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Evaluation of surface and positional trueness of removable dies fabricated through fused filament fabrication

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A R T I C L E I N F O

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Surface trueness

A B S T R A C T

Objectives: To evaluate the surface and positional trueness of removable dies fabricated using fused filament fabrication (FFF), compared to dies produced with digital light processing (DLP), addressing the limited evidence on the deviations of FFF-based removable dies.

Methods: A typodont with a prepared right mandibular first molar was digitized to design a removable die and corresponding hollow partial arch cast. Forty dies ($n = 10$) and four casts ($n = 1$) were fabricated using FFF (Filadent Aligner [FF-AL], Filadent Gypsum [FF-GP], Filadent Tray [FF-TR]) or DLP (DentaModel [DM]). Dies and their positions in the casts were digitized to assess surface (crown, root, root base, overall) and positional (crown region and point-based) deviations. Data were analyzed either with one-way analysis of variance (surface deviations) or Kruskal-Wallis tests (positional deviations, $\alpha = 0.05$).

Results: DM exhibited the lowest crown region and overall deviations, followed by FF-TR ($P < 0.001$). Root deviations increased in the order of DM, FF-TR, FF-AL, and FF-GP, whereas FF-TR had the lowest base of the root deviations ($P < 0.001$). Seated FF-GP dies had lower crown region deviations than the other FFF-based dies, while DM led to lower deviations than FF-TR ($P \leq 0.041$). FF-AL showed lower point-based deviations than FF-GP ($P = 0.001$).

Conclusions: FFF-fabricated dies showed lower surface trueness than DM dies, with FF-TR achieving the highest trueness among FFF dies. Positional deviations remained within clinically acceptable limits, though FF-TR dies tended to be positioned coronally and the others apically. FFF may be used to produce clinically acceptable dies, but DLP offers superior surface trueness.

Clinical Significance: Removable dies produced with the tested polylactic acid filaments and FFF printer may serve as alternatives to those fabricated with the tested resin and vat polymerization printer, given the small and potentially clinically irrelevant differences in surface deviations and clinically acceptable mean positional deviations.

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1. Introduction

Stone casts obtained from elastomeric impressions have traditionally served as the reference standard for fixed dental prostheses [1,2]. However, certain clinical limitations, such as distortion during impression or cast fabrication [3,4], have prompted the integration of digital workflows [5,6]. Advances in computer-aided design and computer-aided manufacturing (CAD-CAM) technologies, together with intraoral scanning, now facilitate fully digital, model-free workflows for many single crowns and short-span restorations [7]. Despite this trend, complex restorative cases, restorations requiring enhanced esthetics, or indirect procedures that benefit from verification outside the mouth may still necessitate physical casts with removable dies derived from intraoral scans using CAD-CAM techniques [3,8,9]. Additive manufacturing offers a reproducible and sustainable alternative to subtractive methods, enabling fabrication of complex geometries, such as removable dies, while minimizing material waste [10–14]. Unlike stone dies, additively manufactured removable dies are produced and post-processed separately prior to cast assembly, making it important to understand the factors affecting their dimensional and positional accuracy to achieve precise restorations [14]. Therefore, investigating incremental improvements in removable die trueness retains scientific and practical value in contemporary prosthodontics.

Although various additive manufacturing technologies can be used to fabricate polymer-based appliances, they all rely on building objects layer by layer [5,15]. Among these technologies, vat-polymerization methods such as digital light processing (DLP) are commonly used in dentistry [16], particularly for manufacturing dental casts and removable dies [12,15,17]. However, appliances produced using vat-polymerization techniques must be cleaned to eliminate residual unpolymerized resin [18], typically with organic solvents such as isopropyl alcohol (IPA) [19,20], which can pose hazard if waste is not appropriately handled [21]. In addition, polymerization shrinkage may introduce internal stresses and dimensional distortion, particularly in large objects such as dental casts [22]. Fused filament fabrication (FFF) is another additive manufacturing method based on fused deposition modeling, in which thermoplastic materials are heated, extruded through a fine nozzle, and deposited layer by layer to form solid objects [23]. FFF may provide a simpler, more cost-effective alternative to vat polymerization, with minimal, solvent-free post-processing, no separate polymerization step, and the option to use recyclable or degradable materials [24,25]. While a range of biocompatible materials are applicable with FFF [26,27], polylactic acid (PLA) is widely used because of its low melting temperature, which supports strong interlayer bonding and intricate geometries, as well as its biodegradability, biocompatibility, and renewable origin [28].

Previous studies have focused on the dimensional and positional deviations of additively manufactured removable dies [1,3,9,11–13,29–34]. However, these investigations mainly focused on how different additive manufacturing methods or processing parameters influenced die deviations, and to the authors' knowledge, only one study has evaluated the surface trueness of removable dies fabricated using FFF in comparison with other additive manufacturing technologies [35]. Exploring the potential of FFF for removable dies is particularly relevant, as this approach may offer a cost-effective solution [36–38], while avoiding certain postprocessing steps that require chemical handling [16], thereby enhancing safety and practicality in clinical workflows. In addition, previous studies have reported that casts produced using FFF can achieve similar or higher dimensional trueness compared with casts fabricated with other additive manufacturing technologies [39–41], further supporting its potential clinical applicability. Therefore, this study aimed to evaluate the dimensional and positional trueness of removable dies fabricated by FFF using different PLA filaments and to compare their accuracy with dies produced by DLP. The null hypotheses were that material type would not affect the i) surface and ii) positional trueness of tested removable dies.

2. Materials and methods

The mandibular right first molar of a typodont (ANA-4; Frasaco GmbH, Tettnang, Germany) was prepared with a 1 mm-wide chamfer finish line. A partial arch scan including the adjacent premolar and molar was made using an intraoral scanner (CEREC Primescan v5.2; Dentsply Sirona, Bensheim, Germany). The resulting file was imported into a CAD software program (DentalCAD 3.0 Galway; exocad GmbH, Darmstadt, Germany), where a removable die (1.5 mm pin height, 1 mm seating width, 10 mm taper height, 0-degree taper angle) and a hollow cast (0.12 mm shaft gap, 0 mm pedestal height, 0.5 mm average ditch width and depth, 2 mm average ditch height, 2.5 mm wall thickness, 1 mm cavity fill diameter) were designed using the software program's model creator tool [1]. After finalizing the designs, reference standard tessellation language (STL) files were exported for the removable die (D-STL) and the hollow partial-arch cast, both with the die (CWD-STL) and without the die (CWOD-STL).

The D-STL and CWOD-STL files were imported into slicing software program (Bambu Studio; Bambu Lab, Shenzhen, China), positioned on their bases, and had supports generated automatically. Thirty removable dies (n = 10) and corresponding partial arch casts (n = 1) were then produced using an FFF three-dimensional (3D) printer (X1 Carbon; Bambu Lab, Shenzhen, China) with 3 PLA filaments: FF-AL (Filadental Aligner Spezial Grey; 3dk.berlin, Berlin, Germany), FF-GP (Filadental Plaster White; 3dk.berlin, Berlin, Germany), and FF-TR (Filadental Tray; 3dk.berlin, Berlin, Germany). General printer settings included a layer height of 0.15 mm, a first-layer height of 0.2 mm, four outer contours, five solid layers on both top and bottom surfaces, and a 30 % grid infill pattern, with a printing speed of 150 mm/s. Material-specific temperatures were set according to manufacturer recommendations: FF-TR specimens were printed at a nozzle temperature of 265 °C and a bed temperature of 85 °C, while the other specimens were printed at 230 °C with a bed temperature of 60 °C [22]. The same files were imported into the nesting software program (Composer v2.0.8; Asiga, Sydney, Australia) for a DLP-based 3D printer (MAX UV; Asiga, Sydney, Australia). After orienting the files and generating supports, 10 removable dies and one partial arch cast were fabricated using the printer manufacturer's proprietary dental cast resin (DM, DentaModel; Asiga, Sydney, Australia) with 100 μm layer thickness [13,29]. After fabrication, DM specimens were cleaned with IPA (5 min of first wash and 5 min of second wash), then postpolymerized using a xenon flash unit (Otoflash G171; NK Optik GmbH, Baierbrunn, Germany) for a total of 4000 flashes (2 × 2000) under a nitrogen atmosphere [3]. Support structures of all removable dies and partial arch casts were manually removed with a small bur (Lab Carbide #71 G; Keystone Industries, Gibbstown, NJ, USA) under optical magnification loupes (EyeMag Pro; Carl Zeiss, Carl Zeiss, Oberkochen, Germany) at × 3.5 magnification and no additional processing was performed.

All removable dies and hollow casts were scanned within 24 h after fabrication using the same intraoral scanner. Each die was positioned perpendicularly on a scanning plate, and scanning began with the crown portion, followed by the axial surfaces and the ditch at the tip of the root. The resulting STL file from this scan was saved as the removable die test STL (DT-STL). Next, the removable die was seated into its corresponding cast, and the entire assembly was scanned to generate cast with removable die test STL (CWDT-STL). This process was repeated for all removable dies. All scans were performed by one operator (E.E.) in a room with controlled temperature and humidity, and the intraoral scanner was calibrated prior to scanning each group to ensure accuracy.

All STL files were imported into metrology-grade 3D analysis software program (Geomagic Control X v.2022.1.1; 3D Systems, Morrisville, NC, USA) to assess the dimensional and positional trueness of the dies. The D-STL was used as the reference file and was virtually segmented into 3 regions, crown, root, and the base of the root, using the software program's region tool, allowing evaluation of both individual regions and overall deviations. A DT-STL file was then imported as the target and superimposed over the segmented D-STL using initial and iterative closest point algorithm-based best-fit alignment methods. Dimensional deviations for each region and overall were automatically calculated using the root mean square (RMS) method, as RMS values provide a robust measure of deviations by combining both positive and negative differences. Higher RMS values indicate lower trueness, whereas lower RMS values reflect higher congruence, making this metric suitable for comparative assessment. In addition, color maps with ±10 μm tolerance and ±100 μm nominal values were generated with the 3D compare tool for qualitative analysis (Fig. 1) [1]. The region tool was also used to isolate the crown portion of the die and the adjacent teeth on the CWD-STL. A CWDT-STL was then superimposed over the segmented CWD-STL using the same alignment algorithms, while excluding the crown region of the removable die by applying the "use selected data only" function. Positional deviations for each die were defined based on the automatically calculated RMS values of the crown region. Deviations of the adjacent teeth were also recorded for each CWDT-STL, and the average values were used to evaluate the potential effect of the 3D printer and intraoral scanner on the measured die deviations within casts (Fig. 2). Positional deviations were deliberately assessed using one hollow cast per resin group to maintain consistency across measurements and to limit additional labor and material costs

A previously established point-based measurement was also applied to further evaluate the positional deviations of the dies [1,3,13,29]. For this analysis, a two-dimensional plane was generated through the crown portion of the die in the mesiodistal direction, and five points were virtually identified once on the CWD-STL: the most distal point of the margin, the tip of the distal cusp, the deepest point of the occlusal fossa, the tip of the mesial cusp, and the most mesial point of the margin (Fig. 3). These reference points were saved as a template to ensure consistent correspondence and to minimize operator-related bias from repeated manual identification. After each CWDT-STL was superimposed on the CWD-STL, the software program automatically calculated the distance deviations of these points, with values recorded as positive or negative depending on the relative position of each point. A negative value indicated that the point on the CWDT-STL was positioned below its counterpart on the CWD-STL, whereas a positive value indicated the opposite. The absolute values of these deviations were used for statistical analysis.

The Shapiro-Wilk test was used to evaluate the normality of measured deviations. While the surface deviations showed normal distribution, positional deviations did not. Therefore, one-way analysis of variance and Tukey tests were used to evaluate the surface deviations of the removable dies, whereas Kruskal-Wallis and Bonferroni-corrected post hoc tests were used for positional deviations of the dies. All statistical analyses were performed with an analysis software program (SPSS v26; IBM Corp, Armonk, NY, USA) at a significance level of $\alpha = 0.05$.

3. Results

Significant differences were observed among the test groups in surface deviations of different die regions ($P < 0.001$, $F = 337.106$ for crown, $F = 118.853$ for root, $F = 27.658$ for base of the root, and $F = 168.126$ for overall deviations). When the crown region was considered, DM dies had the lowest deviations, followed by FF-TR dies ($P < 0.001$). However, the difference between FF-AL and FF-GP dies was not statistically significant ($P = 0.709$). When the root region was considered, measured deviations significantly increased in the order of DM, FF-TR, FF-AL, and FF-GP ($P < 0.001$). When the base of the root region was considered, FF-TR dies had the lowest deviations ($P < 0.001$) and the differences among other groups were not significant ($P \geq 0.185$). When the overall deviations were considered, DM dies had the lowest values ($P < 0.001$). In addition, FF-TR dies had lower deviations than FF-AL and FF-GP dies ($P < 0.001$), which had statistically similar values ($P = 0.999$, Table 1).

Figs. 4 and 5 present the box plot graph of measured positional deviations. Positional deviations of tested removable dies showed significant differences ($P < 0.001$, test statistics = 28.220 for crown region deviations and $P = 0.003$, test statistics = 14.287 for point-based deviations). Seated FF-GP dies had lower crown region deviations in the cast than FF-AL and FF-TR dies ($P \leq 0.041$). In addition, DM dies had lower deviations than FF-TR dies ($P = 0.008$). The only significant differences in point-based deviations of tested dies were between FF-AL

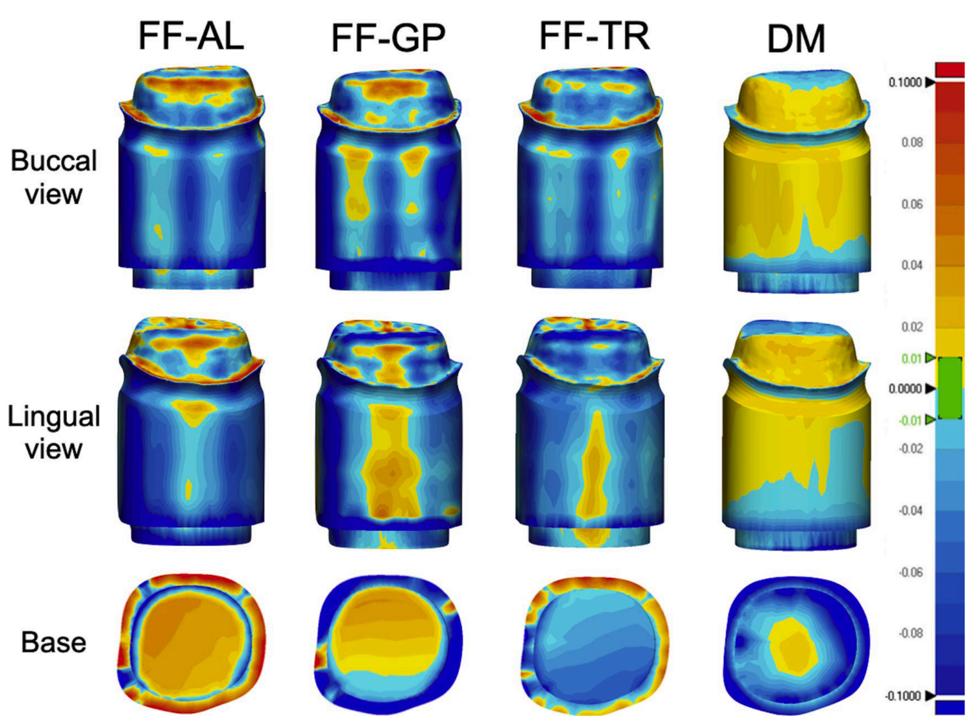

Fig. 1. Representative color maps of tested removable dies. DM, DentaMODEL; FF-AL, Filadental Aligner Spezial Grey; FF-GP, Filadental Plaster White; FF-TR, Filadental Tray.

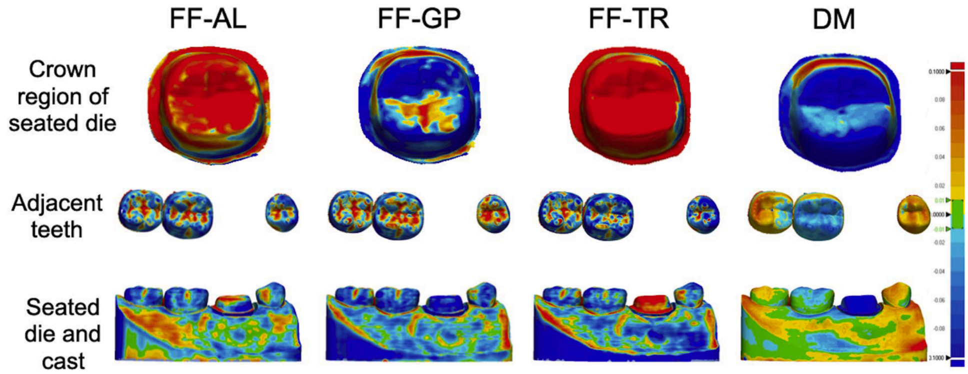

Fig. 2. Representative color maps of removable dies seated in their respective partial arch casts. DM, DentaMODEL; FF-AL, Filadental Aligner Spezial Grey; FF-GP, Filadental Plaster White; FF-TR, Filadental Tray.

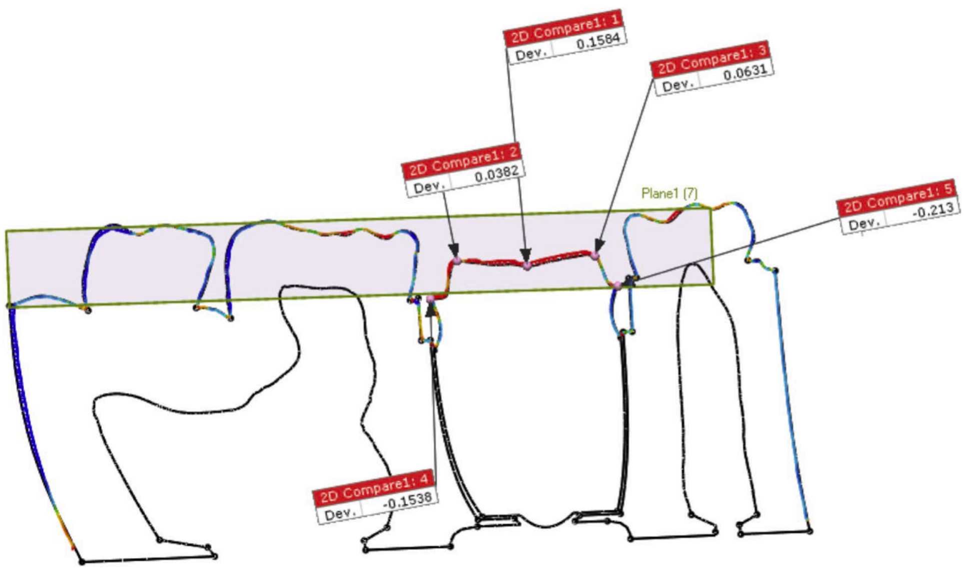

Fig. 3. Cross-sectional view of two-dimensional plane and predetermined points generated for point-based deviations.

Table 1
Mean surface deviation values and standard deviations (95 % confidence intervals, μm) for each region.

Material	Crown region	Root region	Base of root region	Overall
FF-AL	60.1 ± 4.5^{c}	101.5 ± 7.6^{c}	84.5 ± 8.8^{b}	86.2 ± 5.6^{c}
	(56.9–63.4)	(96.0–106.9)	(78.3–90.8)	(82.1–90.2)
FF-GP	58.7 ± 2.4^{c}	114.9 ± 7.8^{d}	92.1 ± 8.6^{b}	85.8 ± 5.9^{c}
	(57.0–60.4)	(109.3–120.5)	(86.0–98.2)	(81.6–90.0)
FF-TR	48.8 ± 2.9^{b}	87.4 ± 3.6^{b}	61.2 ± 4.5^{a}	67.3 ± 3.4^{b}
	(46.8–50.9)	(84.9–89.9)	(58.0–64.4)	(64.9–69.8)
DM	22.5 ± 1.4^{a}	61.3 ± 6.8^{a}	86.2 ± 9.8^{b}	42.0 ± 5.1^{a}
	(21.5–23.5)	(56.4–66.1)	(79.1–93.2)	(38.3–45.6)

Different superscript lowercase letters indicate significant differences among subgroups within each column ($P < 0.05$).

and FF-GP dies, as FF-AL dies had lower deviations ($P = 0.001$, Table 2). Fig. 6 shows the raw point-based deviation values of tested dies, while Table 3 displays the deviations of the partial arch casts.

4. Discussion

DM dies exhibited the highest surface trueness across all tested regions, except at the die base, in which FF-TR dies exhibited the highest trueness. Based on these results, the first null hypothesis was rejected. Fundamental differences in the fabrication processes of FFF-based dies and DM dies may be related to observed differences. In FFF manufacturing, PLA filaments undergo a change from solid to semi-liquid and then resolidify, a sequence that might introduce irregularities or voids between layers and reduce surface trueness [27]. In contrast, DLP printers polymerize each layer of photosensitive resin in a single projection and repeat this process sequentially to produce the object [5,6]. Post-fabrication polymerization may further enhance inter- and intra-layer bonding, which may contribute to the higher trueness observed in DLP-produced dies. Nevertheless, although statistically significant differences were identified among the surface deviation values of the tested dies, the largest mean differences ranged from 30.9 μm (FF-GP vs FF-TR at the base of the root) to 53.6 μm (FF-GP vs DM in the root region). These discrepancies are relatively small, potentially imperceptible visually, and considered clinically negligible, given that previously reported acceptability thresholds for additively manufactured casts range from 120 μm to 200 μm [5,15]. From a clinical standpoint, such small deviations may suggest that crown seating accuracy is unlikely to be adversely affected when appropriate verification and adjustment protocols are followed.

Considering the relatively small significant differences observed among the surface deviations of tested dies, a qualitative assessment of the demonstrative color maps could provide supplementary insight by helping to contextualize and support the quantitative dimensional deviation findings. The crown region of FFF-based dies was mainly characterized by different shades of blue indicating undercontours; however,

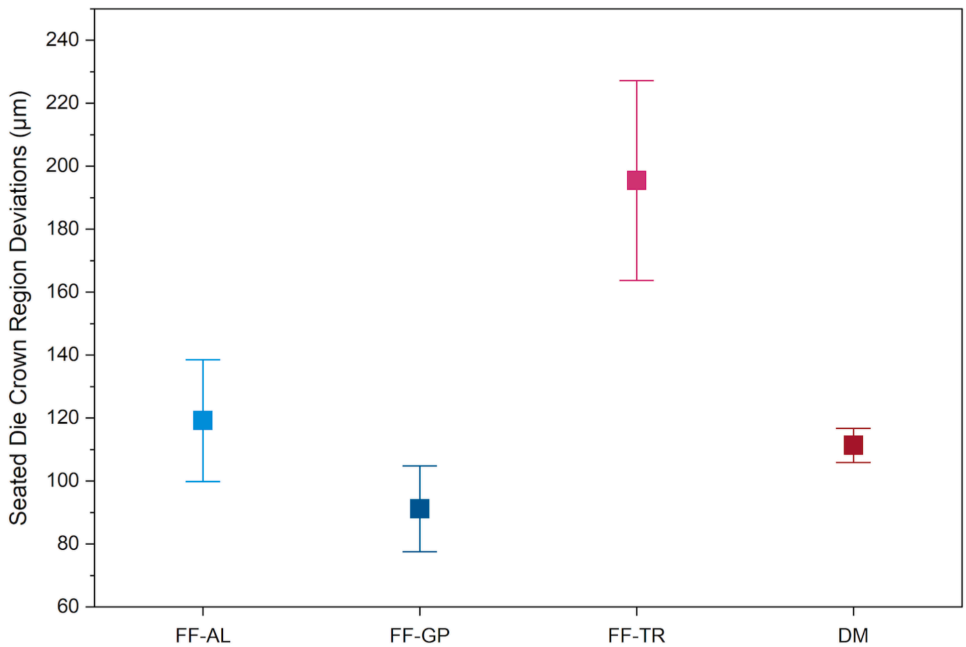

Fig. 4. Box plot graph of measured seated crown region deviations of tested materials (μm). DM, DentaMODEL; FF-AL, Filadental Aligner Spezial Grey; FF-GP, Filadental Plaster White; FF-TR, Filadental Tray.

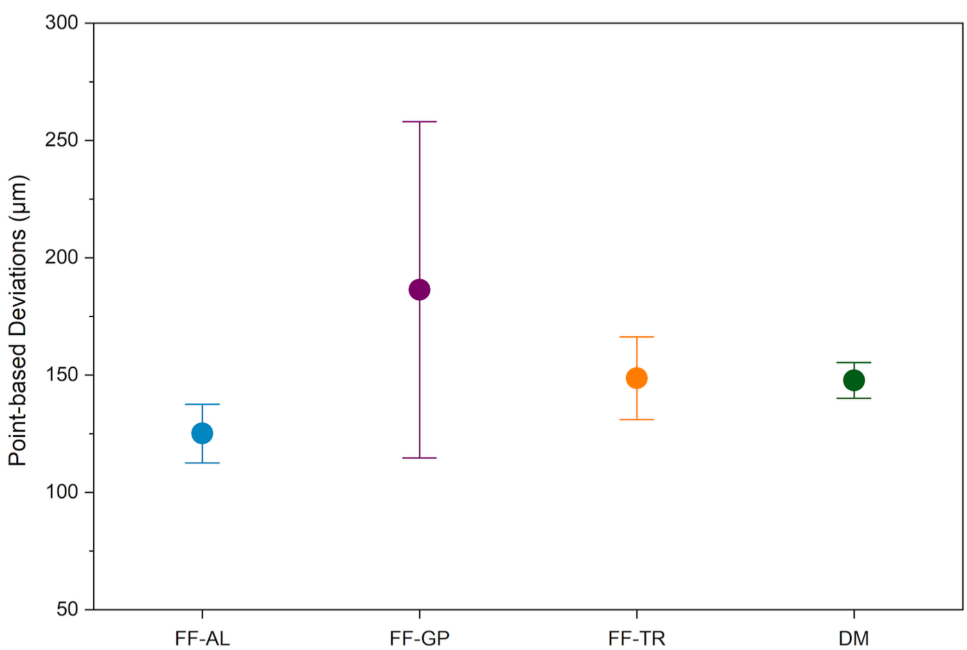

Fig. 5. Box plot graph of measured point-based deviations of tested materials (μm). DM, DentaMODEL; FF-AL, Filadental Aligner Spezial Grey; FF-GP, Filadental Plaster White; FF-TR, Filadental Tray.

yellow, orange, and red, which indicate overcontours, were also visible on the coronal part and the margins. Localized overcontours in these regions may interfere with complete crown seating and require selective adjustment prior to definitive placement. DM dies also exhibited a heterogeneous color distribution of yellow and light blue, but yellow was the dominant color, indicating that occlusal or axial adjustments may still be required even with higher surface trueness. The root region of the dies followed a similar color pattern as their crowns, irrespective of the material. Although adjustments of the root regions of the dies may improve their fit, FFF-based dies predominantly exhibited different shades of blue. Such undercontoured regions may require careful adjustment, as excessive correction of overcontours could compromise die stability and affect seating reproducibility. The base of the root was the most heterogeneous region for each material, with distinct color patterns ranging from light blue to red, which may be related to manual support removal.

The second null hypothesis was also rejected, as significant differences were found in the positional trueness of tested dies for both evaluated outcomes. Consistent with previous studies [1,3,13,29], positional trueness was quantified using surface deviation measurements and point-based analyses of the crown region of seated dies, and was further supported by qualitative assessment of color maps showing the

Table 2
Median (interquartile ranges) positional deviation values of seated dies (µm).

Material	Crown region deviations	Point-based deviations
FF-AL	114.8[bc] (104.8–125.0)	124.9[a] (109.7–135.0)
FF-GP	87.8[a] (79.2–105.2)	153.4[b] (149.3–166.5)
FF-TR	201.2[c] (190.3–217.9)	144.6[ab] (137.4–165.0)
DM	112.2[ab] (106.8–115.6)	146.7[ab] (137.6–158.8)

Different superscript lowercase letters indicate significant differences among subgroups within column ($P < 0.05$).

crown region within their corresponding partially dentate casts. All dies presented a nonuniform color pattern; however, FF-AL and FF-TR were predominantly represented by red areas, whereas the remaining dies showed mainly dark blue regions. Despite this general trend, FF-GP and DM dies also displayed overcontoured areas of varying magnitude on the axial and occlusal surfaces. These patterns indicate that uncorrected positional deviations may result in premature occlusal contacts, compromised interproximal relationships, and increased chairside adjustment requirements. Additionally, post-adjustment instability of seated crowns may occur if corrections are not performed cautiously, particularly in situations with combined surface and positional deviations. The crown region deviation values of dies seated in the casts in the present study may be even smaller when the trueness of the cast fabricated without a die is taken into account. The mean RMS values of the casts ranged from 33.8 µm to 73.7 µm, which fall within the previously reported acceptability limits for additively manufactured casts [5, 15]. These deviations may therefore be regarded as fabrication-related errors, potentially originating from the scanning and printing processes of the cast, irrespective of the presence of a removable die. Interpreting the raw point-based data offers further insight into the spatial positioning of the dies within their corresponding dentate casts, with negative values representing apical displacement and positive values indicating coronal displacement. Based on this analysis, FF-AL, FF-GP, and DM dies mainly showed an apical shift relative to their design file, whereas FF-TR dies predominantly exhibited a coronal displacement. Although these positional deviations remained clinically acceptable [5,15], confirmation of die seating is essential to minimize occlusal discrepancies and ensure predictable crown fit. Seating or verification matrices [14], may assist in identifying vertical discrepancies, thereby reducing the risk of uneven load distribution, occlusal wear, and patient discomfort during function.

Kim et al. [35] evaluated the crown region surface trueness of removable dies representing four clinical situations (anterior crown, posterior crown, posterior occlusal inlay, and posterior mesio-occlusal inlay) fabricated using FFF, DLP, or SLA printers. One FFF printer produced the lowest trueness, while one SLA printer produced the highest, and the clinical situation also influenced the results. The deviations of FFF-based dies reported by Kim et al. [35] ranged from 35.2 µm to 93.9 µm, whereas those of DLP-based dies ranged from 27.9 µm to 45.8 µm. These values are comparable to the surface deviation ranges observed in the present study, in which FFF-produced dies exhibited higher crown region deviations than DLP dies but remained within clinically acceptable thresholds [5,15]. This agreement with prior literature supports the clinical reliability of FFF-fabricated dies and suggests that, when optimized, such dies may contribute to stable crown seating, reduced occlusal adjustment requirements, and favorable long-term prosthesis performance.

The study was limited by the use of only PLA filaments, and the absence of other available FFF materials constrains the applicability of the findings to other commonly used filaments. The study therefore focused on a controlled comparison within a standardized PLA-based workflow rather than a broader material evaluation. Another limitation was the absence of a stone die control group, which prevented direct

Table 3
Mean surface deviation values (µm) of dentate partial arch casts without dies.

Material	Partial arch cast surface deviation
FF-AL	54.6
FF-GP	67.0
FF-TR	73.7
DM	33.8

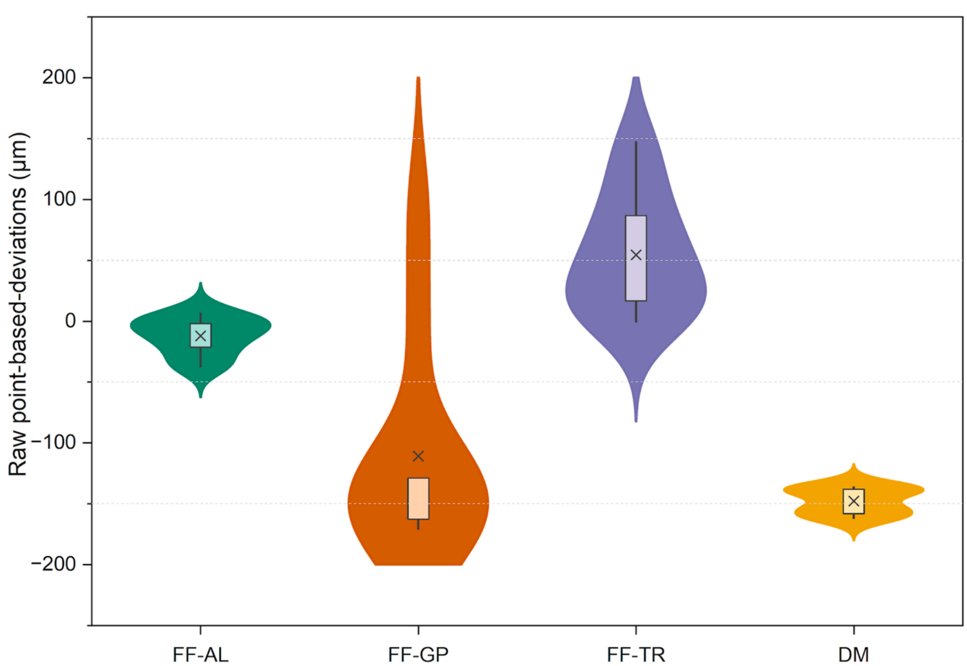

Fig. 6. Violin graph of raw point-based deviations (µm) of each group displaying the magnitude and the direction of deviations. DM, DentaMODEL; FF-AL, Filadental Aligner Spezial Grey; FF-GP, Filadental Plaster White; FF-TR, Filadental Tray.

comparison with the conventional clinical standard. This decision reflected the ongoing shift in prosthodontics toward fully digital workflows, in which digitally fabricated casts and dies are increasingly preferred. The use of DLP-based control dies was therefore aligned with current digital practice and the workflow clinicians and technicians are progressively adopting. Although commonly referenced clinical thresholds for additively manufactured casts provide useful benchmarks [5,15], they are not directly comparable to stone die performance. Because the manufacturer did not fully disclose the chemical composition and formulation of the PLA filaments, it remains unclear how specific material properties may have contributed to the observed deviations. All FFF specimens were produced using one printer and fixed printing parameters, and variations in equipment or settings could lead to different outcomes. In addition, certain printing parameters could not be fully standardized across methods, as layer thickness, build orientation, support placement, and post-processing requirements are inherently dependent on the specific material and fabrication technique. While all efforts were made to maintain consistent workflows within each method, these material- and method-specific constraints mean that some observed differences may reflect inherent procedural requirements rather than material properties. Geometric factors also contributed to limitations, as variations in taper or structural form of additively manufactured components, as well as design parameters of the dies and casts, may affect fit. Additionally, using one hollow cast per group to assess positional deviations may have introduced potential bias, because any cast-specific distortion would have influenced all measurements. Despite the high dimensional stability reported for partial arch casts [13,29], using multiple casts per group in future studies may help validate positional findings. All removable dies and hollow casts were digitized using an intraoral scanner, a method commonly adopted in similar studies [1,3,13,29] and reported to provide accuracy comparable to extraoral scanners [42]. Continuous scanning reduced potential stitching errors, yet scanner selection, digitization protocols, and analysis software may still have contributed to variability. Finally, precision was not formally evaluated, which limits the interpretation of accuracy for the tested manufacturing methods in removable die fabrication. Future research should explore strategies to optimize the dimensional and positional accuracy of FFF-produced removable dies, particularly in the context of clinical procedures such as crown contact adjustments. Incorporating multiple casts, varied printing parameters, and long-term stability assessments under different storage conditions will enhance reliability and support greater integration into digital workflows, where optimized printing parameters may improve crown seating, reduce occlusal adjustment needs, and enhance prosthesis longevity, with artificial intelligence-assisted parameter optimization, predictive print simulation, and automated processes offering potential to reduce variability and improve reproducibility.

5. Conclusions

Within the limitations of this study, the following conclusions were drawn:

1. DM dies mostly had the highest surface trueness across evaluated regions, whereas FF-TR dies showed the highest surface trueness among the FFF-fabricated removable dies.
2. FF-GP dies mostly had higher crown region surface trueness, whereas FF-AL dies had higher point-based trueness than FF-GP dies. However, measured deviations remained within clinically acceptable thresholds for additively manufactured casts.
3. FF-AL, FF-GP, and DM dies exhibited an apical displacement relative to their design file, whereas FF-TR dies predominantly showed a coronal positioning.
4. Removable dies produced with the tested PLA filaments and FFF printer may serve as practical alternatives to DM dies, as differences in surface and positional deviations were small and likely clinically irrelevant.

CRediT authorship contribution statement

Gülce Çakmak: Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Mustafa Borga Dönmez:** Writing – review & editing, Writing – original draft. **Ece Ersöz:** Writing – review & editing, Methodology, Investigation. **Almira Ada Diken Türksayar:** Writing – review & editing, Formal analysis. **Hakan Arınç:** Writing – review & editing, Writing – original draft. **Ufuk Adali:** Writing – review & editing, Validation, Data curation, Conceptualization. **Burak Yilmaz:** Writing – review & editing, Validation, Supervision. **Stefano Pieralli:** Writing – review & editing, Visualization, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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