ORIGINAL SCIENTIFIC ARTICLE

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Influence of print layer height and printing material on model accuracy and precision: A 3D surface comparison of models printed using fused filament fabrication

KEY WORDS *3D printing, 3D superimposition, digital light processing, fused filament fabrication, orthodontic models*

Objectives: *To investigate the effect of layer height on the accuracy of orthodontic models utilising fused filament fabrication, particularly with regard to optimising in-office aligner manufacture. The suitability of fused filament fabrication was assessed by comparing the results to a high precision digital light processing control group.*

Materials and methods: *Based on a digital sectioned maxillary model, 18 physical models were printed using fused filament fabrication technology at different layer heights (50.0 µm, 80.9 µm, 100.0 µm, 150.0 µm, 160.8 µm, 200.0 µm, 250.0 µm, 300.0 µm and 332.6 µm) using two different materials (polylactide PLA NX2 and lignin-based polymer Green-TEC PRO [Extrudr, Lauterach, Austria]). Two DLP models with a layer height of 20.0 µm were produced, representing the control group. Subsequently, all physical models were digitally scanned and compared via 3D superimposition using GOM Inspect software (GOM, Braunschweig, Germany).*

Results: *The Dahlberg analysis and intraobserver intraclass correlation proved the accuracy of the 3D superimposition measurement to be excellent and repeatable. Models printed using fused filament fabrication technology from lignin-based polymer within the range of 100.0 to 332.6 µm decreased in precision as layer height increased. Furthermore, the analysis recorded declining precision of fused filament fabrication models below 100.0 µm. Models printed using lignin-based polymer were superior in precision compared to those made from polylactide.*

Conclusions: *The accuracy and precision of fused filament fabrication models can be regulated by altering layer height; however, other parameters such as optimised printing material and print settings are necessary for consistent high quality. As such, fused filament fabrication printing is an accurate, cost-effective and sustainable technology to create aligner models in orthodontic practice.*

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Introduction

As a result of the rapid technological advances that have taken place over recent decades, 3D printing is now a viable option in orthodontic practice. The symbiosis of intraoral scanning, virtual planning and appliance manufacturing offered by this technology allows for a complete digital in-office workflow.

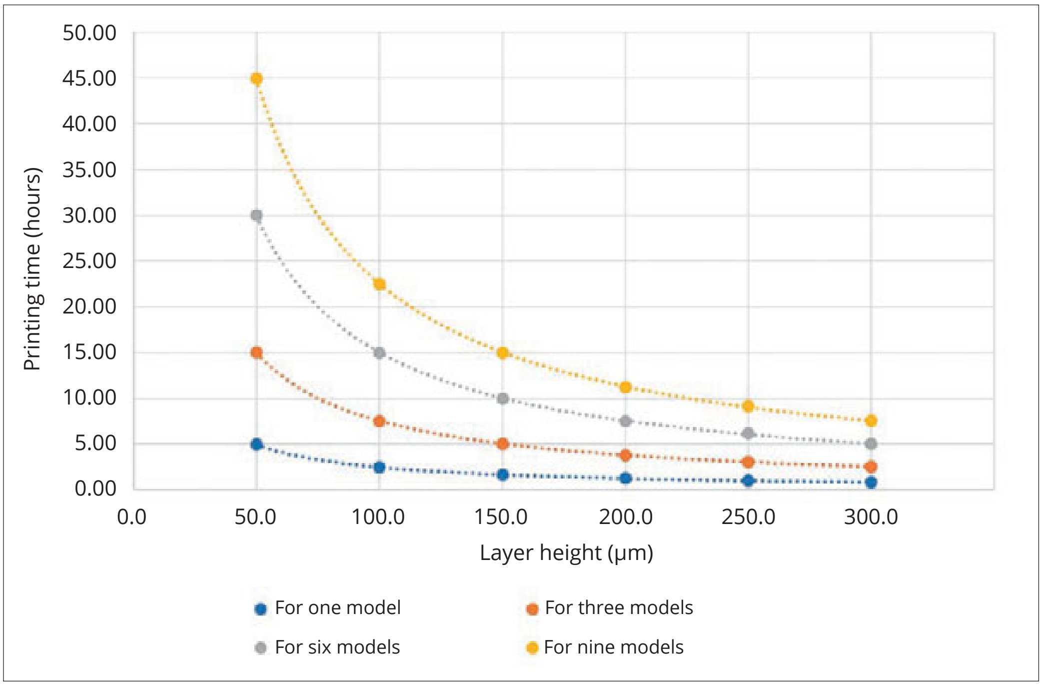

Fig 1 Printing time according to layer height.

Table 1 Simulation of printing times in relation to Z-resolution for the TEVO Tornado FFF printer

Layer height (μm)	Printing time for one model	Printing time for nine models
50.0	4 h 55 min	44 h 58 min
100.0	2 h 27 min	22 h 28 min
150.0	1 h 38 min	14 h 58 min
200.0	1 h 14 min	11 h 14 min
250.0	1 h 0 min	9 h 10 min
300.0	49 min	7 h 31 min

The origins of rapid prototyping date back to 1981 when the Japanese automobile designer Hideo Kodama invented an additive technology using ultraviolet light to cure polymers layer by layer. In 1986, Charles Hull established the first 3D printer utilising stereolithography (SLA). This was followed by the development of digital light processing (DLP) by Larry Hornbeck in 1987, fused filament fabrication (FFF) by Scott Crump in 1988, and the concept of inkjet-based 3D printing, also known as PolyJet photopolymer printing (PPP), in 1998[1].

SLA, DLP, PPP and FFF play a key role in the creation of orthodontic dental models. They mainly differ in terms of print resolution, printing speed, and the cost of the technology itself and its associated materials. Other factors include print volume, printing orientation, carbon footprint and post-processing procedures. Print resolution, which can be adjusted by altering the layer height, has been found to have a particular impact on the accuracy of dental casts[2]. Previous studies found a higher Z-resolution, which equates to a reduced layer height, to be correlated with higher accuracy of the printed object[2,3]. Interestingly, decreasing layer height leads to a higher amount of material to be printed and exponentially higher printing times (Fig 1, Table 1), resulting in higher overall modelling costs[4].

Consequently, FFF printing with as low a Z-resolution as is clinically possible is of crucial importance to enable cost-efficient in-office aligner production.

Taking into account the economic advantages and simplicity of use of FFF printers, it is surprising that numerous studies have examined the accuracy of dental models printed using SLA, DLP and PPP technology[3,5-9], whereas there is little research on FFF technology[2,4,10]. Concerning FFF printing, Kamio et al[4] utilised whole mandibles with layer heights from 200 to 500 µm, Lee et al[10] used single replica teeth with a layer height of 330 µm, and Pérez et al[2] focused on various printing parameters, working with cylindrical samples and layer heights of 150 and 250 µm.

The aims of the present study were twofold. First, the effect of Z-resolution on the accuracy of orthodontic models printed using FFF technology was examined utilising a sectioned maxillary model with layer heights ranging from 50.0 to 332.6 µm. Second, the clinical suitability of FFF printing was evaluated by comparing their accuracy to a high precision DLP control group with a layer height of 20 µm.

Materials and methods

To examine the quality of the models printed using FFF, a maxillary arch was taken from a randomly selected digital dental model and modified in OnyxCeph 3D Lab (Image Instruments, Chemnitz, Germany) by slicing at the bottom of the gingiva and distally from the maxillary right first premolar and maxillary left central incisor. Subsequently, additive attachments and a subtractive recess were added to this sectioned digital model. With the aid of the resulting master STL file (Fig 2), two identical physical models with a layer height of 20.0 µm were printed using DLP technology (SprintRay, Los Angeles, CA, USA, with die and model resin provided by the same company) (Fig 2), representing the control group. Then, 18 sectioned maxillary models were produced with FFF printing (TEVO Tornado, TEVO 3D Electronic Technology, Zhanjiang, China) with two different biopolymers: the polylactide PLA NX2 and the lignin-based polymer Green-TEC PRO (Extrudr, Lauterach, Austria) (Fig 2), each divided into nine different groups: 50.0 µm, 80.9 µm, 100.0 µm, 150.0 µm, 161.8 µm, 200.0 µm, 250.0 µm, 300.0 µm and 332.6 µm.

All the physical maxillary models were then digitised using a 3D model scanner (S600 Arti, Zirkonzahn, Gais, Italy, resolution 10 µm) to produce stereolithography (STL) test files. Utilising GOM Inspect 2019 (GOM, Braunschweig, Germany), the test files were superimposed onto the STL master file with the aid of an automated best fit algorithm matching the two virtual models according to the characteristics of the teeth. Applying the module "Surface comparison to CAD", the accuracy was evaluated using measurement tools analysing 101671-point deviations, and also visually, using a continuous colour spectrum. Blueish nuances revealed deficiencies of the scanned model surface in comparison to the master file, whereas reddish nuances indicated an excess of scanned material and green indicated measurement agreement. With reference to previous studies[3,8,11,12], the critical threshold was set at 0.25 mm. Using the inspection tool, arithmetic mean (AM), standard deviation (SD), minimum absolute deviation and maximum absolute deviation were calculated. These values were gained by measuring the orthogonal distance between the corresponding points of the CAD polygon mesh and the point cloud of the test file. Subsequently, reports were drawn up from each 3D superimposition, including colour maps and measurement data (Figs 3 and 4). In the interest of examining the reliability of the 3D superimposition method of measurement, all the test files that originated from the models printed using FFF and lignin-based polymer were measured twice.

Statistical analysis

To evaluate the trueness of the dental models produced, the AMs of the deviation of the corresponding points of the superimposed surfaces of the test and master files were analysed. Precision was estimated by assessing the SD of the discrepancy between the compared surfaces of the files. For further evaluation, the percentage of points within the critical bounds of ± 0.25 mm and within the nominal bounds of ± 0.05 mm were analysed based on the normality of measurement points[13]. With the aid of the colour map analysis of the 3D superimposition, information was gained concerning the location and degree of deviation or congruence of the corresponding surfaces. Reliability was evaluated using SPSS Statistics (version 26 2019, IBM, Armonk, NY, USA). First, the intraclass correlation coefficient (ICC) of repeated measurements for a single observer on the basis of absolute agreement was calculated. Second, the Dahlberg error was analysed to assess variability due to technical inconsistencies.


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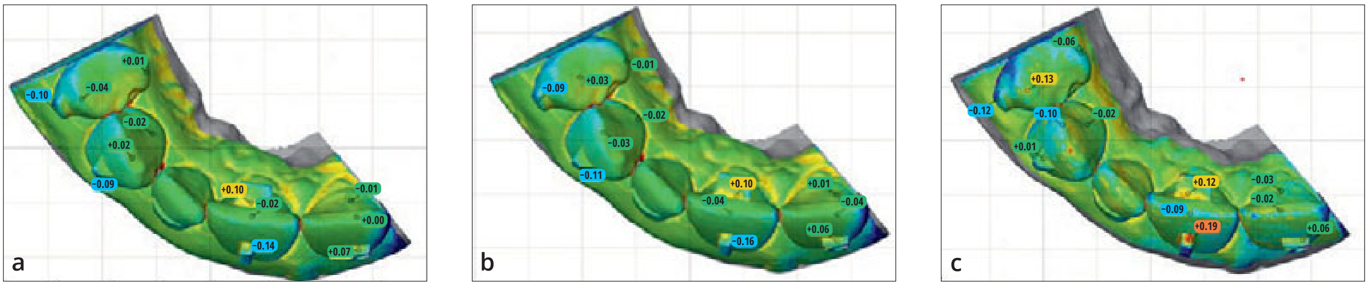
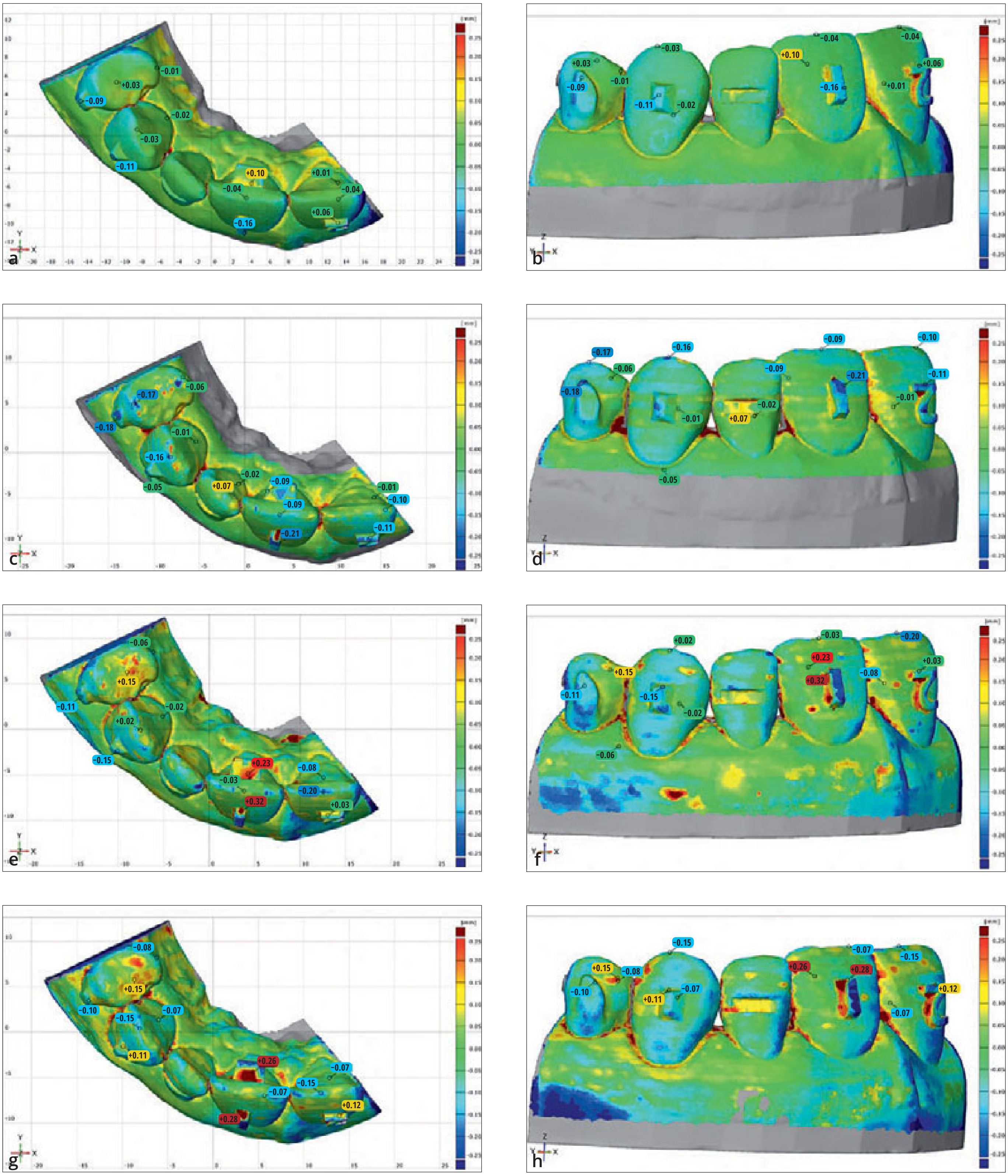
Figs 2a to x Sectioned maxillary dental model: **(a to c)** STL master file; **(d to f)** DLP control model (layer height 20.0 µm); **(g to i)** Lignin-based model (layer height 50.0 µm); **(j to l)** Polylactide model (layer height 50.0 µm); **(m to o)** Lignin-based model (layer height 150.0 µm); **(p to r)** Polylactide model (layer height 150.0 µm); **(s to u)** Lignin-based model (layer height 300.0 µm); **(v to x)** Polylactide model (layer height 300.0 µm).



Figs 3a to c 3D superimposition colour map analysis of test files and CAD reference file: **(a)** DLP control model (layer height 20.0 µm); **(b)** Lignin-based model (layer height 100.0 µm); **(c)** Polylactide model (layer height 100.0 µm).



Figs 4a to h 3D superimposition colour map analysis of FFF printed lignin-based dental model with different layer heights and CAD reference file: **(a and b)** Layer height 100.0 µm; **(c and d)** Layer height 150.0 µm; **(e and f)** Layer height 200.0 µm; **(g and h)** Layer height 250.0 µm.

Table 2 Reliability of 3D superimposition method of measurement in GOM Inspect 2019 for AM and SD

Layer height (µm)	AM measurement 1 (mm)	AM measurement 2 (mm)	SD measurement 1 (mm)	SD measurement 2 (mm)
50.0	−0.03	−0.03	0.11	0.11
80.9	−0.04	−0.04	0.10	0.10
100.0	−0.03	−0.03	0.09	0.09
150.0	−0.04	−0.04	0.10	0.10
161.8	−0.03	−0.03	0.10	0.10
200.0	−0.03	−0.02	0.12	0.11
250.0	−0.03	−0.03	0.12	0.12
300.0	−0.02	−0.02	0.12	0.12
332.6	−0.02	−0.02	0.13	0.13
Dahlberg error (mm)	0.002357		0.002357	
ICC (absolute agreement)	0.900		0.967	

Results

The reliability examination of the 3D analysis is shown in Table 2. From the values of the intraobserver ICCs (ICC AM 0.9; ICC SD 0.967), it can be stated that the applied measurement method via 3D superimposition has high reliability. Moreover, having quantified the technical measurement error by implementing the Dahlberg formula (Dahlberg error AM ≈ 0.002 mm; Dahlberg error SD ≈ 0.002 mm), the excellent suitability of 3D analysis using GOM Inspect is reinforced.

The outcome of the comparison of the 3D superimposition of test and source files is summarised in Table 3. Further statistical calculations of the percentage of points within nominal bounds for the lignin-based polymer models printed using FFF and the DLP control group are presented in Table 4.

Examining the parameters of accuracy, namely the AM, SD and percentage of points within the critical bounds, the overall differences between the experimental groups (FFF printed lignin-based polymer, FFF printed polylactide and DLP control group) were determined (Table 3).

The AM of the deviation of the corresponding points of the superimposed surfaces ranged from −0.04 to −0.01 mm in the groups that used FFF printing and from −0.02 to −0.01 mm in the DLP control group. Concerning trueness, FFF printed models seemed to have smaller overall dimensions[10], whereas those fabricated using DLP printing only had slightly smaller dimensions.

In terms of precision, the lignin-based polymer models printed using FFF displayed overall lower SDs and a higher amount of measurement points within the critical bounds of ± 0.25 mm than the polylactide models printed using FFF (Table 3, Fig 3). When compared to the DLP control group, the precision requirements were only met by lignin-based models with layer heights between 80.9 and 161.8 µm considering the SD and percentage of points within the critical bounds (> 98%). Moreover, all the lignin-based models printed using FFF, with the exception of the model with a layer height of 332.6 µm, had over 95% of points within the critical bounds, displaying a high level of consistency over a wide range of layer heights (50.0 to 300.0 µm). Interestingly, only the FFF printed polylactide model with a layer height of 250.0 µm also met these requirements.

Table 3 Measurement data for the 3D superimposition and percentage of points within the critical bounds as a function of layer height, technology and material of the dental models studied

Material/technology	Layer height (µm)	AM (mm)	SD (mm)	Points within critical bounds ± 0.25 mm (%)
Lignin-based/FFF	50.0	−0.03	0.11	97.18
	80.9	−0.04	0.10	98.02
	100.0	−0.03	0.09	99.18
	150.0	−0.04	0.10	98.02
	161.8	−0.03	0.10	98.35
	200.0	−0.03	0.12	95.65
	250.0	−0.03	0.12	95.65
	300.0	−0.02	0.12	96.04
	332.6	−0.02	0.13	94.28
Poly-lactide/FFF	50.0	−0.01	0.22	74.31
	80.9	−0.02	0.19	80.91
	100.0	−0.03	0.18	82.94
	150.0	−0.02	0.20	78.64
	161.8	−0.02	0.20	78.64
	200.0	−0.02	0.21	76.58
	250.0	−0.03	0.12	95.65
	300.0	−0.03	0.24	70.02
	332.6	−0.03	0.15	89.85
Control group/DLP	20.0	−0.01	0.10	98.58
	20.0	−0.02	0.10	98.71

Table 4 Comparison of models printed using FFF with lignin-based polymer and the DLP control group based on the percentage of points within the nominal bounds

Material/technology	Layer height (µm)	Points within nominal bounds ± 0.05 mm (%)
Lignin-based/FFF	50.0	33.87
	80.9	35.57
	100.0	40.04
	150.0	35.57
	161.8	36.74
	200.0	31.61
	250.0	31.61
	300.0	31.77
	332.6	29.64
Control group/DLP	20.0	37.59
	20.0	38.11

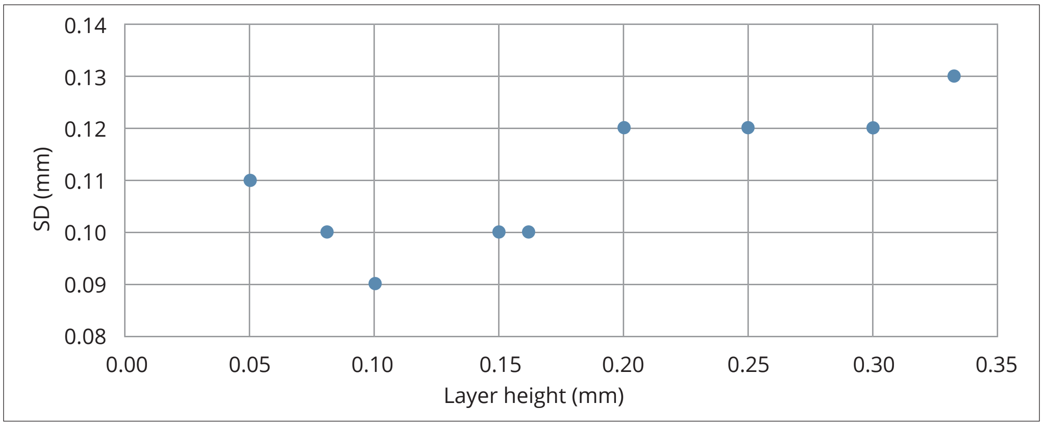


Fig 5 Relation between layer height and SD with an increase below 100.0 µm and above 100.0 µm through the example of FFF printed lignin-based models.

After examining the influence of Z-resolution in each of the experimental groups, some assumptions can be made (Table 3). In the lignin-based group, the most accurate and precise values were reached at a layer height of 100.0 µm (AM −0.03 mm; SD 0.09 mm; 99.18% of data points within the critical bounds and 40.04% within the nominal bounds), even surpassing the precision parameters of the DLP control group (Table 4). In contrast, the lowest consistency was found at a layer height of 332.6 µm (AM −0.02 mm; SD 0.13 mm; 94.28% of data points within the critical bounds). Interestingly, the best results for consistency in the FFF printed polylactide group were observed at a layer height of 250.0 µm (SD 0.12 mm, 95.65% of data points within the critical bounds), whereas polylactide models with a layer height of 300.0 µm (AM −0.03 mm, SD 0.24 mm, 70.02% of data points within the critical bounds) were the least accurate in their experimental group.

Analysing the SD independently of the layer height of the lignin-based models printed using FFF, an increase in SD was observed as layer height increased from 100.0 to 332.6 µm (Figs 4 and 5), whereas the SD decreased as layer height increased from 50.0 to 100.0 µm. Aside from the correlation between layer height and SD, a dependence was also observed between trueness and layer height in the lignin-based group, representing a slightly increasing AM with increasing layer height. In the FFF printed polylactide group, a similar relation was found between SD and layer height with the exception of layer heights of 250.0 and 332.6 µm (Table 3).

With the aid of the colour map analysis (Figs 3 and 4), the extent and location of the deviation of the corresponding surfaces of the test and source file could be explored. Greenish areas indicated an excellent match of the compared surfaces within the tolerated bounds, a transition into blue nuances indicated deficiencies or smaller dimensions of the tested surface in relation to the source file, and reddish areas represented an excess of scanned material. Generally, very precise greenish areas were found on cusp slopes and vestibular and oral smooth surfaces. Blueish colour patches were detected interdentally, at the cervix dentis and incisal edges, and on the vestibular, oral, mesial and gingival attachment surfaces. Reddish nuances, namely excessive dimensions, were found on the occlusal and distal attachment areas, occlusal fissures, cusp tips, cavity surfaces, and interdentally.

Discussion

The present study assessed the influence of layer height on the accuracy of FFF printed dental models applying a 3D superimposition and investigated the clinical suitability of FFF printing by comparing the printing quality to DLP, the gold standard.

When assessing trueness and precision, the model in printed, scanned and STL file form was compared to the source file, measuring point deviations between the test and master file in both negative and positive directions. Taking the Dahlberg error and the intraobserver ICC into account, an excellent measurement method can be ascertained (Table 2); however, additional sources of error were encountered during the scanning process that were not inspected in the present study. First, since the model scan utilised a light beam that dispersed linearly, certain locations were at greater risk of scanning error, such as obscured surfaces, namely occlusal grooves, interdental spaces and retractions on attachments[10,14]. Thus, to avoid artefacts, scanning images taken from different angles were combined. Second, the transformation of the scan data into an STL file may have caused errors due to data conversion[10]. Nonetheless, the clinical suitability of the S600 Arti model scanner was proven in a previous study[15].

Interestingly, the increase in accuracy that was anticipated to occur with a decrease in layer height, i.e., an increase in Z-resolution, did not entirely occur with the FFF printed sequential dental models. With the lignin-based group in particular, a continuous improvement in accuracy with regard to SD and the percentage of points within critical bounds was noted as layer height decreased within the range of 336.2 to 100.0 µm (Table 3). When layer height decreased beyond 100.0 µm, however, accuracy also decreased (Fig 5). In general, there appeared to be an optimal layer height of 100.0 µm in the lignin-based group, which was not found in the highest Z-resolution recommended in the manufacturer's instructions for the FFF printer. This may have been because, on the one hand, reducing the height of each layer leads to an increase in the number of layers and heightens the risk of printing errors such as artefacts or failure during the printing process itself[8]. To illustrate this point, a layer height of 50.0 µm has six times more layers than a dental cast with a layer height of 300.0 µm, and the former increases the likelihood of printing errors simply due to the additional number of layers to be printed. On the other hand, the FFF printer used exhibited obvious difficulties in pulling the previous layers from the printing platform due to an inaccurate distance between the nozzle and the platform at the beginning of the printing process when printing smaller layer heights such as 50.0 and 80.9 µm. It was difficult to level the print bed in first layer distances under 100.0 µm in practical handling, even if the printer being used was equipped with an auto-levelling system (BLTouch, Antclabs, Seoul, South Korea).

Comparing the accuracy between both FFF printed experimental groups with regard to printing material, models made from lignin-based polymer had a consistently lower SD and thus more measurement points within the clinical bounds than the PLA models (Table 3, Fig 3); as such, the printing material also seemed to affect accuracy. A previous study found that both polylactide and lignin-based polymers have excellent printing properties[16]. Differences could arise due to temperature resistance, as indicated on the data sheets for the materials provided by the manufacturer[17,18]. The lignin-based polymer Green-TEC PRO received a maximum of 10 points for temperature resistance according to the data sheet, whereas the polylactide PLA X2 only received 4 points[17,18]. Likewise, the lignin-based polymer scored slightly higher in the categories of impact resistance and maximum stress than the polylactide did. Equal values were recorded for visual quality, layer adhesion and elongation at break. In general, better accuracy seemed to arise due to the better material attributes of the lignin-based polymer utilised[17,18].

In terms of clinical suitability, it would be interesting to know how accurate and precise dental casts need to be to ensure the delivery of successful orthodontic therapy with aligners; however, there is currently no consensus concerning accuracy. Previous studies set limits of clinical agreement ranging from 0.2 to 0.5 mm[19-21]. Given that a considerable number of previous studies set their clinical threshold at 0.25 mm[3,5,8,10-12], the present study did the same. One reason for which a deviation of 0.25 mm was accepted was that the American Board of Orthodontics Grading System (ABO-OGS), established to evaluate dental casts for finished orthodontic treatments, considers a deviation of up to 0.50 mm to be clinically suitable in terms of alignment and marginal ridges[3,22]. The 3D superimposition algorithm applied compared the point deviations of corresponding surfaces, whereby a maximum deviation of 0.25 mm in both a positive and negative direction would equal a linear deviation of 0.50 mm maximum according to the ABO-OGS. Nonetheless, further studies are required to define a reasonable boundary for clinical suitability depending on the actual incoming transmission of tooth movement from the printed dental model to the vacuum-formed aligner.

The advantages of FFF printing are the cost-effective acquisition and maintenance of the printer, high variability and duration of the printing materials, ease of handling, time effectiveness in production and adequate reliability of the printing results[2]. Moreover, increased layer height offers significant economic benefits due to the slightly lower filament consumption and exponentially shorter printing times (Fig 1)[4]. Thus, printing time doubles when layer height decreases from 100.0 to 50.0 µm; as such, the total production time for nine 50.0-µm dental models would be 44 hours and 58 minutes, whereas printing the same number of models with a layer height of 100.0 µm would take half the time, namely 22 hours and 28 minutes. For a layer height of 300.0 µm, printing nine models would take no longer than 7 hours and 31 minutes, which is six times less time than that required to print nine models with a layer height of 50.0 µm (Table 1).

Although printing dental models with a high Z-resolution such as 50.0 µm is a more time-consuming process, it is not necessarily justified by proportionally higher accuracy. Despite the fact that the most accurate and precise printing result in the present study was found in the lignin-based group at a layer height of 100.0 µm (AM −0.03 mm; SD 0.09 mm; 99.18% of data points within the critical bounds and 40.04% within the nominal bounds), the benefit gained in accuracy was not in reasonable proportion to a printing time over 1.5 times longer compared to a layer height of 161.8 µm (AM 0.03 mm; SD 0.10 mm; 98.35% of data points within the critical bounds and 36.74% within the nominal bounds). Based on this, it would be interesting to determine whether even models with a layer height of 300.0 µm (AM −0.02 mm; SD 0.12 mm; 96.04% of data points within the critical bounds and 31.77% within the nominal bounds) transform adequate forces to the tooth using vacuum-formed aligners. Further research is required for clarification.

A clinical study by Davis at al[23] focused on the potential health concerns arising from volatile gases and particles during the FFF printing process. The commonly determined hazardous volatile compounds emitted by FFF printers were formaldehyde, a human carcinogen; styrene and methylene chloride, considered probably carcinogenic for humans; and toluene, a toxic hydrocarbon[23]. Nevertheless, the total volatile air compound emissions (TVOC ERs) were generally two orders of magnitude lower than those from dry process copiers, laser printers and personal computers[23]. Among the analysed printing filaments, namely nylon, acrylonitrile butadiene styrene, high impact polystyrene, polyvinyl alcohol and polylactic acid, the latter released the least TVOC ERs, and was the only one whose primary emitted monomer, lactide, was not considered a health risk[23]. Thus, an enclosed printer with an air filtration system may be recommended.

In terms of environmental longevity, polylactide and lignin-based polymer are excellent printing materials due to the quantity of renewable resources they contain. Furthermore, both filaments are biodegradable to some degree; indeed, the manufacturer's specifications state that the lignin-based polymer is compostable[17,18], although no time span is indicated for this.

Overall, FFF printing with cost-efficient, high quality and environmentally sustainable printing filaments represents an ingenious additive technology to be used in aligner orthodontics.

Conclusions

Considering the limitations of the system studied, it can be concluded that layer height affects accuracy and precision, but that other parameters, such as printing materials and settings, influence the results of FFF printing. A higher Z-resolution does not necessarily lead to higher accuracy and precision; rather, there seems to be an optimum range of layer heights depending on FFF print settings and material. In the present study, the lignin-based polymer was shown to be an excellent FFF printing material with an optimum layer height of 100.0 µm, even surpassing the precision requirements of the DLP printing control group.

FFF printing is a high quality, cost-effective and sustainable technology for producing aligner models with respect to optimised layer height, print settings and material. Indeed, a higher layer height results in a higher printing velocity and thus exponentially shorter printing times (Fig 1, Table 1). The optimal layer height with regard to accuracy and precision in printing is approximately 100.0 µm. For FFF printing, a lower layer height offers no advantages in terms of accuracy, but rather leads to long printing times and thus non-efficient print loads. Ultimately, a Z-resolution lower than 100.0 µm does not seem to yield any economic or clinical benefit. Moreover, dental models printed using FFF with layer heights higher than 100.0 µm show barely any loss of accuracy within a certain range. It would be interesting to investigate how the high precision of FFF printed models correlates with the clinical efficacy of orthodontic aligners. Thus, future studies are required to determine the minimum effective layer height that transforms optimal forces onto the teeth using vacuum-formed aligners.

Declaration

The authors declare these are no conflicts of interest relating to this study.

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