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Evaluation of three-dimensional printed virtual setups

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Introduction: Digital setups are reliable and show numerous benefits to the orthodontic practice. Fused deposition modeling can build physical replicas of these setup models. The purpose of this study was to compare 3-dimensional printed and conventional setups. **Methods:** Ten sets of pretreatment plaster models were randomly selected and scanned to obtain digital replicas. Conventional and virtual setups were constructed based on the treatment plan, anchorage needs, and extraction pattern. The same arch form was used for corresponding conventional and digital setups by replicating the archwire on the screen with the use of the 1:1 real scaling tool in the Orthoanalyzer software (3Shape, Copenhagen, Denmark). Printed and manual setups were measured to compare dimensional accuracy and inter- and intra-arch characteristics. The differences were assessed by means of paired *t* test analyses. **Results:** The majority of measurements showed higher values on the manual setup models. Statistically significant differences were found in 6 dimensional-accuracy measurements (from −0.04 to 0.32 mm). One intra-arch (from 0.01 to 1.55 mm) and all inter-arch (from 0.87 to 0.95 mm) characteristics showed statistically significant differences. Maxillary models exhibited greater variations than mandibular setup models. **Conclusions:** Three-dimensional setups printed with fused deposition modeling are not comparable to conventional setups. The digital setup process should be managed with care to avoid tooth collision and overcome software limitations. (Am J Orthod Dentofacial Orthop 2019;155:288-95)

Digital impressions and scanning systems were introduced into the dental practice in 1980.[1] Three-dimensional (3D) imaging and modeling technology has undergone significant advances, allowing more precise models, complete analyses, and editing tools such as virtual setup models, occlusal maps, and model segmentation on demand. Virtual models also have many actual or at least potential benefits against plaster models, such as reducing physical storage demand, lowering risk of loss or damage, facilitating classification, improving communication, and data sharing.[2-9]

Numerous studies have proven that measurements made on 3D digital study models of dental casts have the same accuracy and precision as those those made directly on traditional plaster models.[3,10-13] Digital and manual setup models have been shown to be reliable when measured.[14,15] These results imply that virtual setup models can be used for treatment planning, better understanding of treatment limitations, anchorage needs, and predictive assessment of treatment results.[16] Virtual setups can also be merged with cone-beam computerized tomographic scans to include roots, providing a complete view of tooth position.[4,17-20] However, physical models and setup models are still being used for some laboratory procedures, such as indirect bonding, customized appliance, clear aligners, and surgical wafer fabrication.[21-28]

3D model reconstruction can be made by several techniques, called additive manufacturing, rapid prototyping, and 3D printing. The use of some of these procedures in dental practice is still limited because of high production costs.[28] One of the more affordable options on the market with different 3D printing techniques is fused deposition modeling (FDM). FDM printers are easy to install and maintain, occupy less space, and are widely available. This makes them very convenient for in-office applications such as patient communication, model duplication, and appliance fabrication.

Fused deposition modeling is a fast process, and owing to technological advancements, it can achieve

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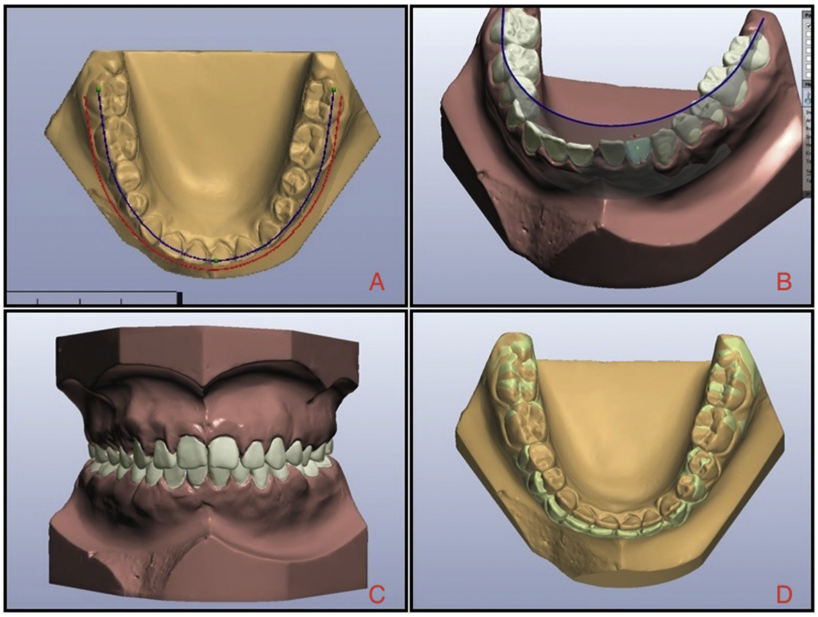

Fig 1. Virtual setup process: **A,** on-screen archform using 1:1 feature; **B,** archform used as a template for tooth alignment; **C,** finished virtual setup model; **D,** superimposition of initial and setup model.

high-resolution prints at less than one-third the cost of other options.[29] Polylactic acid (PLA) material is used for FDM printing; it is a biodegradable polymer that can be produced from lactic acid. This material is harder than acrylonitrile butadiene styrene (ABS) material used for injection molding and melts at a temperature of 180°C, which makes it suitable for thermoforming applications. Few studies have assessed 3D printing accuracy,[5,8,28-31] no one has evaluated printed virtual setups, and there is a lack of information in the literature about FDM printing.

The present study aimed to compare 3D printed setup models using FDM technology versus conventional setup models by measuring its dimensional accuracy and various occlusal parameters, with the purpose of evaluating whether FDM is clinically applicable. The null hypothesis tested was that there are no significant differences between the measurements taken on FDM printed setups and conventional setups.

MATERIAL AND METHODS

A sample of 10 sets of pretreatment plaster models were randomly selected. Each set contained a maxillar and a mandibular model, giving a total of 20 models that represented numerous malocclusions. All models had fully erupted and complete permanent dentition from first molar to first molar. Models with abnormal tooth morphology, fractured or missing tooth material, ectopic teeth, tooth decay, or severe tooth wear were excluded from the sample.

Each model was scanned with the use of a laser scanner (R700; 3Shape, Copenhagen, Denmark) to obtain the 3D models. With the use of the treatment planning tool in the Orthoanalyzer software (3Shape), the virtual setups were created and saved as stereolithography (STL) files following the procedure described by Barreto et al (Fig 1).[15] A manual setup was created with each scanned set of models (Fig 2).[32] Both the virtual setup and the manual setup were based on the individual treatment plan, anchorage needs, and extraction pattern, to obtain a desired occlusion according to the Andrews 6 keys.[33] The same arch form was used as a template for the manual and virtual setup with the use of the 1:1 real scaling feature in the Orthoanalyzer software. This tool displays a real-size image of the digital arch on the screen and allows the replication of the physical arch wire.

STL files were imported to Repetier-Host v1.0.3 software (Hot-World and Co KG, Willich, Germany) to check for mesh errors and define printing orientation. All models were arranged with the occlusal surface looking upward. The Repetier-Host software then slices the models and creates the G-code containing all of the information that the printer needs. The software allows verification of the travel moves that the nozzle will make during printing to avoid errors. After verification, the models were printed in a FDM printer (Replicator 2x; Makerbot Industries, Brooklyn, NY) with the use of PLA material. The nozzle diameter of this printer is 0.4 mm, and the X-Y resolution is 11 μm. We selected

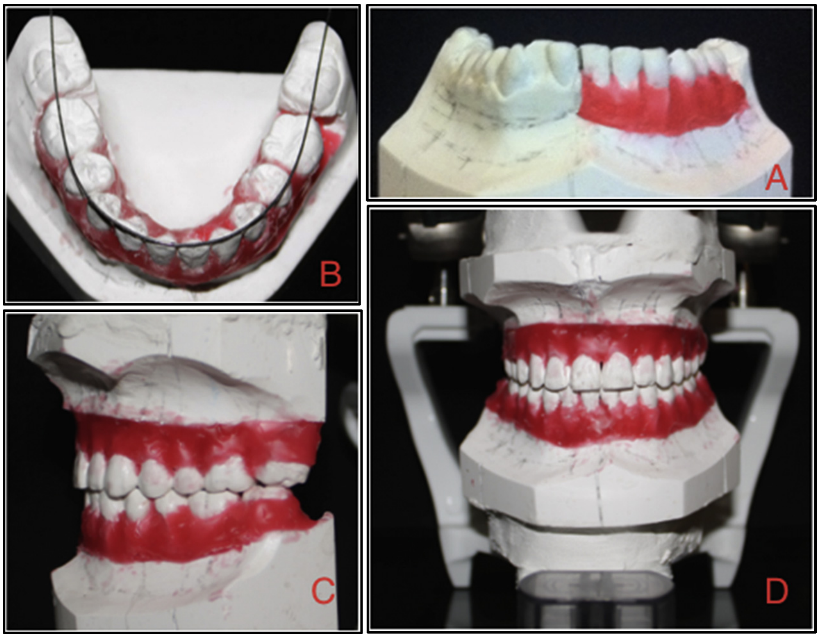

Fig 2. Manual setup process: **A,** lower model with left hemiarch aligned; **B,** archwire used as a template for lower model alignment; **C,** upper model alignment over lower model; **D,** finished setup model.

a layer thickness resolution of 100 μm because that is the minimum layer height recommended by the manufacturer.

Printed and manual setup models were marked with random numbers and measured twice by a trained examiner. Dimensional accuracy measurements were defined as follows: 1) mesiodistal diameter (MDD) from first molar to first molar, taken at the greatest convexity of the mesial and distal surfaces; and 2) buccolingual diameter (BLD) from first molar to first molar, taken at the greatest convexity of the buccal and lingual surfaces. Intra-arch measurements were represented by: 1) dental arch length (DAL), taken from a tangent to the mesial surface of the first molars to the occlusal point of the central incisors; 2) intercanine width (ICW), taken between the occlusal tips of the contralateral canines; and 3) intermolar width (IMW), taken between the mesiobuccal cusp tips of the contralateral first molars. Interarch measurements were assigned to: 1) overbite (OB), measured as the vertical distance between the incisal edges of the upper and lower central incisors; and 2) overjet (OJ), measured as the horizontal distance between the incisal edge of the upper central incisors and the buccal surface of the lower central incisors.

To achieve an accurate dental arch length measurement, landmark points were transferred to a millimeter paper by laying the models over the paper on its occlusal surface and marking all the references on the paper. Measurements were taken to the nearest 0.01 mm with the use of an electronic digital caliper, which is a reliable method for dental models.[13] All measurements were repeated within a 2-week interval.

Statistical analysis

Data were collected in a digital database. Mean values and standard deviations were calculated for each measurement. Differences between means were compared with the use of a paired Student *t* test after the data had been tested for normality by means of the Shapiro-Wilk test. Descriptive statistics were used to compare overall differences. SPSS software (version 21.0; IBM, Chicago, Ill) was used to perform the analyses.

RESULTS

The manual setup values were higher on all measurements except for MDD on the maxillary second premolars and BLD on the mandibular lateral incisors (Table 1).

Statistically significant differences were found in 6 measurements of dimensional accuracy: 4 on the maxilla and 2 on the mandible. OB and OJ differences were also statistically significant. Both measurements were higher on the manual setup models. The variables with the

Table I. Comparison of dimensional accuracy (mm) between the manual and printed setups

		Manual setup		*Printed setup*		*Difference*		
Arch	*Measurement*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	P *value*
Upper	MDD							
	FM	10.97	0.84	10.84	0.81	0.13	0.35	0.11
	SP	7.41	0.44	7.45	0.52	−0.04	0.21	0.40
	C	8.31	8.31	8.12	0.56	0.20	0.36	0.03*
	LI	7.57	0.57	7.46	0.54	0.11	0.18	0.01*
	CI	9.16	0.62	9.10	0.50	0.06	0.27	0.38
	BLD							
	FM	11.76	0.71	11.65	0.80	0.11	0.29	0.11
	SP	10.20	0.59	10.07	0.61	0.14	0.27	0.05
	C	7.03	2.25	6.88	2.24	0.15	0.35	0.07
	LI	6.77	1.05	6.62	1.05	0.15	0.24	0.01*
	CI	7.56	0.81	7.24	0.76	0.32	0.38	0.00*
Lower	MDD							
	FM	11.71	0.65	11.62	0.54	0.09	0.25	0.12
	SP	7.86	0.42	7.72	0.43	0.14	0.28	0.04*
	C	7.20	0.50	7.06	0.43	0.14	0.27	0.03*
	LI	6.45	0.60	6.37	0.64	0.07	0.24	0.19
	CI	5.82	0.35	5.74	0.32	0.08	0.21	0.11
	BLD							
	FM	11.05	0.82	10.95	0.81	0.10	0.24	0.08
	SP	9.06	0.71	8.90	0.57	0.16	0.36	0.06
	C	6.67	1.34	6.55	1.32	0.12	0.38	0.18
	LI	6.24	0.72	6.33	0.53	−0.08	0.65	0.58
	CI	5.84	0.59	5.72	0.56	0.12	0.54	0.34

MDD, mesiodistal diameter; *BLD*, buccolingual diameter; *FM*, first molars; *SP*, second premolars; *C*, canines; *LI*, lateral incisors; *CI*, central incisors.
*$P < 0.05$ (95% CI paired *t* test).

Table II. Comparison of intra-arch and interarch values (mm) between the manual and printed setups

		Manual setup		*Printed setup*		*Difference*		
Arch	*Measurement*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	P *value*
Intra-arch								
Upper	DAL	28.15	4.42	26.60	3.99	1.55	2.02	0.04*
	ICW	38.23	2.41	37.54	2.10	0.69	1.23	0.11
	IMW	55.28	2.58	54.43	2.61	0.85	1.61	0.13
Lower	DAL	21.62	3.88	21.61	4.06	0.01	1.20	0.98
	ICW	29.02	3.12	28.71	2.33	0.31	1.97	0.63
	IMW	47.76	3.89	46.77	3.85	0.99	1.81	0.12
Interarch	OB	3.61	0.68	2.66	0.48	0.95	0.88	0.01*
	OJ	4.11	0.74	3.24	0.76	0.87	0.98	0.02*

DAL, dental arch length; *ICW*, intercanine width; *IMW*, intermolar width; *OB*, overbite; *OJ*, overjet.
*$P < 0.05$ (95% CI paired *t* test).

largest discrepancies were DAL (1.55 mm; $P < 0.05$) on the maxilla and IMW (0.99 mm; $P > 0.05$) on the mandible. However, the IMW measure did not show a statistically significant difference (Table II).

Dimensional accuracy (from −0.04 to 0.32 mm) showed fewer differences than intra-arch (from 0.01 to 1.55 mm) and interarch variables (from 0.87 to 0.95 mm), with mean differences of 0.11 ± 0.08 mm, 0.73 ± 0.53 mm, and 0.91 ± 0.05 mm (Fig 3), respectively. Maxillary models exhibited greater differences than mandibular setup models.

The overall differences between manual and 3D printed setup models were 0.24 mm ($P < 0.05$) for the maxillary arch and 0.14 mm ($P < 0.05$) for the mandibular arch.

The MDD of the second premolars showed the best agreement on the maxilla (0.04 mm; $P > 0.05$) and DAL (0.01 mm; $P > 0.05$) for the mandible (Tables I and II).

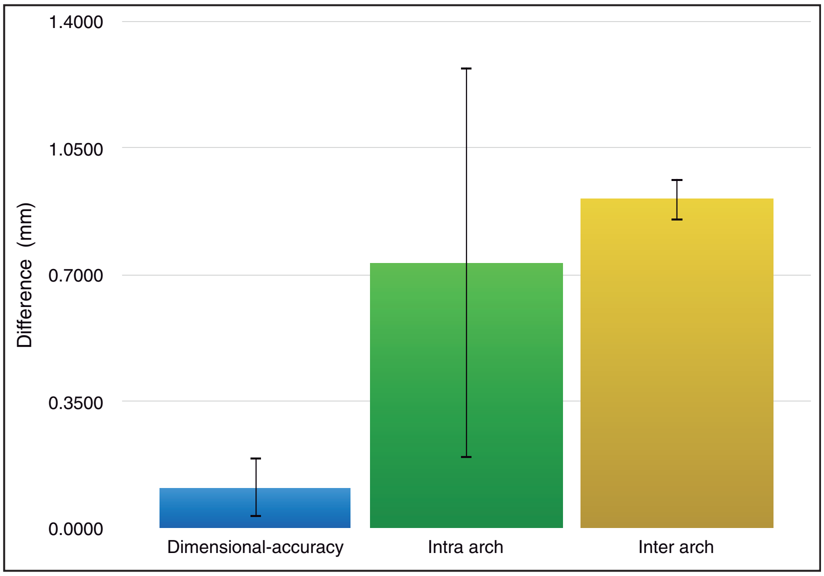

Fig 3. Differences: means and standard deviations.

DISCUSSION

In this study, a model scanning process was used instead of direct intraoral scanning. This was done to avoid errors due to the incorrect manipulation of the latter or to the intraoral conditions (limited space, saliva, etc).[34,35] In addition, plaster casts are trimmed, cleaned, and polished during the model base preparation. These procedures are not carried out on intraoral digital models, which could result in disparities between digital and plaster models. Model scanning creates exact digital copies of the same models that were used for the conventional setup construction.

3D printing technology was introduced to the industry in 1986 by Chuck Hull (3D Systems) with the stereolithography process (SLA). Later that decade, selective laser sintering (SLS) technology was released by DTM. Meanwhile, Scott Crump developed FDM technology. Dental model construction with the use of SLA was assessed by Keating et al in 2008.[30] Other technologies studied include digital light processing, jetted photopolymer, binder jetting, and FDM. Digital light processing uses a projector as the light source to cure a photopolymer layer by layer until the 3D model is complete. Jetted photopolymer deposits tiny drops of building and supporting materials to form each layer with an array of inkjet printheads. After this an ultraviolet light cures both materials. Binder jetting selectively deposits a binder through a jet head into a powder bed. This is done to fuse the material a layer at a time and create the finished model. FDM is an additive manufacturing technology that works by laying down thermoplastic materials, which are extruded through a nozzle and deposited on a platform layer by layer.

The measurement variables were chosen to represent any changes that may occur during the printing or the setup fabrication process. They were grouped into 3 categories: dimensional accuracy, intra-arch, and interarch. No vertical measurements were taken owing to the difficulty of setting landmark points on the gingival side, as described by Barreto et al.[15] Because the gingival part of the models get distorted by the software during the setup process, it is impossible to determine a reliable reference on this part. Consequently, clinical crown height data were not available for comparison with other studies. Hazeveld et al mentioned that this measurement requires a difficult cervical landmark identification (Fig 4).[28]

We found smaller values on the printed models, similarly to Santoro et al's findings between plaster and digital models.[36] However, we did not obtain significant differences on most of the dimensional accuracy measures. The loss of surface details in crowded cases owing to the scanning and printing process could be the main reason for the mesiodistal discrepancies, as stated by Nurazreena et al.[8]

Our findings agree with those of Im et al, who found that the dental arch length is bigger on the manual setups. This can be attributed to tooth overlapping throughout the digital setup process.[14] Mesial and distal contacts are preserved during a conventional setup by carefully executing tooth segmentation and alignment. Nevertheless, in a digital setup, the software has no

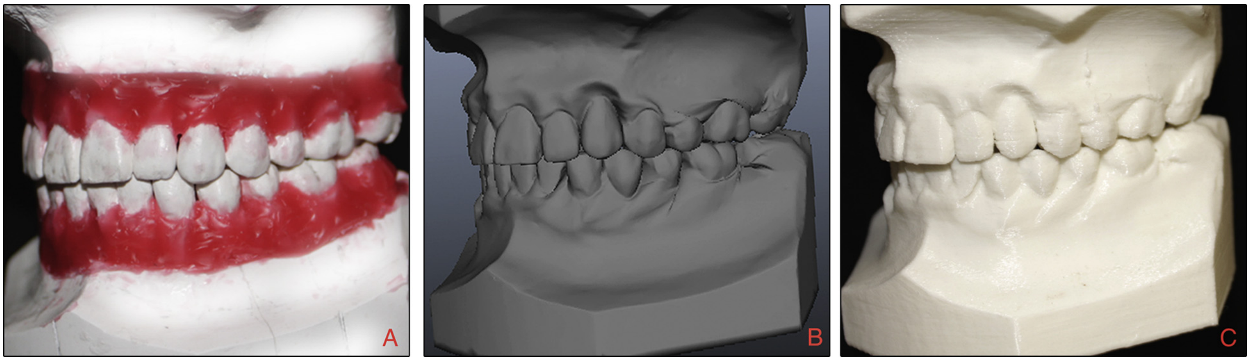

Fig 4. A, Conventional setup; **B,** virtual setup; **C,** 3D printed virtual setup.

restriction on tooth movement when a collision occurs. Buccolingual inclination is difficult to visualize on a screen. These limitations can reduce the arch length and most likely the arch perimeter. Upper arch length disparities are even bigger, because the setup process starts with the lower arch alignment and then the upper arch is adapted to it. Contrary to Barreto et al's findings, our results showed a statistically significant difference in the maxillary arch length (1.55 mm; $P < 0.05$), thus coinciding with Im et al's study.[14,15] Such a difference would also be clinically significant in the treatment outcome, and possibly a limitation of the use of this technology.

When we compared our findings with the Hazeveld et al study,[28] the results coincided on a statistically significant difference for the mesiodistal diameters. We obtained a mean difference of 0.10 mm (−0.04 to 0.19 mm; $P < 0.05$) for these measurements with the use of FDM technology, which are similar to mean differences of −0.08 mm (0.34 to −0.49 mm) for jetted photopolymer, −0.05 mm (0.34 to −0.45 mm) for digital light processing, and −0.05 mm (0.37 to −0.48 mm) for binder jetting in the Hazeveld study.[28] Similarly to Nurazreena et al, we found statistically significant differences for the buccolingual diameters. Printed models presented smaller values, with a mean of 0.13 mm (−0.08 to 0.1 6 mm; $P < 0.05$) compared with a mean range of 0.10 to 0.15 mm in the Nurazreena et al study.[8] These differences seem consistent with the printer resolution of 100 μm. For ICW and IMW, we obtained results compatible with those of Im et al and Barreto et al,[14,15] which reported no statistically significant difference in these measurements. We found larger values for overbite and overjet, coinciding with Im et al; nevertheless, in contrast to their results we obtained statistically significant differences.

Kasparova et al concluded that FMD models could potentially replace plaster casts. Their study assessed 3D printed models made by means of FDM with a 0.35-mm layer thickness of ABS material. They compared linear measurements representing 4 planes: x-plane (intercanine distance), y-plane (tip of the canine to the mesiopalatal cusp of the first molar), z-plane (clinical crown height of canine), and a mixed plane (edge of the first incisor to the canine cusp). Our results differ from the Kasparova et al study probably because mesiodistal and buccolingual measurements describe multiple planes at the same time.[5] Qualitative observation of the printed models showed an uneven surface in accordance with the layer by layer printing process. Murugesan et al found by means of scanning electron microscopy analysis a uniformly smooth surface with thick ridges across on FDM models. A faint demarcation among the cusps and a poor representation of developmental grooves were also observed on those models.[31] Similar characteristics were displayed on our printed setups. The present study corroborates other authors' conclusions on the reliability of digital and manual setups, because most of the intra-arch measurements did not show a statistically significant difference. However, the dimensional-accuracy and interarch characteristics seem to differ when these setup models are printed. The reduced surface detail in these prints, which increases the difficulty of landmark identification, could be one of the reasons for such disparities.[14,15]

There is an important learning curve in the digital setup process owing to the fact that a 3D object is being visualized in a 2D medium.[14] However, digital setup construction can be done in less time than a traditional manual setup, as mentioned by Barreto et al.[15] Digital setup software is a developing technology, and further updates could bring even faster and more precise results.

Despite the good agreement found on dimensional accuracy between conventional and FDM printed setups, detail loss on incisal edges and cusp tips may affect the seating of some appliances that use the occlusal surface as a reference. Some newer printer models can get resolutions up to 50 μm, which could result in smoother surfaces and more accurate details, but also increasing the printing time. Besides these limitations, models printed with the use of FDM technology could be used on selected applications, such as patient instruction or to aid communication between health professionals. This study was limited to assessing the differences between FDM printed and conventional setups. Further studies may evaluate FDM applications with higher printing resolutions.

CONCLUSIONS

Based on these findings we can conclude that fused deposition modeling technology can be used for digital setup model construction. However, there is a statistically significant difference when these printed setup models are compared with conventional setups, becoming inadequate for clinical applications if an accuracy less than 1 mm is desired. Intra-arch characteristics showed good agreement, except for the dental arch length on the upper arch. The mean dimensional accuracy difference was small. The digital setup process should be managed with great care to avoid tooth collision and to overcome software limitations.

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