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Evaluation of the Trueness and Precision of Cast, Milled-Cast, Milled, and 3D-Printed Post-and-Core Techniques Using Matching Software: An In Vitro Study

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Study Design A
Data Collection B
Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
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Background: Accurate adaptation of post-and-core restorations is critical for optimal stress distribution, retention, and long-term prognosis of endodontically treated teeth. While conventional lost-wax casting remains widely used, digital workflows such as computer-aided design/computer-aided manufacturing (CAD/CAM) milling and 3-dimensional (3D) printing have emerged as alternative fabrication methods.

Material/Methods: This in vitro study evaluated the trueness, precision, and clinical tolerance of 4 fabrication techniques using 3D deviation analysis. A standardized digital model of a maxillary central incisor with a 10 mm post space was used to generate the reference standard tessellation language (STL) file for the corresponding post-and-core restoration. Forty post-and-core specimens were fabricated (n = 10/group): (I) conventional casting, (II) milled wax-cast, (III) CAD/CAM-milled zirconia, and (IV) 3D-printed zirconia. Specimens were scanned using a high-resolution laboratory scanner and analyzed with digital metrology software. Trueness was assessed using root mean square (RMS) deviation, precision by standard deviation of RMS values, and clinical tolerance by the percentage of points within ± 100 µm.

Results: Conventional casting demonstrated significantly superior trueness (0.299 ± 0.047 mm) and the highest clinical tolerance (3.9). All digital workflows exhibited significantly greater RMS deviations ($P < 0.001$), with 3D-printed zirconia showing the lowest trueness. Precision differed significantly among groups ($P < 0.001$), with conventional casting showing greater reproducibility, while milled and 3D-printed zirconia demonstrated comparable precision. Clinical tolerance remained low across all groups.

Conclusions: The conventional casting technique offered greater relative trueness and precision than the evaluated digital workflows. However, the absolute clinical accuracy across all groups was suboptimal. Despite workflow advantages, digital methods require further optimization to achieve clinically acceptable trueness, precision, and reliability.

Keywords: Computer-Aided Design • Printing, Three-Dimensional • Post and Core Technique • Zirconium • Oxides • Workflow

Abbreviations: **CAD/CAM**, Computer-Aided Design/Computer-Aided Manufacturing; **RMS**, root mean square; **3D**, three-dimensional; **STL**, standard tessellation language; **ANOVA**, analysis of variance; **SD**, standard deviation; **SPSS**, statistical package for the social sciences; **HSD**, honestly significant difference; **df**, degrees of freedom; **SS**, sum of squares; **MS**, mean square; **F**, F-value (ANOVA test statistic); **CI**, confidence interval; **MD**, mean difference; **SD**, standard deviation; **SE**, standard error; **ZrO_2**, zirconium dioxide (zirconia)

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Introduction

An endodontic post is a rigid restorative component placed within the root canal of a treated tooth to retain and stabilize the core, thereby supporting the definitive crown [1,2]. It is indicated in cases of extensive coronal tooth loss where insufficient structure remains for core retention. Cast-metal post-and-core systems have traditionally been considered the gold standard due to their favorable canal adaptation, durability, and high clinical success rates [3,4]. Custom post-and-core restorations can be fabricated using direct or indirect techniques [5,6]. The direct technique allows intraoral pattern fabrication with improved adaptation and single-visit completion; however, it is time-consuming and susceptible to pattern distortion during removal. Conversely, the indirect technique reduces chairside time through laboratory fabrication but requires multiple visits and may introduce dimensional inaccuracies during impression and processing stages [7].

Advances in digital dentistry have introduced alternative fabrication workflows, including computer-aided design/computer-aided manufacturing (CAD/CAM) milling and 3-dimensional (3D) printing, demanding systematic evaluation of their accuracy and clinical reliability. CAD/CAM milling is a subtractive process in which restorations are shaped by removing material from prefabricated blocks or disks. This technology is widely used and has demonstrated high accuracy and efficiency compared with conventional fabrication methods [8]. However, it produces considerable material waste and may be limited in replicating complex canal geometries due to limitations related to milling bur diameter and machine axis configuration. Moreover, inaccuracies arising from intraoral scanning and production-related factors can negatively influence the fit of CAD/CAM-fabricated post-and-core restorations [9].

Additive manufacturing, commonly known as 3D printing, allows fabrication of complex geometries that are difficult to achieve using conventional or subtractive approaches. This technique reduces material waste, shortens production time, lowers manufacturing costs, and may improve the internal adaptation of post-and-core restorations [10]. CAD/CAM-fabricated post-and-core restorations have demonstrated fracture resistance comparable to conventional customized posts, while offering improved adaptation in flared or elliptical canals and reduced luting cement thickness and void formation [11]. Nevertheless, the rapid evolution of digital technologies necessitates continuous validation of their accuracy and clinical applicability.

Modern CAD/CAM workflows enable fabrication of custom intra-articular posts from a range of materials, including zirconia, titanium, cobalt-chromium alloys, polyetheretherketone (PEEK), and fiber-reinforced composites. Each material exhibits distinct mechanical and biological characteristics. Zirconia and metallic posts provide superior strength and dimensional precision but possess a high elastic modulus that may increase the risk of root fracture. In contrast, PEEK and fiber-reinforced composite materials more closely approximate the elastic modulus of dentin, potentially reducing stress concentration, although they exhibit lower absolute strength.

The accuracy of post-and-core restorations is commonly described using the parameters of trueness and precision. International standards (ISO 5725) define manufacturing accuracy as comprising 2 components: trueness and precision. Trueness measures the structural fidelity of the fabrication procedure and the precise closeness of agreement between the 3D digitized geometry of the fabricated specimen and the reference CAD design standard tessellation language (STL) file, which reflects systematic error. Precision enumerates random error, indicating the repeatability and reproducibility of the fabrication process under identical operating conditions. Both parameters are critical for clinical success, as they influence stress distribution, microleakage, cement thickness, and root fracture risk [12]. In digital workflows, trueness and precision are frequently quantified using root mean square (RMS) deviation values derived from 3D analyses [13]. Although cast post-and-core systems remain widely used because of their strength and adaptability, the casting process is technique-sensitive and prone to distortion and adaptation errors that may compromise retention and long-term performance [14].

Previous investigations of digital post-and-core fabrication have predominantly focused on resin-printed or composite-milled materials rather than ceramics. In 2023, Gibson et al [15] reported inferior fatigue resistance of 3D-printed resin posts compared with cast-metal post-and-core systems, emphasizing the importance of fabrication accuracy. Conversely, Perucelli et al [7] demonstrated superior adaptation of CAD/CAM-milled composite resin post-and-cores compared with cast-metal posts, particularly with reduced cement thickness and improved retention, highlighting the influence of scanning and milling parameters on accuracy. Jensen and Sayardoust [16] reported superior internal fit for digitally fabricated posts compared with conventionally cast systems, particularly in the apical region.

Despite growing evidence, the literature remains insufficient for a reliable comparison of the dimensional accuracy and clinical tolerance of cast, milled, and 3D-printed post-and-core restorations [5,14]. Although additive manufacturing of zirconia has been increasingly applied to crowns, frameworks, and implant-supported restorations, evidence regarding its use in post-and-core systems remains limited. While zirconia exhibits favorable mechanical properties and biocompatibility, factors such as sintering shrinkage and layer-by-layer fabrication may influence the trueness and precision of the post-core system, thereby warranting further systematic investigation.

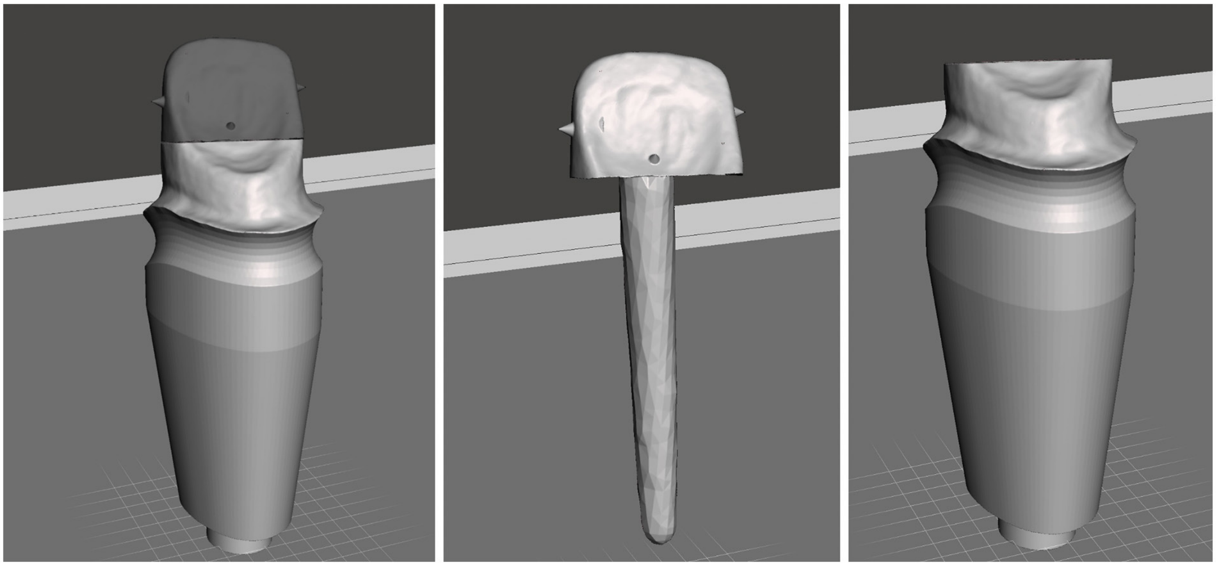

Figure 1. CAD process of reference model. CAD, computer-aided design.

Therefore, this in vitro study aimed to evaluate and compare the trueness, precision, and clinical tolerance of post-and-core restorations fabricated using conventional casting, milled-cast, milled zirconia, and 3D-printed zirconia workflows, employing a standardized digital reference and 3D deviation analysis. The null hypothesis was that variations in fabrication technique and material type would not result in statistically significant differences in the trueness, precision, or clinical tolerance of post-and-core restorations.

Material and Methods

This study was conducted entirely in vitro and did not involve human participants, identifiable data, or biological specimens; therefore, ethical approval and informed consent were not required.

Study Design

This in vitro study utilized the following workflows to fabricate post-and-core restorations: (1) Conventional casted method by lost-wax technique. (2) Cast post and core derived from digitally milled wax patterns. (3) CAD/CAM-milled zirconia post and core. (4) 3D-printed zirconia post and core. The evaluation was based on trueness and precision analysis using digital matching software.

Digital Reference Model

A standardized digital model representing a maxillary central incisor was designed using CAD software, incorporating a 10 mm intraradicular post space preparation (**Figure 1**). Based on this canal geometry, a custom post-and-core restoration was digitally generated. The standalone STL file of this restoration served as the master reference dataset (nominal baseline). This STL file was utilized both to drive the manufacturing systems for all test groups and as the reference file for 3D comparative analysis. To isolate manufacturing trueness from clinical adaptation, all fabricated post-and-core specimens underwent external scanning. The resulting post-fabrication STL files were compared directly to the original restoration CAD design file (Post-to-Post Design), rather than to the root canal space anatomy.

Sample Grouping and Fabrication Protocols

Sample size determination was performed a priori (G*Power v. 3.1.9.7) assuming an effect size of $f=0.5$ and $\alpha=0.05$. For a 1-way analysis of variance (ANOVA) with 4 groups, 38 specimens were required to reach 85% power ($1-\beta=0.85$). Accordingly, 10 specimens were allocated per group ($n=40$), providing an actual statistical power of 87.1%. A total of 40 specimens were equally distributed into 4 groups ($n=10$ per group) as shown in **Figure 2**.

Group I – Cast Post and Core (Lost-Wax Casting Technique)

A standardized master STL reference model was first designed using Exocad DentalCAD (Exocad GmbH, Germany) and exported. For the conventional group, the post and core were fabricated using GC Pattern Resin LS (GC Corp., Tokyo, Japan), a commonly used autopolymerizing resin for precision patterning. The resin was applied incrementally into the prepared

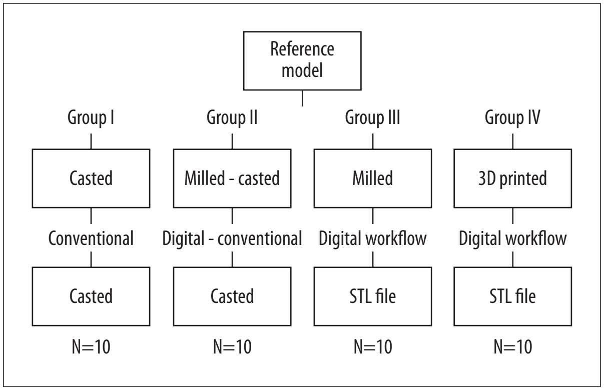

Figure 2. Flowchart depicting the different conventional and digital workflow protocols of each group. STL, standard tessellation language.

post space of the reference model under vibration to minimize voids. The coronal portion of the core was sculpted according to the digital design, ensuring full adaptation and smooth contours. Each pattern was carefully refined with finishing burs and checked under magnification to eliminate discrepancies (**Figure 3A**).

Investment and Casting

The finalized resin patterns were sprued and invested using a phosphate-bonded investment material suitable for high-fusing alloys (Bellavest SH, BEGO, Germany). A conventional burnout protocol was carried out in a programmable furnace: room temperature to 250 °C for complete resin elimination and gradual heating to 950 °C to achieve full burnout and investment strength. Casting was performed with a cobalt-chromium dental alloy (Wironit, BEGO, Germany; 61% Co, 26% Cr, 6% Mo, traces of W and Si) using an induction casting machine (BEGO Miditherm). After cooling, the investment was divested, and the specimens were retrieved.

Finishing and Standardization

Each casting was subjected to airborne-particle abrasion with 50 µm Al_2O_3 at 2.5 bar pressure to remove surface oxides and enhance dimensional stability. Sprues were removed with tungsten carbide burs, and the specimens were polished minimally to avoid dimensional changes. All castings were verified against the master STL to ensure uniformity before digital scanning.

Group II – Cast Post and Core (Digitally Milled Pattern)

The digital post-and-core design was created using Exocad DentalCAD (Exocad GmbH, Germany) and exported as an STL file. The design was milled from a machinable wax blank (Yeti CAD/CAM Wax, Yeti Dental, Germany) using a 5-axis milling machine (DWX-52D, DGSHAPE Corp., Japan) operating at a spindle speed of 20 000 rpm. Carbide bur sequences of 2.5-mm and 1.0-mm were used to achieve precise internal adaptation. The milled wax pattern was then invested in a phosphate-bonded investment material (Bellavest SH, BEGO, Germany) and cast in a cobalt-chromium alloy (Wironit, BEGO, Germany; 61% Co, 26% Cr, 6% Mo, traces of W/Si) using the traditional lost-wax technique (**Figure 3B**).

Group III – CAD/CAM-Milled Zirconia Post and Core

The post and core were designed using Exocad DentalCAD (Exocad GmbH, Germany) and directly milled from pre-sintered zirconia blocks (Katana STML, Kuraray Noritake Dental, Japan) consisting of multilayered 4 mol% / 3 mol% Yttria-Stabilized Tetragonal Zirconia Polycrystal zirconia with an approximate sintering shrinkage factor of 20-25%. Milling was performed using a 5-axis milling unit (DWX-52D, DGSHAPE Corp., Japan) at a spindle speed of 40 000 rpm with fine-grit zirconia burs. Post-milling, all restorations were sintered in a high-temperature furnace (Programat S1, Ivoclar Vivadent) according to the manufacturer's recommended schedule to reach final strength and dimensions (**Figure 3C**).

Group IV – 3D-Printed Zirconia Post and Core

The same digital design, prepared in Exocad DentalCAD (Exocad GmbH, Germany), was used to fabricate the post and core using a zirconia-compatible 3D printing system (CeraFab 7500, Lithoz GmbH, Austria) with a 3 mol% Yttria-Stabilized Tetragonal Zirconia Polycrystal zirconia slurry (LithaCon 3Y 230, Lithoz GmbH). The printed green-state zirconia specimens underwent debinding and sintering in a high-temperature furnace

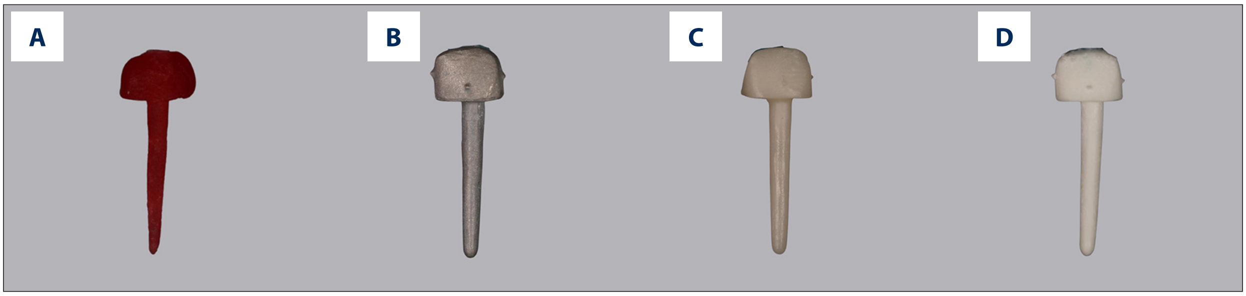

Figure 3. Preparation of samples. (**A**) Group I. (**B**) Group II. (**C**) Group III. (**D**) Group IV.

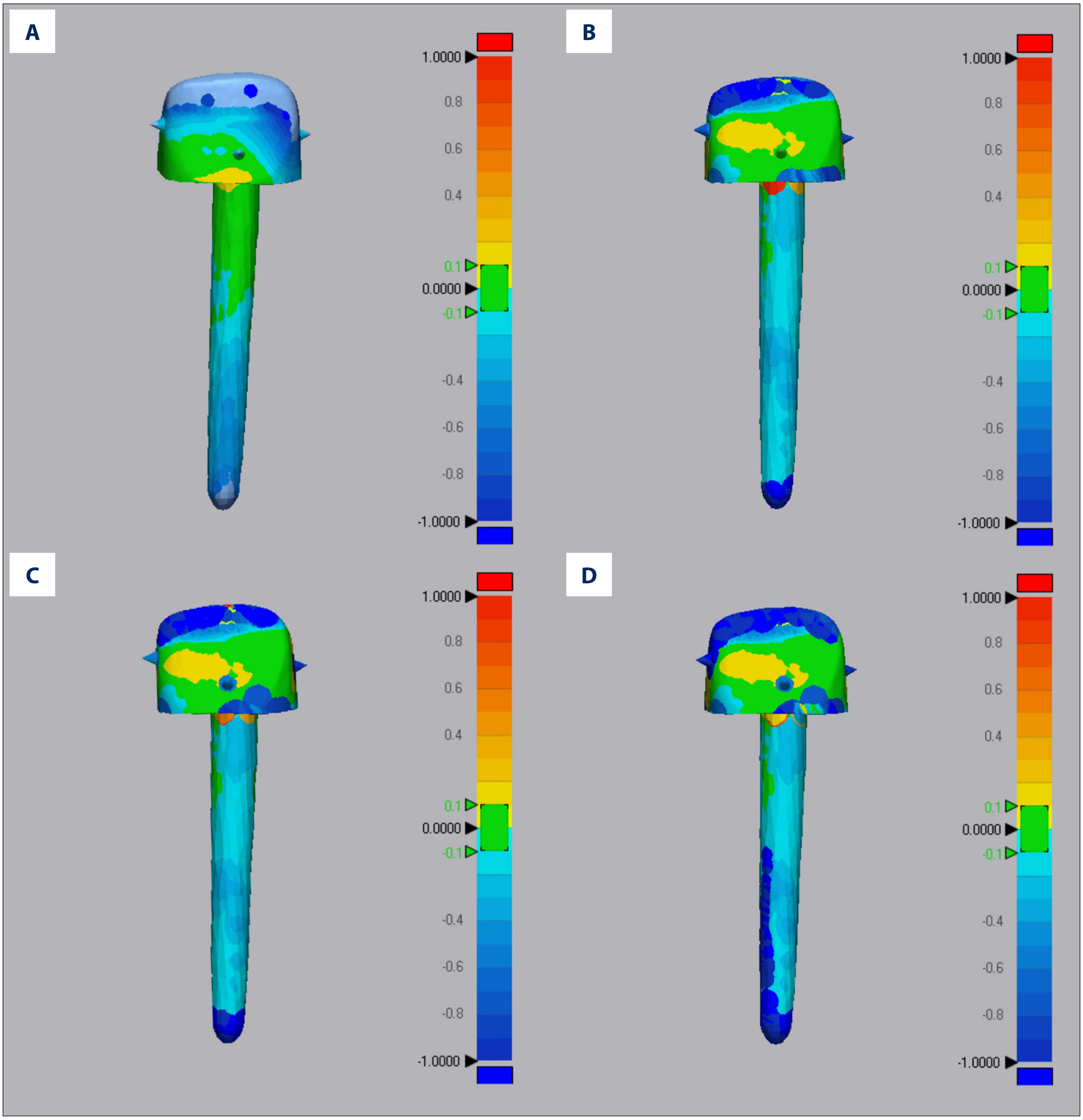

Figure 4. Representative 3-dimensional deviation maps for each group. (**A**) Group I. (**B**) Group II. (**C**) Group III. (**D**) Group IV.

(Programat S1, Ivoclar Vivadent). The sintering cycle accounted for the characteristic 14-20% volumetric shrinkage of Lithoz zirconia, yielding full density and dimensional accuracy as shown in **Figure 3D**. All groups used the same STL reference to ensure consistency in design across all fabrication methods.

Digital Scanning and Alignment

Prior to digitization, each fabricated post-and-core specimen was lightly and uniformly coated with an anti-reflective scanning spray to eliminate surface reflectivity. Each fabricated post and each fabricated core was then scanned using a high-precision laboratory scanner (3Shape D2000, 3Shape A/S Holmens Kanal, Copenhagen Denmark) to generate post-fabrication STL files. This scanner utilizes a blue LED multi-line structured light technology paired with four 5-Megapixel cameras arranged to capture the specimen's volumetric geometry from multiple optical angles simultaneously. Digital metrology software (Geomagic Control X, 3D Systems) was used to compare each scanned STL file with the original reference STL. Alignment was achieved using a best-fit algorithm, allowing for quantitative analysis of surface deviations as shown in **Figure 4**.

Table 1. Summary of mean (SD) values for trueness (RMS), precision, and clinical tolerance of post-and-core restorations fabricated by conventional casting, milled wax-cast, CAD/CAM-milled zirconia, and 3Dprinted zirconia.

Group	n	RMS (mm)	Precision (mm)	Clinical tolerance (%)
I (conventional cast)	10	0.299 (0.047)	0.289 (0.043)	3.9
II (milled wax-cast metal)	10	0.722 (0.014)	0.564 (0.036)	0.7
III (CAD/CAM-milled zirconia)	10	0.729 (0.017)	0.462 (0.026)	1.8
IV (3D-printed zirconia)	10	0.760 (0.013)	0.426 (0.046)	0.9

SD, standard deviation; RMS, root mean square; CAD/CAM, computer-aided design/computer-aided manufacturing.

Accuracy Analysis

Accuracy was assessed according to the following parameters: (1) Trueness was defined as the closeness of agreement between the scanned post-and-core specimen and the reference post-and-core STL file. Trueness was calculated using the RMS error value [12,13]. (2) Precision was defined as the reproducibility of the fabrication workflow. Precision was assessed by evaluating the variability of RMS deviation values among specimens within each group. Lower standard deviation values indicated greater reproducibility and precision [12,13]. Each specimen exhibited an RMS distribution across all measured points, from which a corresponding standard deviation was calculated. (3) Clinical tolerance was defined as the percentage of surface points falling within ± 100 µm deviation. Clinical tolerance was calculated for each specimen to determine clinical acceptability. Earlier studies, such as those by McLean [17], suggested that marginal gaps up to 120 µm were clinically acceptable for conventional cast crowns. However, advancements in CAD/CAM milling and additive manufacturing have led to stricter thresholds of ≤ 100 µm. Contemporary literature [12,13] supports a 100 µm clinical tolerance level based on biological and clinical justification to minimize microleakage, secondary caries, and periodontal complications.

Statistical Analysis

Descriptive statistics (mean ± standard deviation) for trueness, precision, and clinical tolerance were calculated for all 4 fabrication technique groups. For the trueness parameter, Welch's ANOVA was used to compare mean RMS values because the assumption of homogeneity of variance was violated, as confirmed by Levene's test. Post hoc pairwise comparisons were performed using the Games–Howell test. For the precision and clinical tolerance parameters, the homogeneity-of-variance assumption was met; therefore, a 1-way ANOVA was performed to evaluate differences among the 4 groups, followed by Tukey's honestly significant difference (HSD) post hoc test for pairwise comparisons. Statistical significance was set at $\alpha = 0.05$. Analyses were performed using SPSS software (Version 25.0, IBM Corp., Armonk, NY, USA).

Results

Trueness

The results revealed distinct differences in trueness across groups. Group I (conventional cast) exhibited the lowest RMS error (0.299 ± 0.047 mm), indicating the highest trueness. Group II (milled wax-cast) recorded a higher RMS error (0.722 ± 0.014 mm), followed closely by Group III (milled zirconia) (0.729 ± 0.017 mm). Group IV (3D-printed zirconia) showed the highest RMS error (0.760 ± 0.013 mm), reflecting the least accurate adaptation (**Table 1**).

Precision

The lowest variability was observed in Group I (conventional cast), with a mean SD of 0.289 ± 0.043, demonstrating the highest reproducibility. Among the digital workflows, Group III (milled zirconia) showed the most favorable precision (0.462 ± 0.026), while Group II (milled wax-cast) (0.564 ± 0.036) and Group IV (3D-printed zirconia) (0.426 ± 0.046) exhibited greater variability. These findings suggest that although 3D-printed zirconia showed the lowest trueness, its reproducibility was superior to the digitally milled wax-cast group (**Table 1**).

Clinical Tolerance (± 100 µm)

The percentage of surface points falling within the predefined clinically acceptable tolerance range (± 100 µm) differed significantly among the experimental groups. Group I (conventional cast) demonstrated the highest proportion of points within the tolerance threshold (3.9%), followed by Group III (CAD/CAM-milled zirconia) at 1.8%, Group IV (3D-printed zirconia) at 0.9%, and Group II (digitally milled wax-cast) at 0.7% (**Table 1**). Although Group I exhibited comparatively better adaptation than the other fabrication techniques, the overall percentages remained low across all groups, indicating limited conformity to the predefined clinical tolerance threshold. These deviations may contribute to increased cement thickness and internal misfit, potentially compromising retention, facilitating

Table 2. Welch's ANOVA Results for RMS values from different fabrication method groups.

Source	df (between)	df (within)	F	*P*
Welch's ANOVA	3	19.339	267.793	< 0.001

Note. The denominator degrees of freedom are adjusted according to Welch's procedure. ANOVA, analysis of variance; df, degrees of freedom.

Table 3. Games–Howell post hoc pairwise comparisons for mean RMS values.

Comparison	MD	SE	*P*	95% CI	
				Lower	Upper
Group I vs Group II	-0.422	0.015	< 0.001	-0.470	-0.375
Group I vs Group III	-0.430	0.016	< 0.001	-0.478	-0.381
Group I vs Group IV	-0.460	0.015	< 0.001	-0.508	-0.413
Group II vs Group III	-0.007	0.007	0.735	-0.027	0.012
Group II vs Group IV	-0.038	0.006	< 0.001	-0.055	-0.020
Group III vs Group IV	-0.030	0.007	0.002	-0.050	-0.010

RMS, root mean square; MD, mean difference; SE, standard error; CI, confidence interval.

Table 4. One-way ANOVA of precision and clinical tolerance level; mean values between different groups.

Variable	Source	SS	df	MS	F	P
Precision	Between groups	0.388	3	0.129	85.349	< 0.001
	Within groups	0.055	36	0.002		
	Total	0.442	39			
Clinical tolerance	Between groups	66.169	3	22.056	45.881	< 0.001
	Within groups	17.306	36	.481		
	Total	83.475	39			

ANOVA, analysis of variance; SS, sum of squares; df, degrees of freedom; MS, mean square.

microleakage, and adversely affecting the long-term biomechanical stability of the post-core restoration.

Statistical analyses and corresponding outputs were obtained using SPSS. Levene's test revealed a violation of the homogeneity of variance assumption for RMS values (F(3, 36) = 12.716, $P = 0.007$). Therefore, Welch's ANOVA (**Table 2**) was applied, which demonstrated a statistically significant difference in mean RMS values among the groups (Welch's F(3, 19.339) = 267.793, $P < 0.001$, $\omega^2 = 0.982$), indicating variability in trueness across fabrication techniques. Games–Howell post hoc analysis (**Table 3**) indicated statistically significant differences between all pairwise group comparisons, except between Group II (the digitally milled pattern–cast post group) and Group III (the CAD/CAMmilled zirconia post-and-core group), where no significant difference was observed (mean difference = -0.007, 95% CI [-0.027, 0.012], $P = 0.735$)

In contrast, the assumption of homogeneity of variance was satisfied for both precision (F(3, 36) = 2.078, $P = 0.120$) and clinical tolerance (F(3, 36) = 1.525, $P = 0.225$), permitting the use of 1-way ANOVA (**Table 4**). A statistically significant effect of group was observed for precision (F(3, 36) = 85.349, $P < 0.001$, $\eta^2 = 0.877$) and clinical tolerance (F(3, 36) = 45.881, $P < 0.001$, $\eta^2 = 0.793$).

Tukey's HSD post hoc analysis for precision (**Table 5**) indicated that all pairwise comparisons were statistically significant ($P < 0.001$), except between Groups III and IV (mean difference = -.0354, 95% CI [-.0822,.0114], $P = 0.195$). For clinical tolerance (**Table 6**), no statistically significant differences were observed between Groups II and IV or between Groups III and IV, whereas all other pairwise comparisons were statistically significant.

Table 5. Tukey HSD post hoc pairwise comparisons for mean precision values between different fabrication groups.

Dependent variable	Comparison group	Group I	Group II	Group III	Group IV
Precision	Group I	–	< 0.001	< 0.001	< 0.001
	Group II	< 0.001	–	< 0.001	< 0.001
	Group III	< 0.001	< 0.001	–	0.195
	Group IV	< 0.001	< 0.001	0.195	–

HSD, honestly significant difference.

Table 6. Tukey HSD post hoc pairwise comparisons for mean clinical tolerance values between different fabrication groups.

Dependent variable	Comparison group	Group I	Group II	Group III	Group IV
Clinical tolerance	Group I	–	< 0.001	< 0.001	< 0.001
	Group II	< 0.001	–	0.005	0.995
	Group III	< 0.001	0.005	–	0.009
	Group IV	< 0.001	0.995	0.009	–

HSD, honestly significant difference.

Discussion

The findings of this study indicate that posts manufactured using the conventional lost-wax casting technique demonstrated superior performance across both mean RMS error and mean clinical tolerance metrics. The null hypothesis was rejected, as significant differences were observed among the fabrication methods.

The superior trueness of conventionally cast post-and-cores observed in this study is consistent with established evidence supporting the adaptability of lost-wax fabrication to root canal anatomy. Previous studies have characterized conventional casting as technique-sensitive but capable of achieving close adaptation under controlled conditions [18]. The high trueness and reproducibility demonstrated in this investigation likely result from the stability of pattern resin, the compensatory expansion of phosphate-bonded investments, and the controlled shrinkage of cobalt-chromium alloys. These parameters have historically contributed to precise canal adaptation. When executed by skilled technicians, these compensatory mechanisms effectively counteract the expected solidification shrinkage of cobalt-chromium alloys. This process yields a monolithic cast post that closely replicates the mold geometry, contains minimal internal voids, and reduces both apical and cervical discrepancies. Additionally, the inherent stability and low thermal contraction of cobalt-chromium alloys during cooling further enhance the dimensional fidelity of conventionally cast posts [19]. Although digital dentistry has transformed many aspects of fixed prosthodontics, the fabrication of post-and-cores remains challenging due to the long, narrow, and irregular geometry of the root canal space, which complicates both data acquisition and manufacturing.

Compared with the conventional group, fabrication methods utilizing digital workflows produced markedly higher RMS error values and substantially lower clinical tolerance rates. CAD/CAM-milled zirconia exhibited superior trueness compared with 3D-printed zirconia, although it did not exceed it in precision. Digitally milled wax patterns exhibited the most suboptimal outcomes. These results differ from recent studies, such as studies by Jensen and Sayardoust [16] and Perucelli et al [7], which indicated better adaptation for digital workflows than for conventional approaches. This discrepancy may be attributed to variations in materials and fabrication methodologies. While previous studies primarily examined milled composite or resin-based posts, the present study examined sintered zirconia and cast metal produced from digital patterns. The observed decline in trueness for both zirconia workflows corresponds to well-documented challenges related to sintering shrinkage, milling tolerance, and tool diameter constraints [11]. Significant volumetric changes resulting from sintering shrinkage introduce a pivotal factor that can compromise the final geometry unless sufficiently offset by design software. Zirconia undergoes multidirectional shrinkage during sintering, and even slight deviations from manufacturer-specified sintering parameters can exacerbate internal dimensional inconsistencies. Milling inaccuracies, especially in narrow post spaces that exceed the minimum bur diameter, may also contribute to localized mismatches observed in discrepancy maps [20]. These mechanisms are consistent with existing literature in digital prosthodontics, which indicates that the internal fit of zirconia restorations is predominantly governed by milling and sintering parameters rather than digital design alone.

The relatively poor accuracy observed in the digitally milled wax-cast group indicates that this workflow amalgamates limitations from both the subtractive milling and subsequent casting process. This "hybrid" workflow evidently introduces shortcomings of both digital and analogue systems without capitalizing on the manual adaptability of the conventional approach. Owing to its dimensional instability, wax is susceptible to distortion during milling, handling, and investing. Additionally, the casting stage introduces an additional source of shrinkage and investment expansion variability. These factors collectively compounded to produce diminished trueness and clinical tolerance compared with both conventionally cast and milled zirconia restorations.

In the CAD/CAM-milled zirconia group, deviations are likely to stem from the "drill radius compensation" effect intrinsic to subtractive manufacturing. The milling process is limited by the diameter of the burs, preventing the creation of internal line angles sharper than the radius of the smallest tool. In the apical portion of a post space, which is typically narrow and tapered, the milling bur often cannot reproduce the fine details of the digital design. This limitation leads to premature binding and incomplete apical seating, resulting in the "high spots" observed in deviation maps and reducing overall trueness. Additional limitations of subtractive manufacturing, such as milling path inaccuracies and sintering shrinkage of zirconia, also contribute significantly to higher RMS values. Previous studies on CAD/CAM restorations have reported that, although digital workflows enhance standardization, they may not consistently provide superior internal adaptation compared with conventional techniques [21].

The 3D-printed zirconia group exhibited the lowest trueness, yet displayed better reproducibility compared with the digitally milled wax-cast group [22]. This indicates that although printed dimensions were consistently reproducible, they consistently deviated from the reference model, likely due to post-processing factors [23], suggesting that additive manufacturing currently faces challenges in achieving clinically acceptable fit for intracanal restorations. Potential contributors to these systematic errors include layer-wise fabrication, binder content, potential anisotropy and green-state fragility [24]. Recent systematic reviews have noted that while 3D-printed zirconia shows promise, its dimensional accuracy and fit remain inferior or highly variable compared with milled counterparts [12,13]. The 3D surface deviations, expressed as RMS values, observed across all groups in this study ranged from 0.298 mm to 0.760 mm, exceeding the traditional clinical thresholds (< 100 µm) commonly cited for prosthodontic restorations such as crowns or inlays. This increased discrepancy is attributable to the complex geometry of intraradicular post-and-core restorations. In CAD/CAM milling workflows, the fabrication of a narrow, 10-mm tapered post introduces tool radius limitations, often resulting in over-milling or under-milling of deep internal features. In contrast, 3D printing workflows produce deep resin post structures that are susceptible to cumulative volumetric shrinkage and layer-by-layer distortion along a single, elongated axis during post-polymerization curing. Additionally, this study evaluated global manufacturing trueness (RMS error across the entire external surface area of the post) rather than a localized, 2-dimensional marginal gap, so the cumulative volumetric errors are inherently represented as higher absolute values. Nonetheless, since these deviations were relatively consistent across specimens, precision remained comparable to that of milled zirconia. This outcome characterizes a key limitation of the contemporary zirconia additive manufacturing technique. Despite rapid technological developments, it continues to face limitations related to printing resolution, slurry stability, and sintering dynamics. The current results indicate that while 3D printing of zirconia is promising for crowns and frameworks, its application for the strict internal adaptation requirements of post-and-cores demands further refinement in printing parameters and sintering protocols.

This study demonstrated notable strengths, including the adoption of a single standardized digital reference model, consistent specimen fabrication protocols, high-resolution scanning, and precise 3D deviation analysis. These features enhance comparability across workflows and provide detailed insight into accuracy patterns. Nonetheless, limitations include the restriction to a central incisor model, lack of variable canal morphologies, and omission of intra-oral factors like humidity, temperature fluctuations, or clinical handling of impressions and scans. Furthermore, the analysis was confined to internal accuracy and did not assess mechanical properties like fracture resistance or bond strength. Additionally, reliance on a single scanner type, software, and material brand per workflow may limit generalizability. Finally, it should be noted that the external surfaces of post-and-core specimens—characterized by their smaller thickness and intricate apical configuration—are inherently difficult to capture accurately using optical scanning. These morphological limitations may have contributed to the increased RMS deviation values reported.

The clinical significance of this study lies in the finding that, despite statistically significant differences among the fabrication techniques, the overall clinical tolerance values remained markedly low across all groups. However, among the experimental groups, the conventional casting technique exhibited the highest precision in fabricating post-and-core restorations. These findings underscore the need for continued refinement of digital fabrication techniques to meet contemporary standards of trueness and precision, thereby reducing the risk of biomechanical instability and potential compromise of longterm clinical outcomes. Clinicians employing digital workflows for zirconia posts should recognize potential fitting issues and consider increased cement space settings. Future investigation should investigate the influence of modified sintering protocols, improved printing resolutions, and advanced material formulations on 3D-printed zirconia accuracy. Moreover, assessing the mechanical performance of these materials under fatigue loading would provide a more comprehensive understanding of the clinical applicability of digitally fabricated zirconia posts.

Conclusions

Within the limitations of this study, the traditional lost-wax casting technique exhibited superior trueness, precision, and clinical tolerance compared with the other evaluated fabrication methods. However, the proportion of points within the ± 100 µm tolerance threshold remained low across all groups. Although digital workflows, such as milled-cast, milled zirconia, and 3D-printed zirconia, provide benefits in standardization and efficiency, their current implementation requires further optimization to enhance trueness and precision. Consequently, conventional casting remains the more favorable approach under current conditions.

Declaration of Figures' Authenticity

All figures submitted have been created by the authors who confirm that the images are original with no duplication and have not been previously published in whole or in part.

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