	34 kg	96 x 54 x 100 mm	25- 150 µm	Projector resolution 1920x1080 pixels
XFAB 2000®, DWS Systems, Thiene, Vicenza, Italy	SLA	400 x 606 x 642 mm	50 kg	180 x 180 x 180 mm	60- 100 µm	Laser spot 60 µm
MOONRAY D75®, Sprintray Inc., Los Angeles, CA, USA	DLP (UV LED Light Engine 405 nm)	380 x 380 x 500 mm	14 kg	96 x 60 x 200 mm	20- 50- 100 µm	Projector resolution 1920x1080 pixels

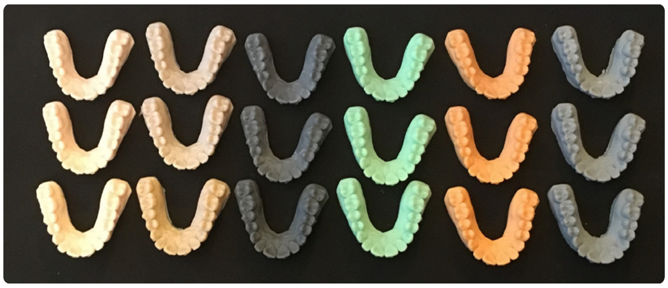

Figure 2: For each printer, 3 dentate models (DMs) were printed with the material indicated by the producer. These DMs were cured and kept for a period of 1 month in a dark box, away from any heat source; after this period of time, they were scanned with a desktop scanner (Freedom UHD®). The standard tessellation language (STL) files obtained from this process were then imported into a reverse engineering software (Studio 2012®) and superimposed on the original reference model, to investigate trueness and stability over time.

they were placed inside a dark box, away from any heat sources, and left for 1 month. This period was chosen to evaluate the volumetric stability and therefore the reliability of the models over time.

A month later, each of the models was scanned using a powerful desktop scanner (Freedom UHD®) with a certified accuracy of 5 µm. The STL files thus obtained were imported into a powerful reverse engineering software program (Studio 2012®) and superimposed here on the original orthodontic model file, to verify the trueness of the models 1 month after printing with the various 3D printers. The superimposition process consisted of three steps. First, a rough point-by-point alignment was manually performed, using landmarks on the dentate surface of the models. Then, after this rough alignment was completed, the best fit algorithm of the software was launched for surface alignment. The parameters set for superimposition were a minimum of 100 iterations per case, and the surface registration was made by a robust iterative closest point algorithm. The distances between the printed models and the reference model were minimised using a point-to-plane method, and congruence between specific corresponding structures was calculated. Using this algorithm, the mean ± SD of the distances between the two superimposed models was calculated. The software generated a colorimetric map for immediate visualisation of the results. This colorimetric map quantified the distances between the specific points, in all space planes. The colour maps indicated inward/contraction (blue) or outward/expansion (red) displacement between overlaid structures, or minimal change (green). The colorimetric map was set from a maximum deviation of +100 and -100 µm, with the best result given by the deviations $-30 < x < +30$ µm (displayed in green).

STATISTICAL ANALYSIS

Statistical analysis was performed with SPSS® 20. Mean and SD of the tree sample dimensions of all the groups (L1, L2 and D1, D2, D3) were calculated according to the printer type. The amplitude was generated by measuring the delta between the lesser value and the larger one for the linear evaluation (L1, L2) for each sample; thus, the average and the standard deviation were calculated, representing the ability of the printer to generate constant results. The average error for each group was measured by subtracting the average values of the tree measurements from the quoted project size. Average error box plots were drawn in order to compare the different printer performances. Correlations between the average error and the amplitude with each printer was assessed for each group (L1, L2 and D1, D2, D3) by the non-parametric test of Kruskal–Wallis to analyse the differences among the group means, with a significance level set at 0.05 and a confidence interval (CI) set at 95%. The non-parametric test was chosen due to the small sample size, to determine whether the differences among the printer performances were significant or not. Finally, means (± SD, median, CI 95%) were calculated for the trueness of DMs, 1 month after printing.

RESULTS

Overall, dimensional analysis by optical microscopy and precision probing highlighted the reliability of the 3D printed models, with acceptable errors, compatible with clinical use in different fields (orthodontics, surgery and prosthodontics). However, the results revealed significant differences between the 3D printers in all measurement comparisons *(Tables 2, 3, 4)*. In fact, linear measurements revealed a significant quantitative difference between the printers *(Table 2, Figure 3)*, setting the best performances for XFAB 2000® and Form 2® (L1) and Vida HD® and Form 2® (L2). In linear measurements, increased linear deviation was present additively in the models from the MoonRay D75® and Sheraprint 40®, and subtractively in the model from the Solflex 350®. The variance of the samples, referring to the amplitude of the results between the 9 measured samples, was higher with the MoonRay D75® at both L1 and L2, giving the poorest repeatability in results *(Table 3, Figure 4)*. Conversely, the best performances were by the Solflex 350® and Form 2® (L1) and Form 2® and XFAB 2000® (L2). With regard to diameters, the best performances were by the Form 2® and Solflex 350® (D1), Form 2® and MoonRay D75® (D2) and Form 2® and XFAB 2000® (D3). Once again, statistically significant differences were found between the different machines, even if the ability to make holes with precise diameters provided less variability *(Table 4, Figure 5)*. The trueness of the models 1 month after printing was low *(Table 5, Figure 6)*, suggesting that all the 3D printed models underwent a dimensional contraction over time, albeit with differences between the different printers.

DISCUSSION

To date, few studies have attempted to investigate the accuracy of 3D printed models, or to compare different printers.[17,22,26,29-31]

Table 2. Mean error (± SD), in mm, generated by the different 3D printers at each linear measurements test. Kruskal-Wallis correlation is given at 95% CI and is set as significant when p ≤0.005. Significant differences are evidenced between the printers performances at both evaluations.

Linear measurements

Printer	L1 Error Mean (± SD)	L2 Error Mean (± SD)
Sheraprint 40®	0.159 (± 0.021)	0.139 (± 0.031)
Solflex 350®	-0.095 (± 0.037)	-0.140 (± 0.041)
Form 2®	0.055* (± 0.093)	0.127* (± 0.052)
Moonray D75®	0.281 (± 0.091)	0.354 (± 0.038)
Vida HD®	0.114 (± 0.011)	0.079* (± 0.012)
XFAB 2000®	-0.021* (± 0.049)	0.155 (± 0.184)
Sig.	≤ 0.001	≤ 0.001

* best performances

Table 3. Average amplitude of results (± SD), in mm, generated by the different 3D printers at L1 and L2 measures, in mm. Kruskal-Wallis correlation is given at 95% CI and is set as significant when p ≤ 0.05. Significant differences are evidenced between the printers performances at both evaluations.

Amplitude

Printer	L1 Error Mean (± SD)	L2 Error Mean (± SD)
Sheraprint 40®	0.114 (± 0.015)	0.132 (± 0.047)
Solflex 350®	0.048* (± 0.01)	0.12 (± 0.013)
Form 2®	0.06* (± 0.014)	0.046* (± 0.003)
Moonray D75®	0.123 (± 0.024)	0.122 (± 0.061)
Vida HD®	0.129 (± 0.024)	0.077 (± 0.013)
XFAB 2000®	0.126 (± 0.053)	0.058* (± 0.012)
Sig.	≤ 0.001	≤ 0.001

* best performances

Table 4. Mean error (± SD), in mm, generated by the different 3D printers at each diameter-related test. Kruskal-Wallis correlation is given at 95% CI and is set as significant when p ≤ 0.05. Significant differences are evidenced between the printers performances at both evaluations.

Diameter measurements

Printer	D1 Error Mean (± SD)	D2 Error Mean (± SD)	D3 Error Mean (± SD)
Sheraprint 40®	-0.101 (± 0.095)	-0.025 (± 0.121)	-0.074 (± 0.051)
Solflex 350®	-0.060* (± 0.016)	-0.081 (± 0.05)	-0.077 (± 0.012)
Form 2®	-0.011* (± 0.018)	0.009* (± 0.056)	-0.02* (± 0.07)
Moonray D75®	0.061 (± 0.011)	0.009* (± 0.026)	-0.078 (± 0.027)
Vida HD®	-0.115 (± 0.032)	-0.107 (± 0.002)	-0.083 (± 0.044)
XFAB 2000®	0.141 (± 0.007)	-0.093 (± 0.054)	-0.056* (± 0.018)
Sig.	≤ 0.001	0.001	≤ 0.001

* best performances

Park *et al.*[22] compared the accuracy and reproducibility of dental casts made by the conventional method and by 3D printing. A master model was designed and fabricated with polyetherketoneketone. Ten specimens were fabricated with type IV dental stone with polyvinyl siloxane.[22] A light scanner was used to scan the master model, and the data were converted to STL files. Three different types of 3D printers (Objet Eden260V®, ProMaker D35® and LC-3Dprint®) were used to make 10 specimens each.[22] All specimens were scanned by the light scanner, and the scanned files were superimposed on the files of the master model with specialised software to analyse the volumetric changes. The volumetric changes in casts made by the conventional method and by the 3D printers were significantly different.[22] The conventional casts showed smaller volumetric change than the 3D printed casts. Significant differences (p<0.05) were found among the different types of 3D printers. The ultraviolet-polymerising polymer with DLP exhibited the smallest volumetric change.[22]

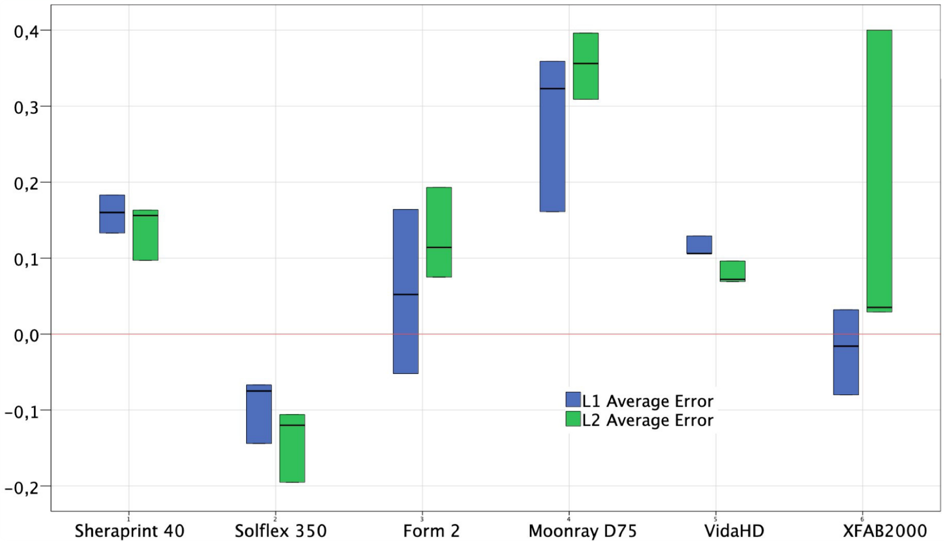

Figure 3: Box plot showing the average error of the linear measures (L1 and L2) according to different 3D printers.

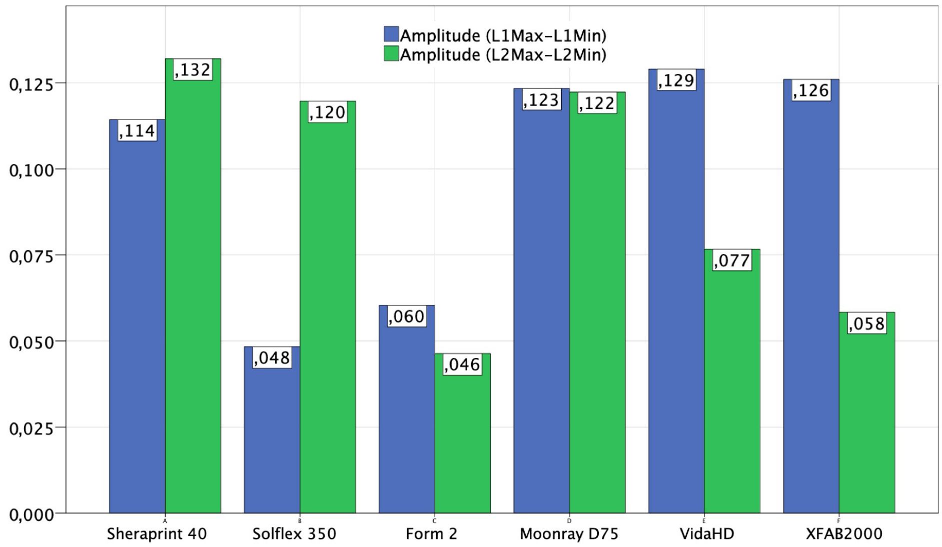

Figure 4: The average amplitude is compared between the different tested 3D printers, in mm. It was generated measuring the delta between the lesser value and the bigger one for the linear evaluations (L1, L2) per each sample, thus the average was calculated.

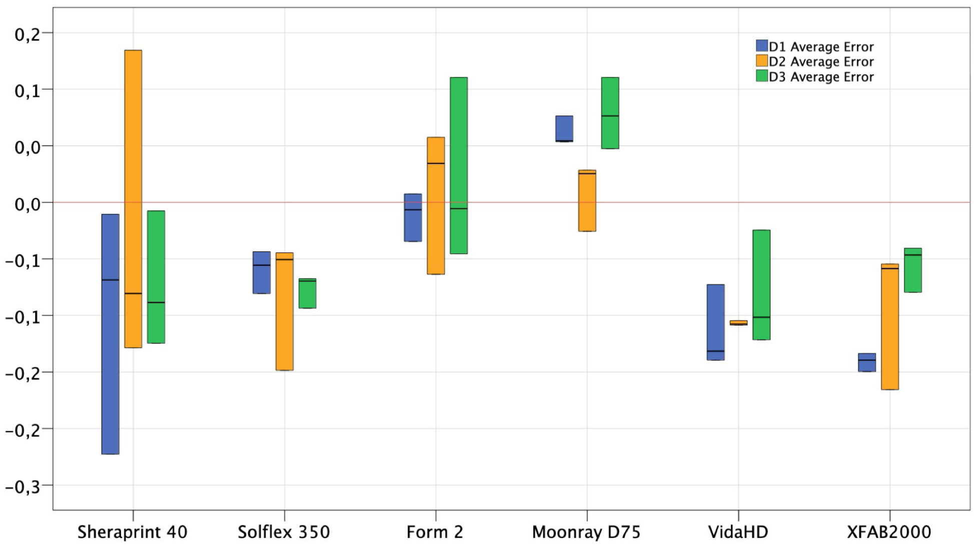

Figure 5: Box plot showing the average error of the diameter measurements according to different 3D printers at D1, D2 and D3.

Table 5. Mean trueness (± SD), in mm, of the different 3D models 1 month after printing. In order to evaluate trueness, the models were cured and then stored for a period of 1 month inside a dark box away from any heat sources; then, they were scanned with a powerful desktop scanner (Freedom UHD®). The .STL files thus obtained were imported into a powerful reverse engineering software (Studio 2012®) and superimposed on the original reference file, in order to verify the trueness.

Trueness of the models 2 months after printing

Printer	Sample 1 (left) mean (± SD)	Sample 2 (center) mean (± SD)	Sample 3 (right) mean (± SD)	Overall mean (± SD)
Sheraprint 40®	-0.081 (± 0.085)	-0.073 (± 0.079)	-0.094 (± 0.099)	-0.082 (± 0.010)
Solflex 350®	-0.088 (± 0.089)	-0.079 (± 0.085)	-0.095 (±0.095)	-0.087 (± 0.008)
Form 2®	-0.078 (± 0.094)	-0.066* (± 0.082)	-0.086 (± 0.097)	-0.076 (± 0.010)*
Moonray D75®	-0.125 (± 0.119)	-0.117 (± 0.103)	-0.126 (± 0.109)	-0.122 (± 0.004)
Vida HD®	-0.056 (± 0.079)	-0.052* (± 0.083)	-0.064 (± 0.089)	-0.057 (± 0.006)*
XFAB 2000®	-0.095 (± 0.081)	-0.090 (± 0.082)	-0.099 (± 0.079)	-0.094 (± 0.004)

* best performances

In 3D colour maps, the deformations were in similar patterns for all the 3D printers. The conventional method of die fabrication was more reliable than that of 3D printers.[22]

Rungrojwittayakul *et al.*[17] evaluated the accuracy of 3D-printed models manufactured using two different printer technologies (Continuous Liquid Interface Production [CLIP] and DLP) with different model base designs (solid or hollow). A typodont was scanned with a desktop scanner to capture a reference STL file, which was exported to CAD software to design two different model bases: solid and hollow.[17] Then, 40 models were printed with two different printers (the Carbon M2®, a CLIP printer; and the MoonRay S100®, a DLP) with different base configurations: 10 CLIP with solid base, 10 CLIP with hollow base, 10 DLP with solid base and 10 DLP with hollow base.[17] All the 3D printed models were scanned with the same desktop scanner and superimposed to the reference model using reverse engineering software to evaluate the deviations. At the end of the study, the accuracy of 3D printed models was affected by the printer technology, rather than by the model base.[17] In fact, although the deviations were clinically acceptable and less than 100 μm different from the reference model, the CLIP technology produced significantly fewer variations than the DLP.[17]

Zhang *et al.*[29] compared the accuracy of models printed with 4 desktop machines with different thickness layers: three DLP (EvoDent®, with thicknesses of 50 and 100 μm; EncaDent®, with thicknesses of 20, 30, 50 and 100 μm; Vida HD®, with thicknesses of 50 and 100 μm) and one SLA (Form 2®, with

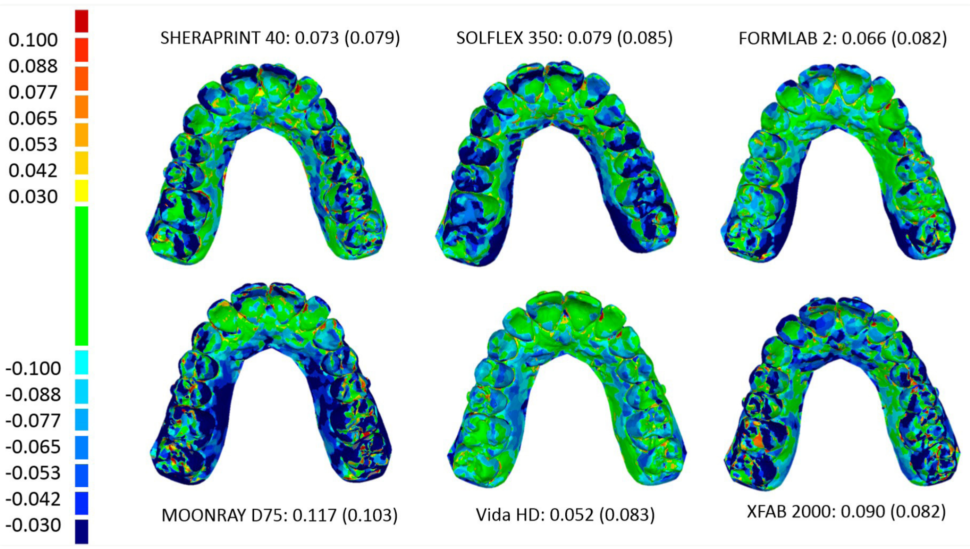

Figure 6: Mean trueness (± SD), in mm, of the different 3D models 1 month after printing: best results obtained with each printer.

layer thicknesses of 25, 50 and 100 µm). The 22 printed models were virtualised using a desktop scanner (D2000®) and compared three-dimensionally to the source files using reverse engineering software.[29] The authors found a higher printing accuracy at 50 µm.[29] When the layer thickness was set at 100 µm, the speed and accuracy of DLP printers were higher than those of the SLA printer. The EvoDent® 50 µm had the highest consistency with the source files (mean absolute deviation of 0.0233 mm in the maxilla and 0.0301 mm in the mandible), whereas the accuracy of the Form 2® 100 µm group was the lowest (mean absolute deviation of 0.0511 mm in the maxilla and 0.0570 mm in the mandible).[29]

Kim *et al.*[30] assessed the trueness and precision of dental models printed with different techniques: SLA, DLP, fused filament fabrication (FFF) and polyjet (PJ). The machines used were the Zenith® (SLA), M-One® (DLP), Cubicon 3DP-110F® (FFF) and Object Eden 260VS® (PJ).[30] Reference virtual models were fabricated with the different printing techniques and the printed models were scanned and evaluated for tooth, arch and occlusion measurements.[30] The 3D printing techniques showed significant differences in precision of all measurements and in trueness of tooth and arch measurements.[30] The DLP and PJ techniques were more precise than the FFF and SLA techniques, and the PJ exhibited the highest accuracy.[30]

In another study,[31] 12 orthodontic plaster casts were digitised, and printed using three different techniques: fuse deposition modelling (FDM), SLA and PJ. The printers used were the Makerbot Replicator® (FDM), SLA 6000® 3D Systems (SLA) and Objet Eden500V® (PJ).[31] Then, measurements were taken with a digital calliper of the plaster models and 3D printed models. Comparison between the plaster casts and 3D printed models showed no statistically significant differences in most of the parameters; however, the FDM had the fewest dimensional measurement differences compared to plaster models. [31]

Our results seem to confirm that there can be statistically significant differences in the accuracy of models produced with different 3D printers. In our present study, a PP of known dimensions (L1 = 30 mm, L2 = 40 mm,) with 3 holes of different diameters (D1 = 1.998 mm, D2 = 2.998 mm, D3 = 3.998 mm), was designed in CAD and printed with 6 desktop 3D printers (Sheraprint 40®, Solflex 350®, Form 2®, MoonRay D75®, Vida HD®, XFAB 2000®). For each printer, 9 samples were printed, with the proprietary material and layer thickness indicated for dental models. The PPs were printed adherent to the printing plate, without support; they were not cured and, to measure the intrinsic accuracy of the printing process, they underwent dimensional analysis by optical microscopy and precision probing. At the end of our evaluation, the best performances in linear measurements were by the SLA 3D printers, XFAB2000® (L1: -0.021 ± 0.049 mm; L2: 0.155 ± 0.184 mm) and Form2® (L1: 0.055 ± 0.093 mm; L2: 0.127 ± 0.052 mm), followed, among the DLP printers, by the Vida HD® (L1: 0.114 ± 0.011 mm; L2: 0.079 ± 0.012 mm) and Solflex 350® (L1: -0.095 ± 0.037 mm; L2: -0.140 ± 0.041 mm). This may be surprising, since the SLA printers examined here were considered to be "entry level", by characteristics and price (they were the cheapest machines investigated in this study). DWS Systems has at present more powerful machines in its portfolio, such as the XFAB 2500®, or at the highest quality, XFAB 3500PD®; Formlabs has recently developed a new printer (Form 3®) based on different working principles. However, considering the construction principle of SLA printers, it is not surprising that the accuracy can be high, even when using entry-level machines: the laser, equipped with a very small spot, moves on the XY axis and cures the resin point-to-point, faithfully replicating all details.[15,28] However, the results of our present study are not easy to interpret, because the desktop 3D printers examined here performed differently in terms of accuracy in the different applications (L1, L2 and D1, D2, D3). In fact, with regard to diameters, the best performances were by the Form 2® and Solflex 350® (D1), Form 2® and MoonRay D75® (D2), and Form 2® and XFAB 2000®; again, a statistically significant difference was found among the different machines, even if the ability to make holes with precise diameter provided less variability. In our present study, the models were printed without supports, and with the thickness layer suggested by the manufacturer; moreover, they were not polymerised, in order to assess the intrinsic accuracy of the production process.

The type of supports used and in particular the layer thickness are factors of great importance, which can influence the accuracy of 3D printed models.[32,33] In a recent study, Arnold *et al.*[32] found that the layer height, as well as the type and number of support structures, can influence the surface roughness of printed models, whereas positioning, structure and alignment cannot. These results confirmed those of Favero *et al.*[33], who reported that print layer height and model can affect the accuracy of 3D printed orthodontic models. Another parameter that can have some influence on the final accuracy of 3D printed models is the printing direction,[34] as may the sterilisation process.[35]

In our present study, however, all the printed models had a sufficient degree of accuracy for clinical use in different applications (orthodontics, surgery and prosthodontics, with the possible exception of implant prosthodontics where digital analogues have to be manually inserted into 3D printed models). In fact, the literature has anticipated that maximum accuracy is not always necessary for successful clinical use.[36-38] Loflin *et al.*[36] demonstrated that 100-µm layer height 3D printed models were clinically acceptable in orthodontics for the purposes of diagnosis, treatment planning, evaluation of treatment outcomes and residency training. These findings have been confirmed in several other studies.[37,38] Application in surgery and prosthetics is certainly possible.[14,15,27] However, the accuracy of conventional plaster models has proven superior to that of 3D printed models in several studies.[39-42] In particular, high accuracy seems to be required in the printing of models for implant prosthodontics, with some studies[40,43] reporting difficulties in the correct insertion of digital analogues with 3D printed models.

Another limit in the use of 3D printed models is in their dimensional stability over time.[14] In our present work, an STL file representative of a DM was printed with the 6 3D printers. For each printer, 3 DMs were printed with the material and layer thickness indicated by the manufacturer, without supports, adhering to the printing area, in 3 different positions (left, right and centre). The DMs were washed and placed in a container in the dark to prevent distortion due to UV and temperature. After 1 month, all 3D printed models were scanned with a desktop scanner. The STL files obtained underwent examination by reverse engineering software, where they were superimposed on the virtual reference model to investigate trueness. At the end of the evaluation, the trueness of the models 1 month after printing was rather low, suggesting that they underwent a dimensional contraction over time, albeit with differences between the different printers. The data should be interpreted with caution, due to the limited number of samples investigated. Nevertheless, these results provide some general indications of the accuracy of the different printers over time.

Finally, the present study has limitations: it is only an *in vitro* study, comparing few printers and with a small number of samples. Further studies on a greater number of samples, and aimed at specific applications, are certainly necessary to draw more precise conclusions on the accuracy of 3D printers in dentistry.

CONCLUSIONS

In the present comparative *in vitro* study, the models printed by 6 desktop 3D printers showed acceptable accuracy, demonstrated by dimensional analysis with optical microscopy and precision probing. Acceptable errors were found, compatible with clinical use, although both linear and diameter measurements revealed statistically significant differences between the machines. However, the trueness of the models 1 month after printing was low, suggesting that 3D printed models may undergo some dimensional contraction over time. Further studies are needed to investigate this topic.

ACKNOWLEDGMENTS

The authors are grateful to CAD4D srl®, Flero, Brescia, Italy, for all the precision measurements provided for this study.

MANUFACTURERS' DETAILS

- Sheraprint 40®, Shera, Lemforde, Germany
- Solflex 350®, Voco, Cuxhaven, Germany
- Form 2®, Formlabs, Somerville, MA, USA
- Moonray D75®, Sprintray, Los Angeles, CA, USA
- Vida HD®, Envisiontec, Gladbeck, Germany
- XFAB 2000®, DWS Systems , Thiene, Italy
- Rhinoceros®, Robert MCNell & Associates, Seattle, WA, USA
- CAD4D srl®, Flero, Brescia, Italy
- QVI Smartscope Flash 200®, OGP, Rochester, NY, USA
- Renishaw R 0.25®, Wotton-under-Edge, Glouchestershire, UK
- Excel®, Microsoft, Redmond, WA, USA
- Freedom UHD®, Dof, Seoul, South Korea
- Studio 2012®, Geomagics, Morrisville, NC, USA
- SPSS® 20, SPSS Inc, Chicago, IL, USA
- Objet Eden260V®, Stratasys, Eden Prairie, MN, USA
- ProMaker D35®, Prodways, Les Mureaux, France
- LC-3Dprint®, Nexdent, Soesterberg, Nederlands
- Carbon M2®, Carbon 3D, Redwood City, San Francisco, CA USA
- MoonRay S100®, SprintRay, Los Angeles, CA, USA
- EvoDent®, UnionTec, Shanghai, China
- EncaDent®, Encashape, WuXi, China
- D2000®, 3 Shape, Copenhagen, Denmark
- Zenith®, Dentis, Daegu, Korea
- M-One®; MAKEX Technology, Zhejiang, China,
- Cubicon 3DP-110F®, HyVISION System, Sungnam City, Korea
- Objet Eden 260VS®, Stratasys, Eden Prairie, MN, USA
- Makerbot Replicator®, New York, NJ, USA
- SLA 6000®, 3D Systems, Rock Hill, SC, USA
- Objet Eden500V®, Stratasys, Eden Prairie, MN, USA
- XFAB 2500®, DWS Systems , Thiene, Italy
- XFAB 3500PD®, DWS Systems , Thiene, Italy
- Form 3®, Formlabs, Somerville, MA, USA

ABBREVIATIONS

3D: three dimensional; PP: parallelepiped; DM: dentate models; CBCT: cone beam computed tomography; CAD: computer-assisted-design; SLA: stereolithography; DLP: digital light processing; STL: standard tessellation language; SD: standard deviation; CI: confidence interval; DMD: digital micromirror device; LCD: liquid crystal display; CLIP: Continuous Liquid Interface Production; FFF: fused filament fabrication; PJ: polyjet; FDM: fuse deposition modelling.

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