

Article

Evaluation of Dimensional Deviations Across a Digital-to-Physical Workflow for Orthodontic Appliance Fabrication Using CAD Surface Inspection

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Abstract

Digital-to-physical orthodontic workflows combine intraoral scanning, 3D printing, res-canning and thermoforming, but each step may introduce dimensional deviation affecting final appliance geometry. This pilot methodological study evaluated relative dimensional deviations across selected stages of a biomedical manufacturing workflow for orthodontic appliances. Anonymized intraoral scan datasets from two patients with eugnathic occlusion were used, providing four arch-level datasets. CAD inspection compared IOS data, printed models, powder-coated printed models, and thermoformed appliances, with an analysis of global RMS surface deviation, anterior/posterior regional differences, spray-related surface offset and material-thickness effects. The highest mean global RMS deviation was found for IOS vs. a printed model (0.090 mm), followed by IOS vs. a powder-coated model (0.088 mm), whereas the direct printed model vs. powder-coated model comparison showed a lower mean RMS deviation of 0.039 mm. Regional analysis showed higher RMS deviations posteriorly (0.077 mm) than anteriorly (0.047 mm). Thermoformed appliance adaptation was affected by material thickness, with a mean RMS deviation of 0.207 mm for 1.0 mm material and 0.282 mm for 1.5 mm material. Local incisor analysis estimated the spray-related surface offset at approximately 0.030 mm. The main dimensional discrepancy was associated with printed model fabrication, while posterior regions and thicker thermoformed material showed greater deviation.

Keywords: intraoral scanners; orthodontic appliances; three-dimensional printing; computer-aided design; dental models; surface properties; RMS surface deviation; scanning-aid coating



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1. Introduction

Digital workflows have become routine in orthodontic diagnostics, treatment planning and appliance fabrication. Intraoral 3D scanning allows the clinician to replace conventional impressions with a direct digital model, while 3D printing makes it possible to produce physical working models for thermoforming, clear aligner fabrication and laboratory procedures. This workflow is convenient, but it contains several steps where small

deviations may be introduced: image acquisition, software processing, model preparation, 3D printing, post-processing, rescanning and thermoforming [1–4].

Accuracy in this context is usually discussed through trueness and precision. Trueness describes how close a measured or manufactured object is to the reference geometry, while precision describes the repeatability of the process. In full-arch scanning, the problem is not just the accuracy of a single surface point. The scanner software has to stitch a sequence of images into a complete arch, and the accumulated error may become more visible in longer-span scans. Systematic reviews and recent *in vitro* studies show that full-arch Intraoral Scanner (IOS) accuracy depends on scanner type, arch configuration, operator-related factors, scanning strategy and the extent of the scan [1–6].

For example, Moon and Lee [5] compared complete-arch and quadrant intraoral scans and reported larger deviations in the complete-arch scans, supporting the concept that scan span influences accuracy. Nulty [6] compared the trueness and precision of several intraoral and laboratory scanners and showed that scanner type can substantially influence full-arch accuracy. More recently, studies evaluating current intraoral scanners and scanning patterns have further confirmed that model configuration, operator-related factors and scan strategy affect full-arch acquisition accuracy [3,4].

These factors are relevant to the present study because the comparison was performed on complete dental arches rather than on isolated teeth. The printed model is another important part of the chain. Even when the original intraoral scan is accurate, the physical model may differ from the digital file because of printer technology, resin properties, layer thickness, build orientation, washing, post-curing and model geometry. Studies and reviews on dental and orthodontic model printing generally show that 3D-printed models can remain within clinically acceptable ranges, but the degree and distribution of deviations vary between printers, materials, model design, printing orientation and post-processing workflows [7–15].

Grassia et al. [7] evaluated 3D-printed orthodontic models intended for clear aligner production and reported that trueness and precision were influenced by printer technology and dentition configuration. In a systematic review and meta-analysis focused on orthodontic 3D printing, Rajagopalan et al. [8] also emphasized that printing accuracy is affected by printer technology, material characteristics and processing parameters. Etemad-Shahidi et al. [9], in a systematic review of full-arch printed dental models, concluded that the accuracy of printed models varies considerably depending on the printer technology, material and production parameters. Other recent studies have also shown that build orientation, post-processing, resin type, printing design and layer thickness can affect dimensional accuracy [10–15].

Dimensional accuracy in DLP and other photopolymer-based printing processes is closely related to resin formulation, polymerization shrinkage, exposure strategy and post-curing conditions. Recent work on low-shrinkage model resins has shown that volumetric shrinkage correlates with dimensional accuracy and the accuracy stability of DLP-printed full-arch tooth models [16]. Similarly, studies on UV-curing strategies in additive manufacturing indicate that curing conditions, reaction heat and material composition can influence shrinkage, warpage and final part accuracy [17]. In biomedical manufacturing, dimensional changes during post-processing are particularly important when printed components must preserve fit-critical geometry. For example, recent work on FDM-printed HTPLA cutting guides for orthopaedic surgery showed that thermal post-processing can alter fixation-hole dimensions and that design compensation may be required to maintain dimensional accuracy after sterilization-related annealing [18].

Thermoforming introduces an additional source of dimensional change. During heating and pressure forming, the thermoplastic sheet is stretched over the model. Its

final thickness and adaptation are not uniform across the dental arch. Areas with complex morphology, steep inclines, undercuts and embrasures are especially prone to local gaps and thinning. Micro-CT and thickness-measurement studies report that thermoformed appliances show thickness reduction compared with the original sheet and that fit, gap width and thickness vary by material, tooth region and manufacturing approach [19–25].

Bandić et al. [19] measured thickness variations in thermoformed and 3D-printed clear aligners and showed that the final appliance thickness may differ from the nominal material thickness. Palone et al. [20] used micro-computed tomography to evaluate aligner thickness and gap width after thermoforming and reported non-uniform adaptation across different regions. Previous studies have shown that some model-related parameters, such as shell thickness, may influence appliance accuracy, whereas other parameters, including printing layer thickness within the investigated range, may have little or no measurable effect [21,22]. Similarly, studies comparing thermoformed and 3D-printed aligners have shown that material type and manufacturing approach can influence thickness distribution, gap width and fit [23–25].

These findings are consistent with the general behaviour of thermoformed polymer sheets. Thermoforming is governed by sheet heating, polymer deformation, forming pressure, mould geometry and cooling, and the final thickness distribution is generally non-uniform when thermoplastic sheets are formed over complex geometries [26]. Process-optimization studies also show that temperature distribution and forming conditions can be adjusted to influence the material flow and final thickness distribution in thermoformed parts [27].

Scanning powder or scanning spray is sometimes used to improve the optical capture of reflective, translucent or difficult surfaces. Powder creates a more matte surface, but it also adds a physical layer to the object being scanned. Studies on scanning-aid materials show that coating agents can influence scan accuracy and that the type and application method of the scanning aid matter for the resulting surface deviation [28,29].

Oh et al. [28] investigated different scanning-aid materials and demonstrated that they influenced scanning precision and scanning time during full-arch digital acquisition. In a related laboratory study, Oh et al. [29] showed that different scanning-aid agents can affect RMS trueness, confirming that surface coating should be treated as a potential source of measurement deviation rather than only as a scanning aid. Donmez et al. [30] reported that measured deviations in complete-arch digitization depended primarily on the scanning technology, whereas the application of scan powder did not produce a statistically significant effect under their experimental conditions.

For this reason, the effect of powder should be measured separately whenever powder-assisted scanning is included in the experimental workflow. Three-dimensional surface comparisons and CAD-based deviation mapping are widely used to evaluate geometric differences between a physical object and a reference geometry. Studies on additively manufactured parts and complex components have shown that 3D scanning, CAD comparisons and colour-coded deviation maps can be used to identify both global dimensional trends and localized mismatch [31,32].

Scan-based engineering workflows can use 3D acquisition and CAD-based reconstruction to convert physical objects into suitable digital models for dimensional assessment or subsequent numerical validation [33]. This literature supports the use of scan-based geometry and CAD inspection to compare deviations between successive manufacturing stages.

At the same time, point-cloud registration and alignment remain important methodological steps, because registration strategy, scan noise and partial surface capture can influence the final deviation values [34]. Although intraoral scan accuracy, the dimensional stability of 3D-printed dental models and the adaptation of thermoformed orthodontic

appliances have each been investigated in previous studies, few studies have evaluated how these steps interact within a single digital-to-physical orthodontic workflow. Previous research has also used different reference geometries, measurement protocols and deviation metrics, which makes a direct comparison between workflow stages difficult. A consistent inspection approach is therefore needed to compare different sources of dimensional deviation across sequential production steps. In contrast to the studies focusing on a single device, material or manufacturing stage, this study was designed as a methodological analysis of a complete digital-to-physical orthodontic workflow. Using a unified CAD inspection approach and surface-deviation analysis based on RMS-derived indicators, this study followed consecutive workflow stages including intraoral scanning, digital model preparation, 3D printing, powder-assisted rescanning and thermoforming.

The aim of this study was to evaluate relative dimensional deviations in a digital-to-physical biomedical manufacturing workflow for orthodontic appliance fabrication involving intraoral scanning, 3D printing of dental models, powder-assisted surface scanning and thermoforming of orthodontic appliance material. This study was designed to compare selected workflow stages using pairwise surface comparisons, rather than to quantify the cumulative deviation between the initial intraoral scan and the final thermoformed appliance.

The specific objectives were:

1. To compare the digital intraoral scan with the corresponding 3D-printed model;
2. To evaluate the effect of scanning-aid coating on the measured geometry of the printed model;
3. To compare regional deviations in the anterior and posterior regions;
4. To assess the adaptation of thermoformed sheets with nominal thicknesses of 1.0 mm and 1.5 mm;
5. To estimate the local surface offset produced by a coating application on an incisor surface.

The findings are expected to contribute to a better understanding of dimensional-deviation sources in digital orthodontic workflows and to provide a methodological basis for future optimization of orthodontic appliance fabrication procedures.

2. Materials and Methods

2.1. Study Design and Sample

This in vitro pilot study was based on two anonymized intraoral scan datasets showing eugnathic occlusion and the corresponding derived printed orthodontic models. For each dataset, both the maxilla and mandible were analysed, resulting in four arch-level datasets (Dataset 1 maxilla, Dataset 1 mandible, Dataset 2 maxilla, Dataset 2 mandible).

This study was designed to identify the main sources of dimensional deviation and to test whether these deviations could be compared across consecutive steps using the same inspection logic. Rather than evaluating clinical treatment outcomes, this study focused on comparing sequential steps of the digital workflow. All models were processed using the same inspection logic so that global, regional and material-related deviations could be compared within a consistent measurement framework. The complete experimental workflow is shown in Figure 1.

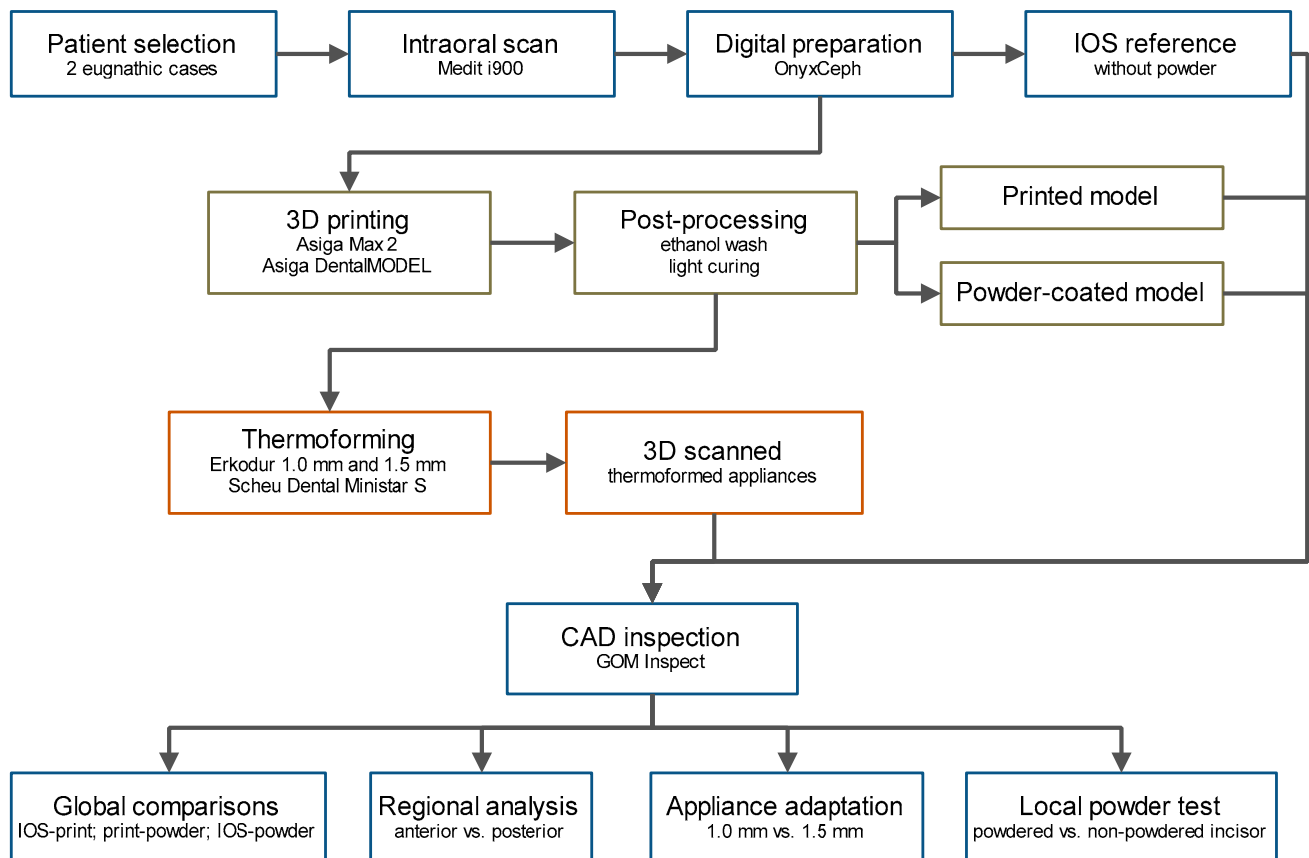


Figure 1. Experimental workflow of this study.

2.2. Intraoral Scanning

The anonymized intraoral scan datasets were acquired using a Medit i900 intraoral scanner (Medit Corp., Seoul, Republic of Korea) with Medit Scan for Clinics v1.14.0 software. According to the manufacturer's technical specifications, the Medit i900 has a reported full-arch scanning accuracy of $10.9 \pm 0.98 \mu\text{m}$, a scanning speed of more than 60 frames per second, a field of view of $18 \times 15 \text{ mm}$ and a scan depth ranging from 12 to 30 mm. The system uses 10-bit colour imaging technology. All scans were acquired using the manufacturer-recommended full-arch scanning strategy. Scanning was initiated on the occlusal surface of the posterior teeth, continued along the occlusal surfaces toward the contralateral side, and then completed by recording the buccal and lingual surfaces. The same general scan path was used for all datasets to reduce protocol-related variability. All intraoral scans and subsequent laboratory rescans were performed by the same operator. The powder-free intraoral scan served as the internal reference geometry for relative comparisons between workflow stages. It was not considered a metrologically traceable reference standard for assessing absolute trueness according to ISO 5725-1 and ISO 20896-1 [35,36].

2.3. Digital Model Preparation

The digital scans were exported and processed in OnyxCeph (Image Instruments GmbH, Chemnitz, Germany). This step was used to prepare the models for 3D printing and to optimize model geometry for the laboratory workflow.

2.4. 3D Printing and Post-Processing

The physical models were printed using an Asiga Max 2 digital light processing (DLP) 3D printer (Asiga, Sydney, Australia) and Asiga DentalMODEL resin (Asiga, Sydney,

Australia). Printing was performed at a layer thickness of 50 µm using a horizontal model orientation and the manufacturer-recommended support settings. After printing, the models were washed in 99.6% ethanol for 10 min and post-cured for 20 min in an Anycubic Wash & Cure 3 device (Shenzhen Anycubic Technology Co., Shenzhen, China). These post-processing steps were kept identical for all printed models. The workflow was performed under routine clinical and dental laboratory conditions. Intraoral scanning was performed in the dental clinic, whereas 3D printing, rescanning and thermoforming were performed in the associated dental laboratory. The procedures were carried out at an ambient temperature of approximately 22 °C, with relative humidity maintained within the standard working range for dental clinical settings (40–60%). This setup was intended to reflect the practical clinical-laboratory workflow used for orthodontic appliance fabrication.

2.5. *Spray-Assisted Rescanning*

Printed models were rescanned with and without the application of an occlusion spray, whereas thermoformed appliances were rescanned with occlusion spray to reduce the optical effects associated with surface transparency during scanning. Mega OkklusionsSpray EXACT Green (Megadental GmbH, Büdingen, Germany) was used to reduce surface reflections during scanning. The spray was applied as a thin, uniform coating immediately before scanning. The comparison between the spray-coated and non-coated printed models was included to isolate the geometric effect of the coating itself and to distinguish this effect from deviations related to printing or thermoformed appliance adaptation. A separate local incisor surface was prepared using a half-and-half design, in which one half of the incisor remained uncoated (covered with tape), and the other half was spray-coated. This allowed a direct visual and numerical comparison of the surface offset between the two regions on the same tooth. Based on the colour map obtained from this single incisor surface, using five measurement points on the flat labial surface, the coating thickness was estimated to be approximately 30 µm. This estimate is specific to the product and measurement site used in this study and should not be generalized to other products, surfaces or clinical situations.

2.6. *Thermoforming*

Thermoformed sheets were fabricated using a Scheu Dental Ministar S thermoforming unit (SCHEU-DENTAL GmbH, Iserlohn, Germany) and Erkodur sheets (ERKODENT Erich Kopp GmbH, Pfalzgrafenweiler, Germany) in two nominal thicknesses: 1.0 mm and 1.5 mm. Thermoforming was performed using positive pressure forming according to the manufacturer-recommended barcode program for Erkodur material. The Ministar S unit automatically loaded the heating parameters for each sheet thickness. The 1.0 mm sheets were formed at approximately 3–4 bar with a heating time of approximately 25 s, whereas the 1.5 mm sheets were formed at approximately 3.5–4 bar with a heating time of approximately 45 s. For both sheet thicknesses, the preset program corresponded to a nominal material activation temperature of approximately 160–170 °C. The sheets were formed after visible sagging and cooling was allowed for approximately 30–60 s before removal. No pre-drying was required.

Physical samples from Dataset 4 are shown in Figure 2 to illustrate the main stages of the experimental workflow.

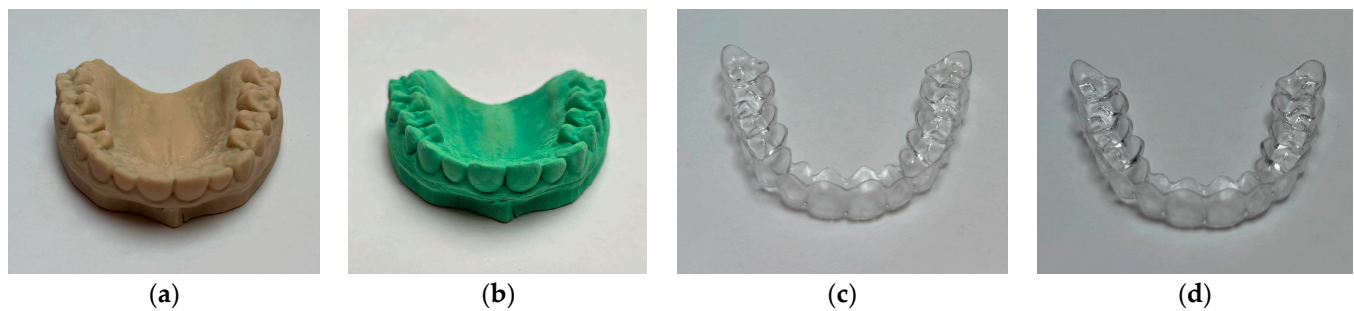


Figure 2. Physical samples from Dataset 4 used to illustrate the orthodontic appliance fabrication workflow: (a) 3D-printed dental model before spray application; (b) spray-coated 3D-printed dental model prepared for rescanning; (c) thermoformed appliance fabricated from 1.0 mm sheet; (d) thermoformed appliance fabricated from 1.5 mm sheet.

2.7. CAD Inspection and Alignment Protocol

CAD inspection was performed in GOM Inspect v2019 (GOM GmbH/ZEISS, Braunschweig, Germany). For each comparison, the reference dataset and test dataset were imported as triangulated surface meshes. The datasets were first brought into an approximate position using an initial alignment procedure and were then registered using global best-fit alignment in GOM Inspect. The best-fit calculation was applied to the tooth-bearing surfaces, while non-relevant regions such as the model base areas, trimmed margins and obvious scan-edge artefacts were excluded where applicable. The same alignment strategy was used for all comparisons to maintain internal consistency across the workflow. All CAD inspections, alignment procedures and exported deviation analyses were performed by the same operator.

A global best-fit alignment was intentionally applied to all comparisons to ensure methodological consistency across workflow stages. Because this registration strategy minimizes the overall distance between the compared surfaces, signed mean deviation values should not be interpreted as direct evidence of systematic dimensional expansion or contraction. After alignment, colour-coded deviation maps were generated, and numerical values were recorded for the mean deviation, standard deviation, maximum deviation and minimum deviation.

The following comparisons were analysed:

1. IOS reference vs. 3D-printed model;
2. 3D-printed model without powder vs. 3D-printed model with powder;
3. IOS reference vs. 3D-printed model with powder;
4. Thermoformed appliance vs. corresponding printed model.

For each arch, the intraoral scan obtained without scanning powder was used as the primary reference for comparisons involving the digital reference geometry (IOS vs. print and IOS vs. powder-coated print). For the print vs. powder-coated print comparison, the 3D-printed model scanned without powder served as the reference, whereas the powder-coated scan of the same printed model represented the test surface. For thermoformed appliance adaptation, each thermoformed appliance was compared with its corresponding 3D-printed model from the same dataset and arch, because the objective of this comparison was to evaluate adaptation to the manufacturing model. For thermoformed appliance evaluation, only the internal (intaglio) surface of each thermoformed appliance was used for a CAD comparison with the corresponding 3D-printed model. The external surface was intentionally excluded because it incorporates nominal sheet thickness. Consequently, the reported RMS values represent an adaptation of the thermoformed appliance to the printed model rather than differences arising from material thickness itself. All powder-assisted

rescans of the printed models and thermoformed appliances were performed using the same powder application and scanning protocol.

2.8. Global and Regional Surface Analysis

The analysis included a global surface comparison and a regional comparison. Global RMS analysis was used to estimate the overall level of dimensional deviation between the reference and analysed geometries and to compare different workflow steps. Regional analysis was introduced to identify local deviations that may remain hidden when only the complete surface is evaluated.

For regional assessment, the arch was divided into anterior (Zone 1) and posterior (Zone 2) regions. Zone 1 included the incisors and canines, whereas Zone 2 included the premolars and molars bilaterally. This division allowed an evaluation of whether dimensional deviations were uniformly distributed or region-dependent.

2.9. Metrics and Data Handling

The exported inspection values were reorganized into a master dataset containing 12 global comparisons, 24 regional comparisons and 8 thermoformed appliance adaptation measurements. For each individual comparison, root mean square deviation (RMS) was calculated from the corresponding mean deviation and standard deviation values using the formula $RMS = \sqrt{(\text{Mean}^2 + \text{SD}^2)}$, where SD represents the standard deviation of pointwise surface deviations. This calculation was applied consistently to all comparisons.

Summary statistics were then calculated for each comparison group. Mean RMS (mm) represents the average RMS value across observations; SD RMS (mm) represents the standard deviation of the RMS values; Mean bias (mm) represents the average signed mean deviation; Mean SD (mm) represents the average standard deviation of local surface deviations; and Max absolute extreme (mm) represents the largest absolute local deviation recorded within a comparison group. Group summaries were calculated according to comparison type, arch, region and material thickness.

Because of the small sample size and unequal variances between comparison groups, the following selected two-group RMS comparisons were evaluated using Welch's *t*-test: anterior versus posterior regions, maxillary versus mandibular arches and 1.0 mm versus 1.5 mm thermoformed materials. Estimated mean differences were reported together with 95% confidence intervals. Owing to the pilot nature of this study and the limited number of arch-level datasets, the statistical analysis was considered exploratory and intended to support descriptive interpretations rather than formal hypothesis testing. Statistical significance was accepted at $p < 0.05$.

RMS deviation was selected as the principal outcome because it provides a single measure of overall surface discrepancy while integrating both the average deviation and dispersion of surface differences. It also reduces the possibility that positive and negative local deviations cancel each other out and gives greater weight to regions with more pronounced mismatch. Mean bias was additionally reported to indicate the direction of a deviation relative to the reference geometry, whereas standard deviation and extreme values were used to characterize variability and localized mismatch.

For the local powder analysis, point-based deviation metrics were extracted from selected labelled points on the isolated half-and-half incisor surface. This analysis was treated separately from the full-arch RMS comparisons and was used only to estimate the local coating-related surface offset. The non-coated half showed values close to zero and was used as a local baseline, whereas the powder-coated half was used to estimate the coating-related surface offset. The estimated powder-related offset was calculated as the difference between the mean deviations of the two halves.

Column n represents the number of observations included in each summarized group. For example, $n = 4$ in the global comparison table corresponds to the four analysed arches (two datasets $\times$ two jaws), whereas $n = 12$ in the regional comparison table corresponds to four arch-level datasets across three comparison types. RMS thresholds of 0.05 mm, 0.10 mm and 0.20 mm were used for practical interpretation. A 0.25 mm threshold has also been used in previous orthodontic model-printing research as a clinically oriented reference value for clear aligner model production [7].

3. Results

The results are presented as global surface comparisons, regional analysis, arch-level comparisons, thermoformed appliance adaptation and local powder assessment. Summary values are reported using RMS-based metrics, signed mean bias, standard deviation and maximum absolute extreme values, depending on the type of comparison.

3.1. Global Surface Deviation

Based on the CAD analysis results, the global RMS values showed that the largest mean deviation occurred in the IOS vs. printed model comparison. The mean RMS for the IOS vs. print comparison was 0.090 mm, with a standard deviation of 0.032 mm. The IOS vs. powder-coated printed model comparison showed a similar mean RMS of 0.088 mm. The direct printed model vs. powder-coated printed model comparison showed a lower mean RMS of 0.039 mm. The CAD inspection and the colour-coded deviation maps are illustrated in Figure 3a,b. The distribution of the three global comparison groups is summarized in Table 1 and Figure 4.

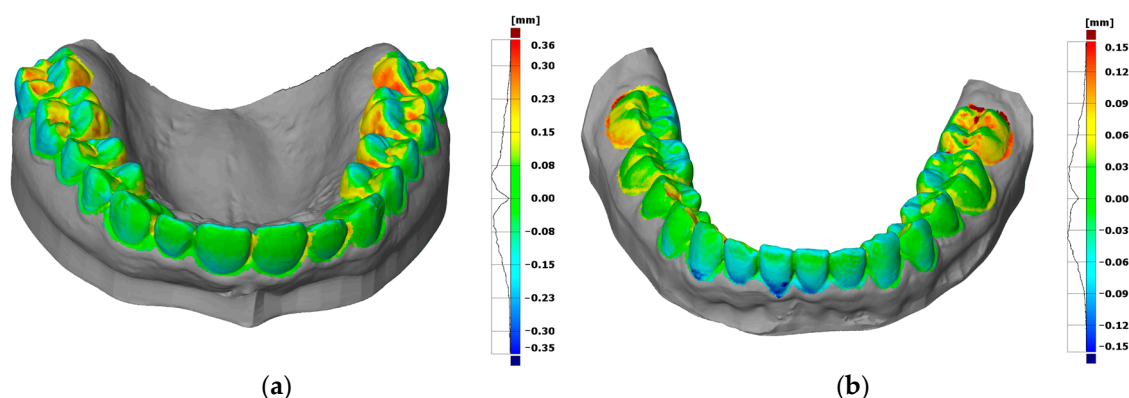


Figure 3. Representative CAD inspection output in GOM Inspect showing surface superimposition and colour-coded deviation mapping for: (a) maxilla and (b) mandible.

Table 1. Global surface deviation by comparison type.

Comparison	n ¹	Mean RMS ² (mm)	SD RMS (mm)	Mean Bias (mm)	Mean SD (mm)	Max Absolute Extreme (mm)
IOS vs. print	4	0.090	0.032	−0.028	0.078	0.850
print vs. powder	4	0.039	0.028	0.000	0.038	0.500
IOS vs. powder	4	0.088	0.017	−0.005	0.088	0.490

¹ The number of observations included in that summarized group. ² Mean RMS represents the average RMS value across observations within that group.

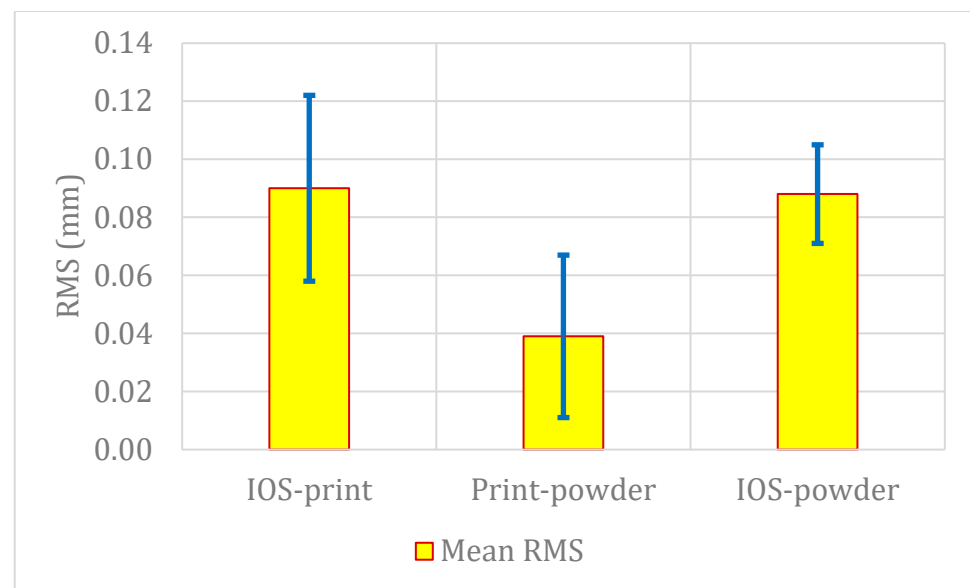


Figure 4. Mean global RMS deviation (mm) for the three main comparison groups, shown from left to right as IOS vs. powder-coated print, IOS vs. print, and print vs. powder-coated print. Error bars represent standard deviation (SD).

The global comparison revealed that the highest mean RMS value was observed for the IOS vs. printed model comparison, indicating that the transition from the digital scan to the physical model represented the stage associated with the greatest overall dimensional discrepancy. In contrast, the print vs. powder-coated print comparison showed a substantially lower mean RMS value, suggesting that the isolated contribution of powder application to total dimensional change was smaller than the overall deviation associated with model fabrication. The Mean bias values remained close to zero in all comparison groups. Because all datasets were registered using global best-fit alignment, these values primarily reflect the characteristics of the alignment procedure and should not be interpreted as evidence for or against systematic dimensional expansion or contraction. The markedly higher Max absolute extreme value observed in the IOS vs. print comparison compared with its mean RMS represented an isolated local extreme. Visual inspection of the deviation map indicated that this value originated at the model boundary, where trimming and incomplete edge capture can produce localized artefacts. Therefore, this value should be interpreted as a localized boundary deviation rather than as representative of the overall surface agreement, which is more appropriately described by the RMS values. The mean RMS of the print vs. powder-coated print comparison was approximately 56% lower than that of the IOS vs. print comparison.

3.2. Regional Analysis

Local analysis showed a higher mean RMS in the posterior zone than in the anterior zone. The anterior region had a mean RMS of 0.047 mm, while the posterior region had a mean RMS of 0.077 mm. The zone-based comparison is presented in Figure 5a,b, while the corresponding regional RMS values are shown in Table 2. The values in Table 2 represent mean regional RMS values averaged across four arch-level datasets and three comparison types (IOS vs. print, print vs. powder and IOS vs. powder), yielding $n = 12$ observations per zone.

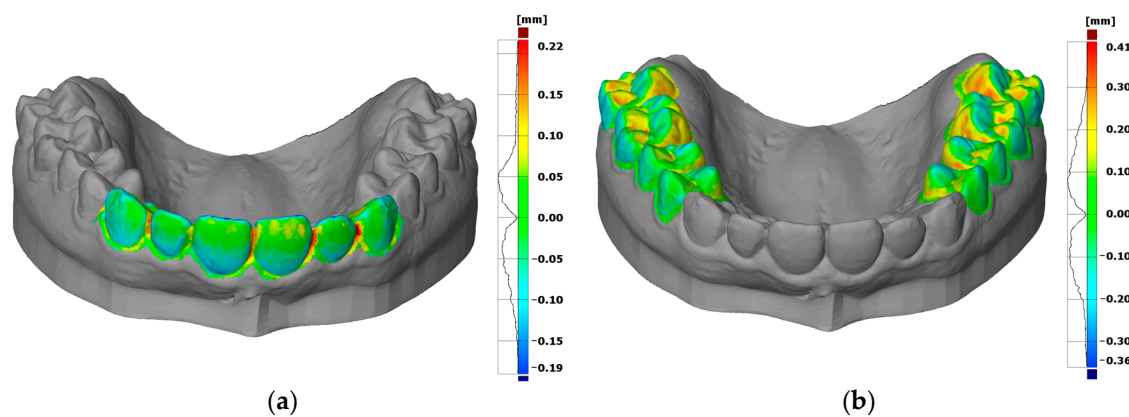


Figure 5. Regional RMS deviation in: (a) anterior and (b) posterior zones.

Table 2. Regional RMS deviation.

Region	n	Mean RMS (mm)	SD RMS (mm)	Mean Bias (mm)	Mean SD (mm)
Anterior	12	0.047	0.017	0.003	0.045
Posterior	12	0.077	0.037	−0.003	0.076

Regional analysis showed a higher mean RMS value in posterior regions than in anterior regions (0.077 vs. 0.047 mm), indicating a consistent trend toward greater posterior deviation. In addition to the higher average deviation, the posterior regions also exhibited increased SD RMS values, suggesting greater variability between observations and less uniform dimensional behaviour. The Mean bias values also remained close to zero. However, owing to the global best-fit registration strategy, these values should be interpreted cautiously because the alignment procedure itself tends to minimize signed deviations. The higher Mean SD observed in posterior regions further supports the presence of a broader distribution of local surface differences and suggests increased heterogeneity of the deviation patterns within these areas.

3.3. Maxilla and Mandible

The comparison between maxillary and mandibular datasets showed similar mean RMS values (0.069 vs. 0.076 mm in Table 3). This comparison did not indicate a meaningful arch-level difference in the present pilot dataset.

Table 3. Global RMS deviation by arch.

Arch	n	Mean RMS (mm)	SD RMS (mm)	Mean Bias (mm)	Mean SD (mm)	Max Absolute Extreme (mm)
Maxilla	6	0.069	0.038	−0.025	0.060	0.500
Mandible	6	0.076	0.033	0.003	0.075	0.850

The SD RMS values were also similar, suggesting comparable variability across both groups. The Mean bias values differed in sign but remained low in absolute magnitude, indicating only minor directional differences relative to the reference geometry. However, the mandibular group showed a higher Max absolute extreme value, suggesting that localized deviations reached greater magnitudes despite similar average deviation levels. This observation indicates that isolated local mismatch may occur independently of overall RMS behaviour.

3.4. Thermoformed Appliance Adaptation

Thermoformed appliance adaptation, evaluated from the internal (intaglio) surface relative to the corresponding printed model, differed between the two tested material thicknesses. Representative deviation maps for both material thicknesses are shown in Figure 6a,b, while summary values according to nominal material thickness are presented in Table 4. The 1.0 mm material showed a mean RMS of 0.207 mm, whereas the 1.5 mm material showed a higher mean RMS of 0.282 mm. This corresponds to an approximately 36% higher RMS deviation for the 1.5 mm material compared with the 1.0 mm material. The thicker material also showed a more negative Mean bias and a higher Mean SD, indicating a less uniform adaptation pattern and a broader distribution of local surface deviations. In contrast, the lower SD RMS value observed for the 1.5 mm material suggests that the increased deviation occurred consistently across observations rather than being driven by a single isolated case. The increase in Max absolute extreme values further indicates that thicker material was associated with more pronounced local mismatch in selected regions.

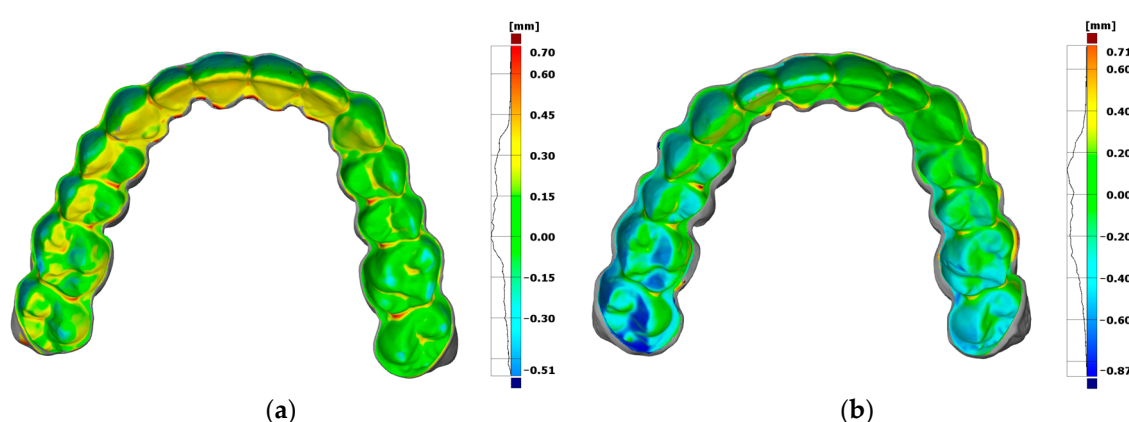


Figure 6. RMS deviation of thermoformed appliance adaptation according to material thickness for: (a) 1.0 mm material and (b) 1.5 mm material.

Table 4. Thermoformed appliance adaptation according to nominal material thickness.

Material Thickness	n	Mean RMS (mm)	SD RMS (mm)	Mean Bias (mm)	Mean SD (mm)	Max Absolute Extreme (mm)
1.0 mm	4	0.207	0.026	0.060	0.198	0.500
1.5 mm	4	0.282	0.012	−0.082	0.270	0.600

3.5. Local Powder Effect on the Incisor Surface

The half-and-half incisor analysis showed higher local deviation values on the powder-coated side. The local colour map used for this estimate is shown in Figure 7, while point-based summary values are presented in Table 5. The powdered half had a Mean deviation of 0.036 mm, whereas the non-powdered half had a Mean deviation of 0.006 mm. The estimated powder-related surface offset was therefore approximately 0.030 mm. The relatively low SD values observed in both regions suggest that the local surface offset was consistent across the selected measurement points. The minimum and maximum values also showed a narrow deviation range, indicating that the local displacement introduced by powder application was relatively uniform rather than concentrated in isolated points.

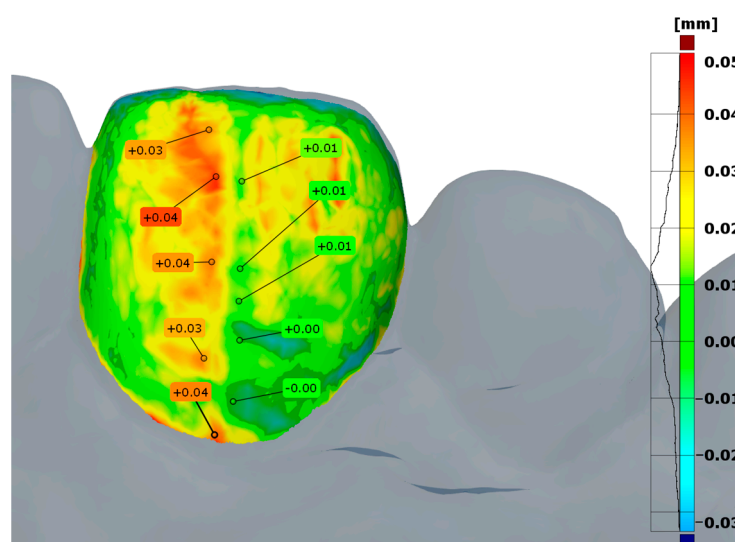


Figure 7. Local incisor analysis of the powder-related surface offset.

Table 5. Local incisor analysis of the powder-related surface offset.

Region	n	Mean Deviation (mm)	SD Deviation (mm)	Minimum (mm)	Maximum (mm)
Powdered half	5	0.036	0.005	0.030	0.040
Non-powdered half	5	0.006	0.005	0.000	0.010
Estimated powder layer	-	0.030	-	-	-

The values in Table 5 were obtained from five labelled measurement points on each half of the incisor surface: five points on the powder-coated side and five points on the non-powdered side. Unlike the global surface comparisons, this point-based analysis was used to estimate local coating-induced surface offset rather than overall surface agreement.

3.6. Practical Threshold Analysis

Practical threshold analysis was used to compare the proportion of RMS values falling below the selected deviation limits (Table 6). In the global dataset, 75% of the RMS values were at or below 0.10 mm and all values were at or below 0.20 mm. In the regional dataset, 83.3% of the RMS values were at or below 0.10 mm and all values were at or below 0.20 mm. In contrast, none of the thermoformed appliance RMS values were below 0.10 mm, and only 25% were at or below 0.20 mm.

Table 6. Practical RMS threshold analysis.

Dataset	≤0.10 mm	≤0.20 mm
Global	75%	100%
Regional	83.3%	100%
Thermoformed appliance	0%	25%

These results support a practical distinction between the relatively small deviations associated with digital model reproduction and the larger adaptation deviations introduced during thermoforming.

Exploratory Welch's *t*-tests were performed to support a descriptive interpretation of the RMS comparisons. A statistically significant difference was found between the anterior

and posterior regions ($t = -2.58$, $df = 15$, $p = 0.021$), with higher RMS values in the posterior region and a mean difference of 0.031 mm (95% CI: 0.005–0.057 mm). No statistically significant difference was found between maxillary and mandibular arches ($t = -0.31$, $df = 10$, $p = 0.761$), with a mean difference of 0.007 mm (95% CI: -0.041 – 0.054 mm). The comparison between thermoformed material thicknesses showed a statistically significant difference ($t = -4.86$, $df = 4$, $p = 0.008$), with higher RMS values for the 1.5 mm material and a mean difference of 0.075 mm (95% CI: 0.031–0.115 mm). These exploratory results should be interpreted cautiously because of the small pilot sample and the grouped structure of the observations.

4. Discussion

This study examined a complete digital-to-physical biomedical manufacturing workflow for orthodontic appliance fabrication rather than a single isolated step. The results show a consistent pattern: the printed model was the main source of dimensional difference relative to the IOS reference, posterior regions showed greater deviation than anterior regions, and the thicker thermoformed material adapted less uniformly than the thinner material.

The mean RMS of 0.090 mm for the IOS vs. print comparison falls within a range that is compatible with the reported values for printed dental and orthodontic models. Grassia et al. reported that orthodontic models printed for clear aligner production remained within a clinically accepted 0.25 mm threshold, although accuracy differed by printer technology and anatomical configuration [7]. The systematic review and meta-analysis by Rajagopalan et al. [8] further support that 3D-printing accuracy in orthodontics is influenced by printer technology, material selection and processing parameters. This is also consistent with broader dental and orthodontic printing studies, which show that model accuracy is influenced by multiple production parameters rather than by printer type alone [9–15].

The present findings are consistent with this literature: the printed models did not show large uniform displacement, but localized deviations were present. In resin-based printing, dimensional changes may also be associated with polymerization shrinkage, UV-curing conditions, material composition and post-curing behaviour [16,17]. Therefore, an RMS-based surface comparison is useful for describing overall surface agreement, whereas isolated maximum or minimum values should be interpreted mainly as indicators of localized mismatch [7–15,37,38].

The mean global RMS values for the IOS vs. print (0.090 mm) and IOS vs. powder-coated print (0.088 mm) comparisons were nearly identical. This small numerical difference should not be interpreted as an improvement caused by powder application. Rather, it suggests that the full-arch effect of the powder layer was below the variability associated with printing, rescanning, best-fit alignment and a full-arch surface comparison in this pilot dataset. The local half-and-half incisor analysis nevertheless confirmed that powder application produced a measurable local surface offset of approximately 0.030 mm. Therefore, powder may be relevant for localized surface measurements, even when its effect does not dominate full-arch RMS values.

The posterior region showed a higher RMS deviation than the anterior region. This trend was supported by the exploratory Welch's test, but should be interpreted cautiously because the regional analysis pooled observations from the same arch-level datasets across different comparison types. The finding is in line with the general behaviour of complete-arch scanning. Intraoral scanners reconstruct the arch from multiple images, and small registration errors may accumulate as the scan progresses. Recent full-arch IOS studies show that scan accuracy depends on scanner type, model configuration, operator-related

factors and scanning strategy, and that full-arch acquisition remains more demanding than short-span scanning [1–6]. Studies comparing complete-arch and quadrant scans also support the idea that longer scan spans are more vulnerable to accumulated error [5]. For this reason, reporting only a single global value can hide clinically relevant local differences. In this dataset, the anterior RMS was 0.047 mm, while the posterior RMS was 0.077 mm. The difference is modest in absolute terms and should be interpreted as a consistent directional trend rather than as definitive evidence of a population-level regional effect.

The direct print vs. powder comparison produced a lower mean RMS than the IOS vs. print comparison, indicating that the powder-related full-arch change was smaller than the combined deviation introduced by printing and rescanning. However, the half-and-half incisor test confirmed that powder application can produce a measurable local surface offset when evaluated point-by-point. This finding is consistent with studies showing that scanning-aid materials can alter the captured surface and influence scan accuracy depending on coating type and application method [28,29]. Donmez et al. [30] observed that scanning technology significantly affected measured deviations, whereas scan powder did not significantly influence overall dimensional deviations under the investigated conditions. The estimated local offset of approximately 30 μm shows that powder may be relevant for localized measurements even when it does not dominate full-arch RMS values.

The thermoformed appliance results are clinically relevant because the 1.5 mm material showed a higher RMS deviation than the 1.0 mm material, indicating less uniform adaptation to the printed model. Because only the internal (intaglio) surface was analysed, the nominal sheet thickness was not directly incorporated into the RMS calculations. Therefore, the observed difference between the 1.0 mm and 1.5 mm materials is interpreted as a difference in adaptation behaviour rather than a geometric offset caused by material thickness itself. The observed increase in RMS deviation for the 1.5 mm thermoformed material is consistent with the findings of Kenning et al. [21], who reported reduced dimensional accuracy when thermoformed appliances were fabricated on 3D-printed models with 1.0 mm and 1.5 mm shell thicknesses and recommended shell thicknesses of at least 2.0 mm. Although shell thickness and thermoforming material thickness represent different variables, both findings indicate that structural thickness can influence the dimensional fidelity of thermoformed orthodontic appliances. Elshebiny et al. [22] reported that changing the printing layer thickness from 100 to 170 μm did not significantly influence model accuracy or the perceived fit of thermoformed retainers, suggesting that this parameter may have a limited effect within the investigated range. Although this study evaluated thermoformed material thickness rather than model shell or printing layer thickness, these findings support the broader interpretation that both the printed model and thermoforming conditions can influence the final appliance geometry.

The observed difference between the 1.0 mm and 1.5 mm materials is also consistent with the general behaviour of thermoformed polymer sheets. During thermoforming, heating and pressure forming create non-uniform stretching of the material, and adaptation depends on tooth morphology, pressure, temperature, material stiffness and local deformation. Studies of polymer thermoforming have shown that sheet heating, forming conditions, mould geometry and cooling influence the material flow and final thickness distribution in thermoformed parts [26]. Micro-CT and mechanical/thickness studies on clear aligners also show that thermoformed appliances may lose thickness compared with the original sheet and that thickness, gap width and adaptation are not uniform across the arch [19–25].

The threshold analysis further supports a practical distinction between the dimensional deviation associated with the printed model workflow and the adaptation deviation of the thermoformed appliance.

As shown in Table 6, the global and regional RMS values were generally within lower deviation ranges, whereas the thermoformed appliance adaptation values were consistently higher. In practical terms, the printed model showed relatively low surface deviation as a working base, whereas thermoforming introduced a larger additional source of dimensional change.

However, this study has several limitations. The sample size was small and included only two anonymized patient-derived datasets and four arch-level datasets. Therefore, the analysis should be interpreted as a controlled pilot investigation rather than as a population-level clinical trial. Because the powder-free intraoral scan served as an internal reference rather than a metrologically traceable reference standard, the present study evaluated relative dimensional deviations between workflow stages rather than absolute trueness of the manufactured components. Consequently, the findings should be interpreted as comparative workflow assessments rather than metrological validation of manufacturing accuracy. Because the thermoformed appliances were evaluated relative to their corresponding printed models, the present analysis primarily describes appliance adaptation to the manufacturing model. A direct comparison between the initial intraoral scan and the final thermoformed appliance would provide additional information on cumulative workflow deviation and should be included in future studies. The results are linked to one intraoral scanner, one model-preparation software workflow, one printer/material combination, one post-processing protocol, one thermoforming system and one scanning-aid product. Repeated scans and repeated registrations were not performed. Therefore, measurement precision and repeatability were outside the scope of the present pilot study. The regional analysis combined measurements from four arch-level datasets across three comparison types. Consequently, the regional observations cannot be considered fully independent, and the reported statistical analyses should be interpreted as exploratory. A mixed-effects modelling approach with patient- and arch-level random effects would be more appropriate in larger future studies. In surface-based 3D analysis, the selected alignment method, comparison region and software environment may influence the final numerical output, especially when reduced or local areas are evaluated [37,38]. Studies on point-cloud registration and CAD-based comparisons of scanned physical objects similarly show that registration strategy, scan noise and partial surface capture can affect deviation values and the robustness of a geometric comparison [34].

Because this study was designed to reflect routine clinical and dental laboratory practice, the procedures were performed under standard dental working conditions, including an ambient temperature of approximately 22 °C and a relative humidity range of 40–60%.

However, the exact storage time between post-processing and rescanning was not continuously monitored and may represent an additional source of variability that should be controlled more strictly in future validation studies. The half-and-half incisor powder analysis provides a useful local estimate of coating-related offset, but it should be interpreted as a controlled surface-level observation rather than as a full-arch statistical endpoint. Despite these limitations, the strength of this study is that the same workflow and inspection logic were applied across related experimental conditions, allowing the main sources of deviation to be compared in a structured way.

Future work should include a larger number of cases, repeated scans and repeated alignments, additional thermoformed materials, and a direct comparison of different printing orientations and post-processing protocols. Micro-CT or high-resolution optical scanning could also be used to examine material thickness and internal gap distribution in

more detail. Future studies should also combine global RMS surface analysis with localized linear distance measurements, as used in previous studies of 3D-printed dental models and clear-aligner model fabrication, to evaluate clinically relevant dimensional deviations in specific anatomical regions [39,40].

5. Conclusions

Based on the results presented in this study, the following conclusions can be drawn:

1. The largest global surface deviation was observed between the IOS reference and the 3D-printed model, with a mean RMS of 0.090 mm.
2. The isolated effect of powder on the printed model was smaller, with a mean RMS of 0.039 mm in the direct print vs. powder comparison.
3. Posterior regions showed greater deviation than anterior regions, supporting the value of regional analysis in complete-arch workflows.
4. The 1.5 mm thermoformed material showed a higher RMS deviation than the 1.0 mm material, indicating less uniform adaptation.
5. The local incisor test estimated the powder-related surface offset at approximately 30 μm .

Overall, the present pilot study characterizes relative dimensional deviations across consecutive stages of a digital-to-physical orthodontic workflow. The results identify 3D printing and thermoforming as the workflow stages associated with the greatest relative deviations, whereas the influence of scanning-aid coating remained limited at the full-arch level but detectable in localized surface analysis.

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Informed Consent Statement: Not applicable. This study used anonymized patient-derived intraoral scan datasets and derived models, and no identifiable patient information is presented.

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