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Trueness and fit of complete-arch implant-supported frameworks in new-generation additively and subtractively manufactured polymers: An in-vitro study

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Abstract

Background: There is limited knowledge on the fabrication trueness and fit of additively or subtractively manufactured complete-arch implant-supported frameworks in recently introduced polymers.

Purpose: To evaluate the trueness and marginal fit of additively or subtractively manufactured polymer-based complete-arch implant-supported frameworks, comparing with those of strength gradient zirconia frameworks.

Materials and Methods: A typodont model with 4 implants (left first molar (abutment 1), left canine (abutment 2), right canine (abutment 3), and right first molar (abutment 4)) was digitized (ATOS Core 80 5MP) and an implant-supported complete-arch framework was designed. This design file was used to fabricate frameworks from 5 different materials: strength gradient zirconia (SM-ZR), high impact polymer composite (SM-CR), nanographene-reinforced PMMA (SM-GR), PMMA (SM-PM), and additively manufactured temporary resin (AM) ($n = 10$). These frameworks were digitized and each scan file was virtually segmented into 4 regions (abutments, occlusal, overall without occlusal, and overall). The surface deviations at these regions, and linear and interimplant distance deviations were evaluated (Geomagic Control X).

Marginal gaps were evaluated according to triple-scan protocol after seating frameworks on the model with the 1-screw test. Data were statistically analyzed ($\alpha = 0.05$).

Results: Surface deviations of all regions differed among tested materials ($p \leq 0.001$). AM frameworks mostly had surface deviations that were similar to or lower than those of other materials ($p \leq 0.031$), except for the occlusal surface, where it mostly had higher deviations ($p \leq 0.013$). Abutment 4 of SM-CR had higher linear deviations than abutment 2 ($p = 0.025$), and material type did not affect the linear deviations within abutments ($p \geq 0.171$). Interimplant distance deviations differed within and among materials ($p \leq 0.017$), except for those between abutments 1 and 2 among materials ($p = 0.387$). Marginal gaps of subtractively manufactured materials differed among abutments, while those of abutments 3 and 4 differed among materials ($p \leq 0.003$). AM frameworks mostly had lower marginal gaps at abutments 3 and 4 ($p \leq 0.048$).

Conclusions: Although there was no clear trend among tested materials for measured deviations, marginal gaps of additively manufactured resin were mostly lower than those of subtractively manufactured materials and did not differ among abutment sites. Nevertheless, the differences in measured deviations among materials were small and marginal gaps were within the previously reported acceptability thresholds.

KEYWORDS

additive manufacturing, complete-arch, implant-supported, marginal gap, subtractive manufacturing, trueness

Summary Box

What is known

- The number of polymer-based materials that are indicated for additively or subtractively manufactured complete-arch fixed implant-supported prostheses is increasing.
- The knowledge on the fabrication trueness and fit of complete-arch implant-supported frameworks in recently introduced additively and subtractively manufactured polymer-based materials is lacking.
- Considering that the fabrication trueness of an implant-supported prosthesis is critical for its passivity, a study on indicated materials in a complete-arch implant-supported situation may elaborate the knowledge of both clinicians and dental technicians on the applicability of these materials.

What this study adds

- Additively manufactured frameworks mostly had fabrication trueness that was similar to or higher than those manufactured subtractively.
- Additively manufactured frameworks had marginal gaps that were either similar to or lower than those of subtractively manufactured frameworks.

1 | INTRODUCTION

With the advancements in computer-aided design and computer-aided manufacturing (CAD-CAM) technologies, various dental materials have become applicable for implant-supported complete-arch fixed prosthesis frameworks fabrication.[1] Zirconia has been commonly used with subtractive manufacturing, due to its superior strength and the esthetic demands.[2] Recently introduced strength gradient zirconia minimizes veneer chipping, a complication frequently encountered with zirconia frameworks,[3] as it combines more translucent cubic zirconia with stronger monolithic zirconia in the same disk in a multilayered construction.[4] Subtractively manufactured new-generation polymers have potential advantages including the possibility of reduced cost, higher resiliency, and less wear of milling unit burs. High-performance polymers, which are a relatively new alternative for implant-supported frameworks,[1] have improved mechanical properties, biocompatibility, and decreased risk of porosities through manufacturing under standardized polymerizing conditions at high temperature and pressure.[5] However, these materials are generally veneered with composite resin or polymethylmethacrylate (PMMA) due to their unfavorable optical properties,[6] and a clinical study reported mechanical complications, mainly veneer bonding issues, while using these polymers as frameworks.[7] A recently introduced high-performance polymer that consists of cross-linked composite and referred as high impact polymer composite (breCAM.HIPC; bredent) is indicated for monolithic fabrication of permanent restorations with only pink resin being layered to mimic gingiva, which may minimize the veneering issues.[8] Another novel reinforced resin is the graphene-reinforced PMMA (G-CAM; Graphenano DENTAL SL), which is indicated for fixed prostheses.[9] Graphene is a crystalline form of carbon[10] with an arrangement in a honeycomb pattern[11] and has been shown to have more favorable mechanical properties than PMMA.[10,12,13] Additive manufacturing may also be an alternative while fabricating implant-supported complete-arch fixed prosthesis frameworks because this technology has advantages over subtractive manufacturing and a wide range of materials, including polymers, are applicable.[14]

Dimensional accuracy after fabrication is a key factor for the optimal fit of a fixed restoration.[15] An inaccurately fabricated prostheses may not passively fit on the implants, which may lead to complications.[16,17] Even though the exact level of misfit considered acceptable in implant frameworks is doubtful,[18] a recent review reported that vertical misfit up to 1 mm and horizontal misfit up to 345 µm did not lead to complications[19]; yet, a fit as passive as possible should be aimed for long-term success. Different methods including triple-scan protocol, which is based on superimposing digital scans of framework, cast, and framework on cast, have been suggested for the evaluation of the adaptation of prosthesis.[1,20]

To the authors' knowledge, the number of studies on the fabrication trueness or marginal fit of implant-supported complete-arch fixed prostheses is limited.[1,2,18,21–24] In addition, only one of those studies focused on frameworks fabricated by using polymers,[1] whereas those involving zirconia[2,18,21,24] did not investigate strength gradient zirconia. Considering that increased knowledge on the advantages and applicability of different materials indicated for implant-supported prostheses would facilitate clinicians' and dental technicians' approach to different clinical situations, a study based on the fabrication trueness and marginal fit of implant-supported complete-arch fixed prosthesis frameworks fabricated by using different materials would be beneficial. Therefore, the aim of the present study was to evaluate the fabrication trueness and marginal fit of implant-supported complete-arch fixed prosthesis frameworks fabricated by using 5 different CAD-CAM materials that were either additively or subtractively manufactured. The null hypotheses were that (i) surface trueness of tested materials would not differ within different surfaces (abutments, occlusal, overall without occlusal, and overall), (ii) linear trueness of different abutment sites would not differ within tested materials and among materials at each abutment site, (iii) interimplant distance trueness of different abutment pairs would not differ within tested materials and that of each abutment pair would not differ among tested materials, and (iv) marginal gap of different abutments would not differ within tested materials and marginal gap of each abutment would not differ among tested materials.

2 | MATERIALS AND METHODS

The present study followed the methodology of previous publications for the generation of the CAD of the framework.[1,18] An industrial blue-light optical scanner (ATOS Core 80 5MP; GOM GmbH) was used to digitize a typodont model with 2 straight implants (Nobel Active RP 4.3 × 13 mm; Nobel Biocare AG) and straight multi-unit abutments (Multi-unit Abutment Plus Conical Connection RP 2.5 mm; Nobel Biocare AG) in the anterior region and 2 implants (Nobel Active RP 4.3 × 13 mm; Nobel Biocare AG) with a 30-degree distal tilt and 30-degree angulated multi-unit abutments (30° Multi-unit Abutment Plus Conical Connection RP 3.5 mm; Nobel Biocare AG) in the posterior region with scan bodies and a framework was designed in standard tessellation language (STL) format by using a CAD software (TRIOS Design Studio; 3Shape) as the reference framework STL (RF-STL).

A CAM milling unit (PrograMill7; Ivoclar AG) was used to mill a total of 40 implant-supported complete-arch fixed prosthesis frameworks in strength gradient zirconia (SM-ZR, IPS e.max ZirCAD Prime; Ivoclar AG), HIPC (SM-CR, breCAM.HIPC; bredent), nanographene-reinforced PMMA (SM-GR, G-CAM; Graphenano DENTAL SL), PMMA (SM-PM, Telio CAD; Ivoclar AG), while a digital light processing-based 3-dimensional printer (MAX UV; Asiga) was used to print 10 frameworks in additively manufactured temporary resin (AM, FREEPRINT temp; DETAX GmbH & Co. KG). The number of specimens in each group was decided with a priori power analysis ($\alpha = 0.05$, $1-\beta = 80\%$, and $f = 0.318$) based on a previously published study on the trueness and marginal fit of implant-supported complete-arch fixed prosthesis frameworks,[18] which yielded nine specimens per group sufficient. However, 10 specimens were fabricated to increase the statistical power. The milling settings were selected according to the milling unit manufacturer's recommendations established for each material, while 3-dimensional printing and postprocessing were performed according to manufacturer's recommendations. The supports were placed away from the margins to prevent any damage on the margins. After fabrication, one experienced dental technician removed any material remnants with a small bur paying the utmost attention to not damage the abutment interfaces of the frameworks. After separation, SM-ZR frameworks were sintered in a zirconia furnace (Programat S2; Ivoclar AG) and no further adjustments were made on any of the frameworks.

All frameworks were digitized by using a metrology-grade industrial optical scanner (Artec Micro; Artec 3D) with 10 μm accuracy[25] to generate test scan framework STLs (TF-STLs). All STL files were imported into a metrology-grade 3-dimensional analysis software (Geomagic Control X 2022; 3D Systems) and RF-STL was virtually separated into 4 regions as the abutments, occlusal (the occlusal surfaces of posterior teeth, incisal edges of anterior teeth, and palatal surfaces), overall without occlusal (areas other than the occlusal region), and overall (Figure 1) with the "region tool" of the software. TF-STLs were then superimposed over the RF-STL by using initial alignment and overall best-fit alignment algorithms. Surface deviations of frameworks from the CAD file at defined regions were analyzed by using the root mean square (RMS) method. Color maps were generated with the "3D compare tool" of the software for the quantitative evaluation of the deviations (Figure 2). Maximum and minimum deviations values were set at +100 and −100 μm, while the tolerance range was set at +10 and −10 μm.[26] Red indicated overcontouring, blue indicated undercontouring, and green indicated deviations within the tolerance range.

To evaluate the linear deviations at each abutment site, "geometric feature" tool of the software was used to generate a cone geometry at each multiunit abutment region of the RF-STL. The software automatically calculated the linear deviations at each abutment site after TF-STL was superimposed over the RF-STL as mentioned above (Figure 3). To evaluate the 2-dimensional interimplant distance deviations, vectors passing through the center of the virtual cones were generated by using the "vector tool" of the software. The "2D distance measurement tool" of the software was used to measure the distance between the left first molar (abutment 1) and the left canine (abutment 2), the left canine and the right canine (abutment 3), the right canine and the right first molar (abutment 4), and the left first molar and the right first molar by using these vectors (Figure 4).

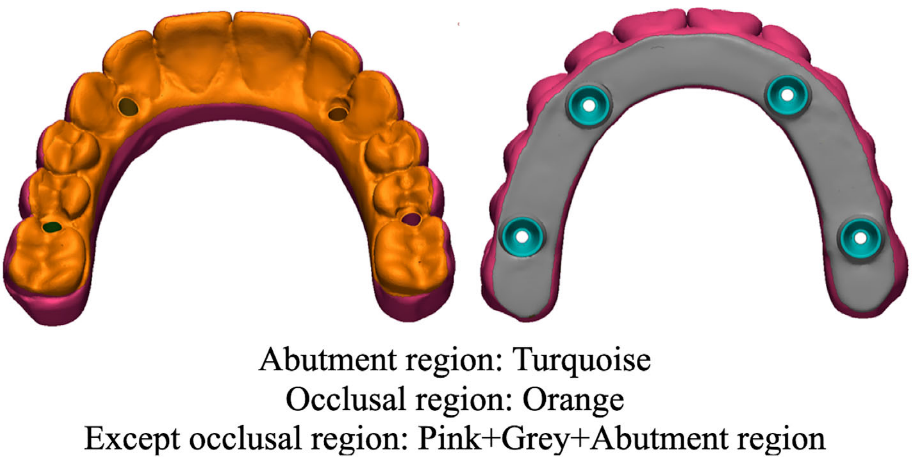

FIGURE 1 Virtually generated regions.

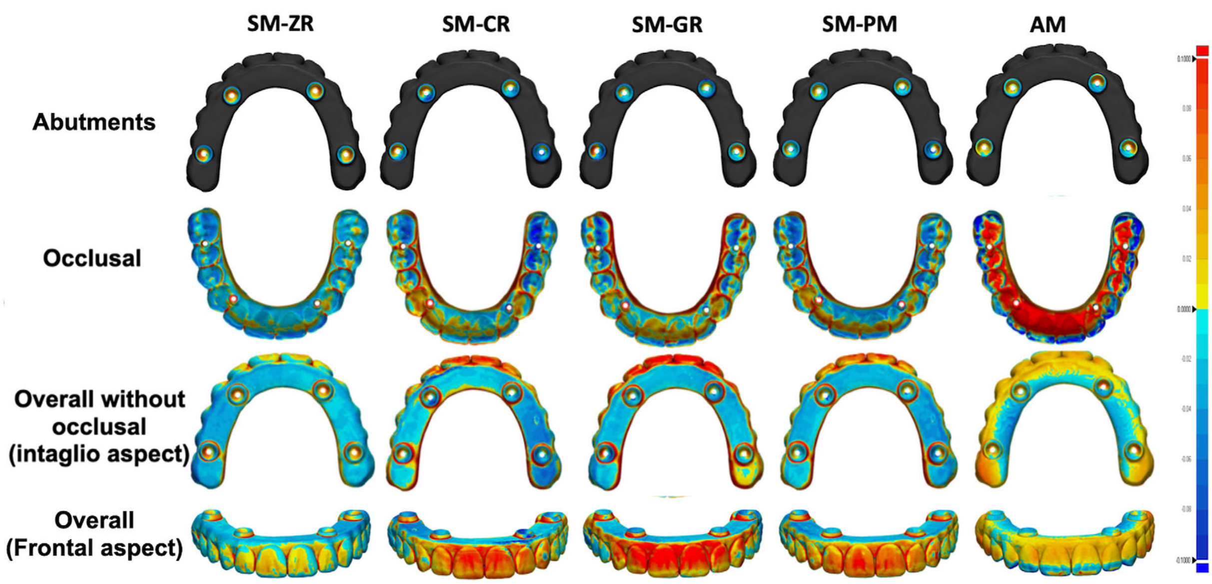

FIGURE 2 Color maps of each region within each material.

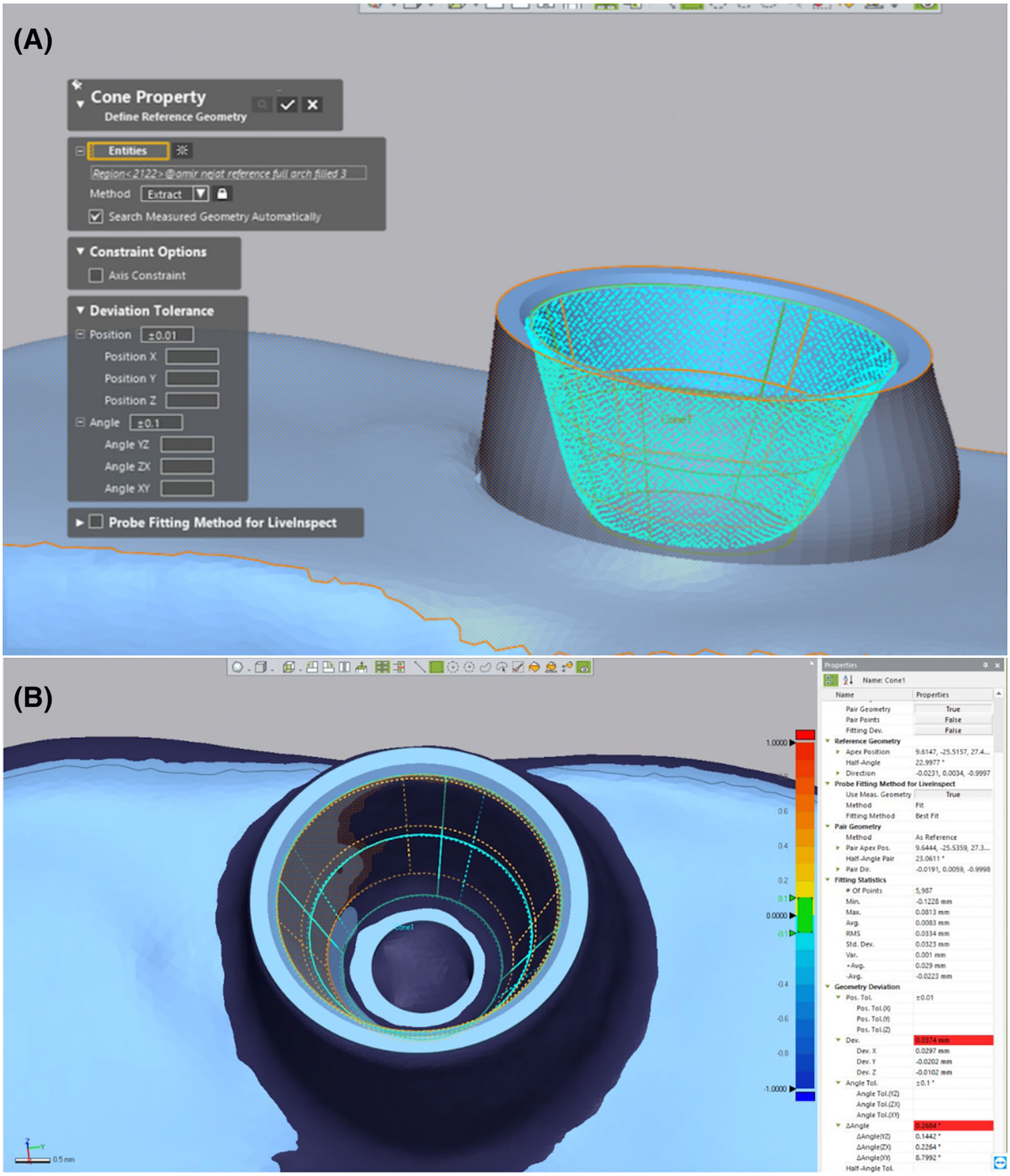

FIGURE 3 (A) Representative image of a cone generated at multi-unit abutment region of RF-STL. (B) Linear deviation measurement of cone after superimposing TF-STL (dark blue) over RF-STL (pale blue).

Interimplant distances were measured on RF-STL and TF-STLs, and the difference between these values was recorded. However, absolute values of these differences were used for statistical analyses.

To evaluate the average gap values, each framework was placed on the master model, and 1-screw test was performed, tightening the prosthetic screws at abutments 1 and 3 with a hand screw driver (Screwdriver Manual Multi-unit 25 mm; Nobel Biocare AG) to enable the initial positioning of the framework. After tightening the prosthetic screw at abutment 1 to 15 Ncm with a torque wrench (Manual Torque Wrench – Prosthetic; Nobel Biocare AG), the screw at abutment 3 was untightened.[1] The same metrology-grade blue-light industrial optical scanner that was used to generate TF-STLs was used to generate 50 frameworks on model STLs (FM-STLs) and one model STL (M-STL). TF-STLs, FM-STLs, and M-STL were imported into the metrology-grade 3-dimensional analysis software to evaluate the average gap values according to the triple-scan protocol.[20] In the first step, M-STL was imported as the reference data and by using initial alignment and overall best-fit alignment algorithms of the software, FM-STL was superimposed over the M-STL. Then, FM-STL was exported as "mesh 1", which allowed the exact location of the FM-STL to be recorded on the spatial coordinate system. In the second step, "mesh 1" file was imported as the reference data, and the TF-

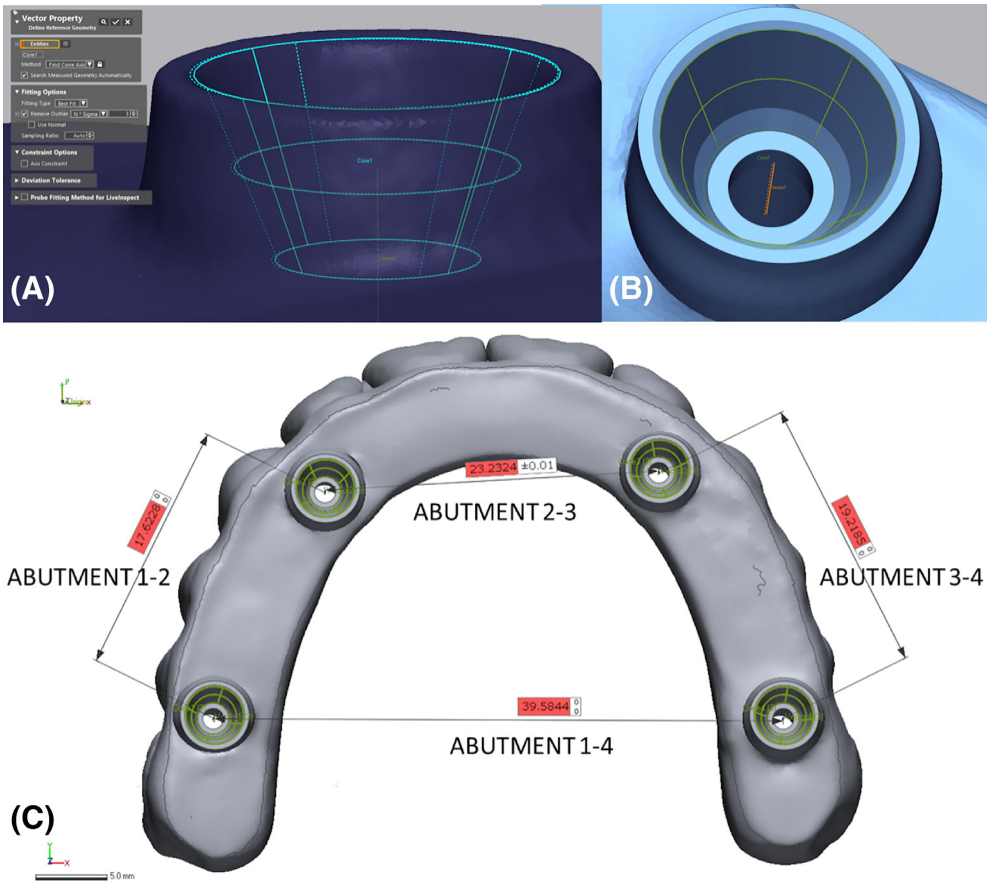

FIGURE 4 (A) Representative image of a vector passing through the center of a virtual cone. (B) Intaglio surface view of generated vector on RF-STL. (C) Measured interimplant distances of RF-STL.

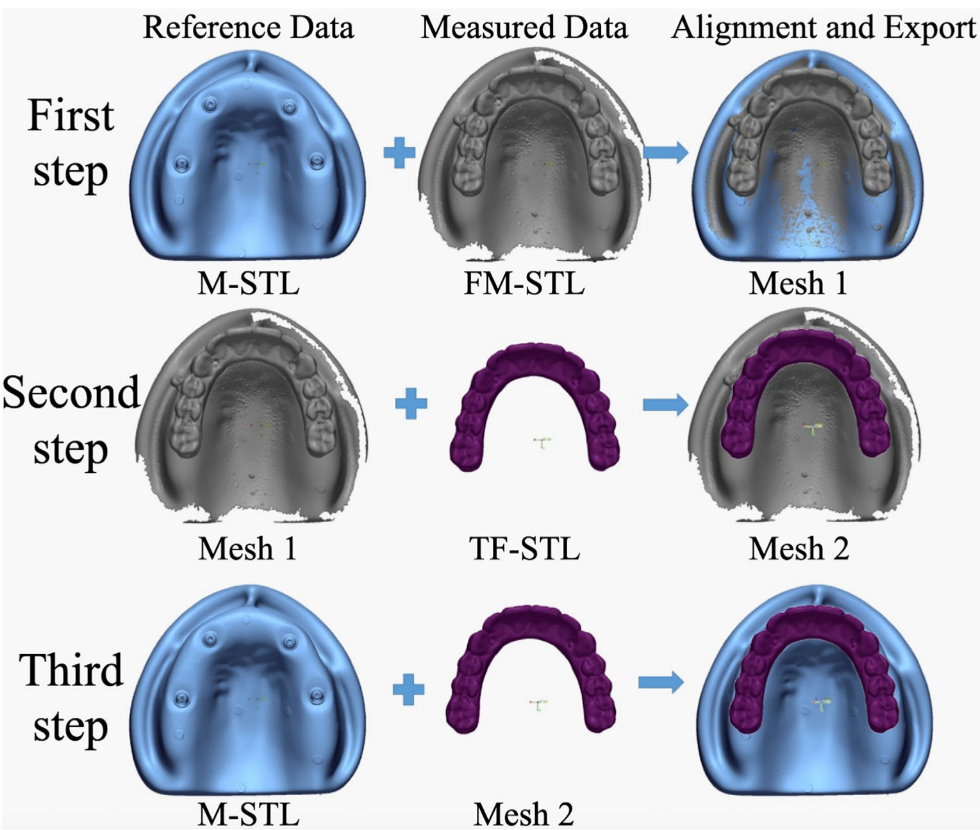

FIGURE 5 Step-by-step representation of triple-scan protocol.

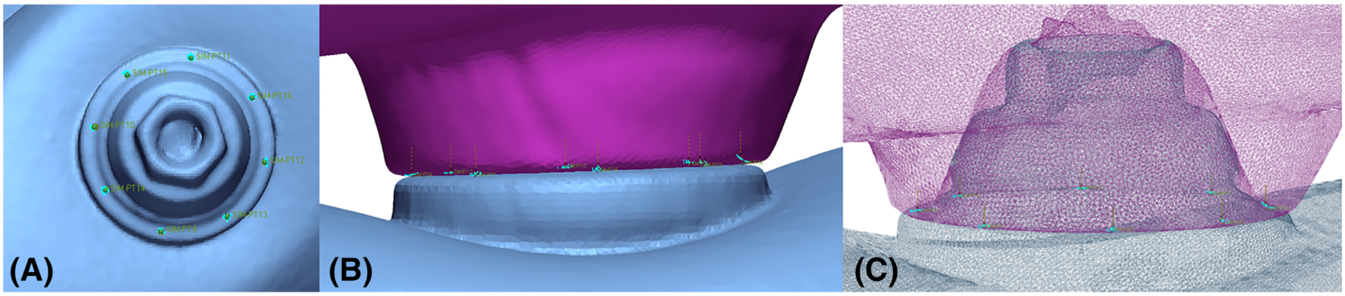

FIGURE 6 Average gap measurement. (A) CMM points defined on abutment. (B) Representation of CMM points on solid framework and model data. (C) Representation of CMM points on mesh framework and model data.

STL file was superimposed over "mesh 1" in the same manner as described in the first step. After this superimposition, TF-STL was exported as "mesh 2." In the third and final step, the software program automatically superimposed "mesh 2" over the M-STL, after M-STL was imported as the reference and the "mesh 2" file was imported as the measured data (Figure 5). After the triple-scan protocol, 8 points with 0.2-mm diameter were generated at the middle of the margin of abutments 2, 3, and 4 of M-STL with equal distances from each other by using the "simulated CMM point tool" of the software. Each CMM point was composed of a minimum of 40 STL nodes, resulting in more than 320 STL nodes for each abutment. The software automatically calculated the distance from each CMM point to the framework and these values for averaged for each TF-STL (Figure 6). A single experienced operator (M.E.G.) performed all deviation and average gap measurements.

Distribution of data was analyzed by using Shapiro–Wilk tests. The comparison among tested materials when RMS values of each surface were considered was performed by using Kruskal–Wallis and post-hoc Dunn's tests. One-way analysis of variance (ANOVA) was used to evaluate the linear deviations. The data within each material were further evaluated by using either Tukey (SM-CR, SM-PM, SM-GR) or Tamhane T2 (AM) tests. While Kruskal–Wallis and post-hoc Dunn's tests were used to evaluate the interimplant distance deviations within SM-ZR, 1-way ANOVA and either Tukey (SM-PM) or Tamhane's T2 tests were used for the remaining materials. Either 1-way ANOVA and Scheffe (abutments 1 and 4, and abutments 3 and 4) or Kruskal-Wallis and post-hoc Dunn's (abutments 2 and 3, and abutments 1 and 2) tests were used to analyze the interimplant distance deviations among tested materials. One-way ANOVA and either Tukey (SM-CR, SM-ZR, and SM-GR) or Tamhane T2 tests were used to analyze the average gap values of abutment 2, abutment 3, and abutment 4 within tested materials, whereas Kruskal–Wallis tests were used for the analyses among tested materials. A statistical analysis software (SPSS v23; IBM Corp) was used to perform all statistical analyses with a significance level of $\alpha = 0.05$.

3 | RESULTS

Tested materials had significant differences in RMS values for each evaluated surface ($p \le 0.001$). When the abutments RMS was considered, SM-ZR frameworks had higher values than AM and SM-PM frameworks ($p \le 0.032$). When the overall without occlusal RMS was considered, AM led to lower values than SM-CR, SM-GR, and SM-PM ($p \le 0.010$), whereas SM-ZR led to lower values than SM-GR ($p = 0.001$). When the occlusal RMS was considered, AM resulted in higher values than SM-CR, SM-ZR, and SM-PM ($p \le 0.013$), whereas SM-ZR frameworks had lower values than SM-GR frameworks ($p < 0.001$). When overall RMS values were considered, SM-GR led to higher values than AM and SM-ZR ($p \le 0.031$) (Table 1).

For linear deviations at the abutment site, only SM-CR frameworks had significant differences ($p = 0.045$). Abutment 4 had higher deviations than abutment 2 ($p = 0.025$). No significant difference was observed among tested materials when linear deviations of the abutments were considered ($p \ge 0.171$) (Table 2).

Interimplant distance deviations had significant differences within each material tested ($p \le 0.004$). For SM-ZR, the distance between abutments 1 and 4 had higher deviations than those between abutments 1 and 2 and between abutments 3 and 4 ($p = 0.010$). For SM-CR, the distance between abutments 1 and 4 had the highest and that between abutments 1 and 2 had the lowest deviations ($p \le 0.007$). For SM-GR, the distance between abutments 1 and 4 had the highest deviations ($p < 0.001$), whereas the distance between abutments 2 and 3 had higher deviations than that between abutments 1 and 2 ($p = 0.037$). For SM-PM and AM, the distance between abutments 1 and 4 had the highest deviations ($p \le 0.003$). Tested materials had significant differences in interimplant distance deviations ($p \le 0.017$), except for the distance deviation between abutments 1 and 2 ($p = 0.387$). SM-CR frameworks had higher deviations than AM frameworks when the deviations between abutments 2 and 3 were considered ($p = 0.041$). SM-CR led to higher deviations than SM-ZR and AM when the deviations between abutments 3 and 4 were considered ($p \le 0.004$). SM-GR led to higher deviations than SM-ZR, AM, and SM-PM when the deviations between abutments 1 and 4 were considered ($p \le 0.001$) (Table 3). Figure 7 shows the distribution of raw interimplant distance deviations among tested materials.

For average gap values at the abutment sites, significant differences were measured within tested materials ($p \le 0.003$), except for AM ($p = 0.347$). For SM-CR, abutment 4 had the highest and abutment 2 had the lowest average gap values; abutment 2 also had lower gap values than abutment 3 ($p < 0.001$). For SM-ZR and SM-PM, abutment 4 had the highest gap values ($p \le 0.019$). For SM-GR,

TABLE 1 Descriptive statistics of RMS (μm) values of each material-surface pair.

		Abutments	Occlusal	Overall without occlusal	Overall
SM-ZR	Mean ± SD	52.7 ± 12.3	39.2 ± 3.2	46.6 ± 8.1	51.5 ± 9.1
	Median (Min–Max)	50.2^{b} (40.3–82.4)	38.9^{a} (33.6–44.8)	44.1^{ac} (37.1–65.2)	53.3^{a} (40.6–64.2)
SM-CR	Mean ± SD	47.4 ± 3.7	60.6 ± 7.9	61.4 ± 7.5	61.4 ± 7.3
	Median (Min–Max)	47.1^{ab} (41.6–52.7)	58.4^{ac} (52–73.1)	59.3^{bc} (47.9–73.6)	59.5^{ab} (50–73.3)
SM-GR	Mean ± SD	47.6 ± 5.2	69.4 ± 4.0	69.1 ± 4.3	79.6 ± 19.3
	Median (Min–Max)	48.3^{ab} (39.3–56.7)	70.4^{bc} (61.3–74.4)	70.8^{b} (61.7–74)	73.4^{b} (62.7–132.1)
SM-PM	Mean ± SD	42.3 ± 3.5	55.8 ± 3.0	57.6 ± 4.5	66.9 ± 13.2
	Median (Min–Max)	41.7^{a} (37.8–48.3)	54.9^{ac} (52.6–61.5)	55.8^{bc} (53.4–68.2)	66.5^{ab} (54.3–95.1)
AM	Mean ± SD	41.0 ± 4.6	85.8 ± 9.3	31.6 ± 1.7	60.8 ± 7.0
	Median (Min–Max)	40.5^{a} (33.6–49.4)	84.4^{b} (70.6–100.4)	31.4^{a} (29.3–34.3)	62.1^{a} (49.2–70.2)

Note: Different superscript lowercase letters indicate significant differences in columns ($p < 0.05$).

TABLE 2 Descriptive statistics of linear deviations (μm) of each material-abutment pair.

		SM-ZR	SM-CR	SM-GR	SM-PM	AM
Abutment 1	Mean ± SD	81.0 ± 59.9^{a}	64.9 ± 23.9^{ab}	79.4 ± 26.9^{a}	49.9 ± 24.0^{a}	69.6 ± 39.1^{a}
	Median (Min–Max)	70.1 (9.9–180.9)	56.8 (37.4–97.6)	82.4 (34.1–126.8)	45.6 (28.9–111.6)	67.6 (18.8–131.8)
Abutment 2	Mean ± SD	77.6 ± 56.5^{a}	45.4 ± 15.8^{a}	76.9 ± 47.9^{a}	54.6 ± 30.5^{a}	84.6 ± 58.8^{a}
	Median (Min–Max)	96.8 (9.9–147.7)	43.2 (29.6–82.3)	60.7 (37.9–177.9)	45.9 (31.6–135.6)	83.2 (7.6–165.8)
Abutment 3	Mean ± SD	82.5 ± 61.6^{a}	64.3 ± 31.1^{ab}	61.9 ± 62.3^{a}	43.7 ± 35.8^{a}	45.1 ± 28.2^{a}
	Median (Min–Max)	61.0 (11.2–188.2)	61.8 (22.5–111.4)	37.7 (13.2–179.2)	38.8 (4.8–107.3)	46.6 (7.2–84.5)
Abutment 4	Mean ± SD	68.7 ± 48^{a}	83.6 ± 38.7^{b}	92.1 ± 59.7^{a}	62.4 ± 23.8^{a}	56.5 ± 25.1^{a}
	Median (Min–Max)	52.2 (33.6–182.2)	70.7 (44.9–164.6)	72.8 (24.3–214.8)	67.7 (26.0–97.3)	55.8 (23.0–106.3)

Note: Different superscript lowercase letters indicate significant differences in columns ($p < 0.05$).

TABLE 3 Descriptive statistics of interimplant distance (μm) deviations.

		SM-ZR	SM-CR	SM-GR	SM-PM	AM
Abutment 1-Abutment 2	Mean ± SD	13.0 ± 19.9	10.6 ± 7.4	11.2 ± 7.5^{a}	12.0 ± 6.0^{a}	7.6 ± 7.8^{a}
	Median	4.9^{aA}	11.0^{aA}	8.9^{A}	10.2^{A}	3.6^{A}
	(Min–Max)	(0.9–62.9)	(0.2–18.9)	(1.3–23.6)	(2.5–20.9)	(0.1–22.9)
Abutment 2–Abutment 3	Mean ± SD	16.3 ± 17.6	24.9 ± 5.9	23.5 ± 9.9^{b}	21 ± 8.6^{a}	11.7 ± 8.2^{a}
	Median	6.6^{abAB}	24.6^{bB}	24.9^{AB}	22.5^{AB}	11.6^{A}
	(Min–Max)	(2.2–46.2)	(17–34.5)	(7.5–42.8)	(3.4–31.3)	(0.5–24)
Abutment 3–Abutment 4	Mean ± SD	7.8 ± 5.9^{A}	22.1 ± 5.7^{B}	16.8 ± 10.2^{abAB}	16.8 ± 8.5^{aAB}	7 ± 4.8^{aA}
	Median	8.1^{a}	23^{b}	16.2	16.4	5.8
	(Min–Max)	(0.1–18.2)	(13.1–28.3)	(0.5–29.6)	(3.1–29.4)	(0.6–15.9)
Abutment 1–Abutment 4	Mean ± SD	44.3 ± 26.4^{A}	73.5 ± 20.5^{AB}	100.8 ± 21.8^{cB}	56.2 ± 16.1^{bA}	44.8 ± 20.3^{bA}
	Median	43.1^{b}	78.3^{c}	103.2	56.6	45.3
	(Min–Max)	(10.8–78.1)	(39.3–102.8)	(66.1–137.1)	(28.1–76.1)	(12.8–73.1)

Note: Different superscript lowercase letters indicate significant differences in columns, while different superscript uppercase letters indicate significate differences in rows ($p < 0.05$).

abutment 2 had the lowest gap values ($p < 0.001$). Average gap values of abutments 3 and 4 had significant differences among tested materials ($p < 0.001$). For abutment 3, SM-GR led to higher gap values than SM-ZR, AM, and SM-PM ($p \leq 0.001$), whereas SM-CR led to higher gap values than SM-ZR and AM ($p \leq 0.048$). For abutment 4, AM led to lower gap values than SM-CR and SM-GR ($p < 0.001$) (Table 4).

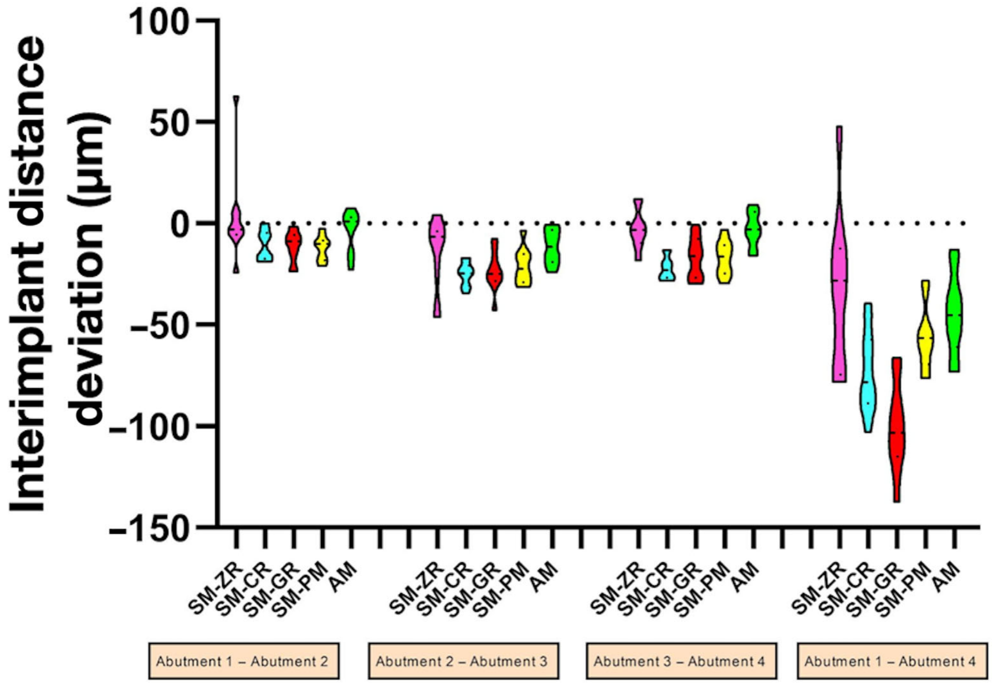

FIGURE 7 Violin graph of raw interimplant distance (µm) deviation data.

TABLE 4 Descriptive statistics of average gap (µm) values of each material-abutment pair.

		SM-ZR	SM-CR	SM-GR	SM-PM	AM
Abutment 2	Mean ± SD	38.4 ± 9.6^{a}	36.4 ± 6.2^{a}	31.9 ± 11.8^{a}	33.6 ± 17.4^{a}	38.9 ± 8.8^{a}
	Median (Min–Max)	39.5^{A} (18.5–54)	37.3^{A} (25.3–47.4)	29.1^{A} (19.6–62.3)	28.7^{A} (13.1–60.4)	36.3^{A} (29.5–54.1)
Abutment 3	Mean ± SD	36.2 ± 16.9^{a}	72.5 ± 11.4^{b}	108.2 ± 31^{b}	45 ± 14.5^{a}	45.2 ± 9.6^{a}
	Median (Min–Max)	29.2^{A} (23.4–73.8)	69.6^{BC} (60.5–97.8)	114.1^{C} (59.2–145)	48.3^{AB} (22.3–72.3)	45.1^{A} (23.4–57.6)
Abutment 4	Mean ± SD	89 ± 48.5^{b}	132.5 ± 29.3^{c}	146.2 ± 64.4^{b}	83.2 ± 33.8^{b}	40 ± 11.7^{a}
	Median (Min–Max)	71.9^{AB} (29–193.6)	127.2^{B} (106.3–207.2)	157.7^{C} (55.7–223.7)	81.3^{AB} (35.6–143.2)	41.9^{A} (25.1–57.9)

Note: Different superscript lowercase letters indicate significant differences in columns, while different superscript uppercase letters indicate significate differences in rows ($p < 0.05$).

4 | DISCUSSION

The first null hypothesis was rejected as significant surface trueness differences were observed among tested materials. The quantitative evaluation of RMS data is critical to interpret possible clinical outcomes as even though SM-ZR had higher deviations than AM and SM-PM within the abutments region, the maximum difference was only 9.7 µm. Therefore, the fabrication trueness of the abutments region of tested materials can be considered similar. However, the color map of SM-ZR was predominantly yellow and red, which indicated overcontouring, and the duration of adjustments for their fit on the multi-unit abutments might be longer. When the remaining regions were considered, the maximum meaningful median difference was 45.5 µm (between SM-ZR and AM at the occlusal region). Given the size of the tested frameworks and the extent of the defined regions, qualitative interpretation of the color maps would be more elaborative for the clinical outcomes. When the occlusal region was considered, AM mostly had higher deviations, which may be related to the fabrication process as in line with the manufacturer's recommendation, the RF-STL was positioned with its occlusal surface facing the build platform; thus, the support structures were automatically generated on the later defined occlusal region. The color maps of occlusal region also support this hypothesis as only the color map of AM was predominantly red indicating potential need for adjustments during maximum intercuspation, protrusion, and eccentric movements. A recent study has concluded that the number of supports on the occlusal surface of an additively manufactured definitive resin crown did not affect its entire external surface trueness.[27] However, considering the size difference between a complete-arch framework and a crown, reducing the number of supports may decrease the occlusal region deviations. SM-ZR had a distinct occlusal region color map with dominant light blue color, which indicated slight undercontouring. In addition, yellow, which indicated slight overcontouring, was visible on the palatal surfaces of anterior teeth and the occlusal surfaces of right posterior teeth. Considering these findings, slight adjustments during maximum intercuspation, protrusion, and laterotrusive movements towards right may be adequate for SM-ZR frameworks to be delivered if occlusal vertical dimension is established.

However, for those situations where occlusal vertical dimension is not established before adjustments, minimal veneering may be required. As for the remaining materials, veneering of the palatal cusps and occlusal adjustment during laterotrusive movements may be required as color maps had a similar color trend with blue and dark blue on the buccal inclination of the palatal cusps and yellow and red at the palatal inclination of the buccal cusps of posterior teeth. In addition, yellow was visible on the palatal surfaces of anterior teeth; thus, adjustments during protrusion may also be required. When the overall without occlusal region and overall color maps were evaluated, all materials had dominant light blue on the intaglio surface of the framework, which might cause esthetic issues and food accumulation, except for AM. As for AM, yellow was evident on the intaglio surface; thus, there might be excessive soft tissue contact that might impair cleanability. Overcontouring of varying magnitudes was evident on the labial surfaces of anterior teeth, regardless of the material. This might lead to esthetic issues; however, the duration of adjustment of these potential issues may be longer for SM-GR as it had the most evident red in its color map.

The second null hypothesis was rejected as significant differences were found in linear trueness among different abutment sites within SM-CR and abutment 4 had lower linear trueness than abutment 2. This difference might affect the fit of SM-CR frameworks, particularly during the evaluation of the frameworks' fit with the 1-screw test using these abutments, as linear deviations were measured by generating a cone that represented the intaglio surface of the framework within each abutment site. However, the material type did not affect the linear trueness within each abutment site.

The third null hypothesis was also rejected as interimplant distance trueness had significant differences within each material and tested materials had significant differences for all deviations except for that between abutments 1 and 2. The distance between abutments 1 and 4 was mostly the highest, which may be attributed to the fact that these two abutments were actually the farthest away from each other and potential fabrication related errors might have had a greater effect on the distance between these abutments. Abutments 2 and 3 had higher distance between them than the remaining adjacent abutment pairs (Figure 4) and regardless of the material, the interimplant distance trueness of these abutments was either similar to or lower than those of other adjacent abutment pairs, which corroborates this hypothesis. Regardless of the abutment pair, AM had interimplant trueness that were either similar to or higher than those of other frameworks. Even though a high-end 5-axis milling unit and proprietary burs of the manufacturer were used for subtractive manufacturing, layer-by-layer manufacturing principle of additive manufacturing, which allows fabrication of more complex and free-form geometries may be related to this result. However, there was no clear trend within subtractively manufactured frameworks. Nevertheless, the distribution of raw interimplant distance deviations (Figure 7) suggests that most of the frameworks were smaller than the RF-STL, regardless of the implant pair considered.

Marginal gaps of abutments had significant differences within each subtractively manufactured framework and tested materials had significant differences when the marginal gaps of abutments 3 and 4 were considered. Therefore, the fourth null hypothesis was rejected. Even though misfit of up to 120 μm has been accepted as a clinical threshold for the fit of implant-supported complete-arch frameworks,[1,18] 150 μm has also been used.[21] In addition, a recent systematic review on the misfit thresholds of implant-supported restorations has reported that vertical misfit up to 160 μm and horizontal misfit values of up to 150 μm did not lead to any mechanical complications. These values were even broader for biological complications with misfit values up to 1 mm for vertical and up to 345 μm for horizontal misfit[19]; however, this review consist of only 13 studies, much of which were in vitro. Therefore, the universally accepted threshold values for the misfit of implant-supported prostheses can be considered conflicting. Nevertheless, considering that the mean marginal gap values ranged between 31.9 μm (SM-GR-abutment 2) and 146.2 μm (SM-GR-abutment 4), which are mostly within the previously reported thresholds, tested frameworks could be considered acceptable. Regardless of the subtractively manufactured material, abutment 4 had higher marginal gaps than abutment 2 and even though not always statistically significant, there was a trend towards increasing marginal gap when tested abutment positioned farther away from abutment 1, which was in line with previous studies that tested the same framework design.[1,18,21] AM frameworks not only had similar marginal gaps among abutments but also had marginal gaps that were either similar to or lower than those of other materials. These results can also be associated with the difference in manufacturing method. As for the subtractively manufactured frameworks, SM-GR led to the highest marginal gaps at abutment 4. Materials with low modulus of elasticity may allow a nonpassive framework to be seated on the multiunit abutments with strain.[21] The manufacturer of SM-GR did not disclose its elastic modulus; however, based on its high marginal gap at abutment 4, a higher rate of prosthetic complications might be expected from an SM-GR framework than those of other materials, if the misfit is unnoticed.

Even though the present study was the first on the fabrication trueness and marginal fit of tested materials when used for the manufacture of complete-arch implant-supported frameworks, previous studies have also analyzed the same parameters by using a similar framework design.[1,18,21,24] Abou-Ayash et al.[1] showed that polyetheretherketone frameworks had higher trueness than those in poleyetherketoneketone (PEKK) and titanium (Ti), while material type did not affect the marginal gap values. In addition, abutment site was shown to affect the marginal gaps of PEKK frameworks. In another study on the fabrication trueness of complete-arch frameworks, deviations of Ti and zirconia frameworks were reported to be similar and more pronounced in the horizontal and sagittal planes.[24] AL-Meraikhi et al.[18] investigated the marginal discrepancy of Ti and zirconia frameworks and reported similar deviations, which is in line with another study.[21] However, Yilmaz et al.[21] also concluded that frameworks in high density polymer had lower marginal discrepancy than those in Ti and zirconia.

A limitation of this study was that the master model only had 4 implants and increased number of implants may affect the results.

Another limitation was that even though tested subtractively manufactured materials varied in chemical composition, only one additively manufactured resin, which is indicated for temporary use was tested. In addition, all frameworks were fabricated by using one milling unit and one 3-dimensional printer. The fabrication trueness of tested frameworks was evaluated by superimposing TF-STLs, which were generated with an industrial optical scanner, over the RF-STL with a metrology-grade 3-dimensional analysis software program that has been indicated by the International Organization for Standardization standard 12 836. Even though with another metrology-grade software program, this methodology has also been used in a previous study on implant-supported complete-arch frameworks.[1] However, different digitization methods such as computerized tomography (CT),[18,21,24] coordinate measuring machine,[28] and optic microscopy[29] have also been used in studies with similar objectives. The triple-scan protocol has been used in dental research for more than a decade[20] to evaluate the fit of different prosthetic structures,[27,30–32] including complete-arch implant-supported frameworks.[1] However, other marginal gap assessment methods, such as micro CT,[29] are also available. Finally, the present study focused on the fabrication trueness and marginal fit of complete-arch implant-supported frameworks, but other mechanical and optical properties of tested materials may also affect their clinical use. Future studies should investigate how measured deviations and marginal gap values affect the relevant clinical outcomes such as fatigue behavior and fracture strength of tested frameworks in the long-term.

5 | CONCLUSIONS

Within the limitations of this study, the following conclusions can be drawn:

1. The surface trueness of additively manufactured frameworks was mostly similar to or higher than subtractively manufactured frameworks in different materials. However, they mostly had lower occlusal surface trueness, which may be related to the presence of supports during fabrication.
2. The linear trueness at abutment sites were similar across frameworks in different materials. With frameworks in high impact polymer composite, abutment at the right first molar had lower linear trueness than the abutment at the left canine, which might lead to seating issues during the 1-screw test.
3. Increased interabutment distance mostly led to the lowest interimplant distance trueness, and additively manufactured frameworks mostly had trueness that were similar to or higher than those of subtractively manufactured frameworks. However, frameworks were mostly smaller than the original design file.
4. Marginal gaps of additively manufactured resin were either similar to or lower than those of subtractively manufactured frameworks and were similar across all abutments.

AUTHOR CONTRIBUTIONS

Burak Yilmaz: Concept/Design, Data interpretation, Critical revision of the article, Approval of the submitted and final versions. **Mustafa Borga Donmez**: Drafting article, Critical revision of article. **Esad Güven**: Data collection, Investigation. **Faris Z. Jamjoom**: Drafting article. **Çiğdem Kahveci**: Formal analysis. **Martin Schimmel**: Critical revision of the article, Approval of the submitted and final versions. **Gülce Çakmak**: Concept/Design, Methodology, Investigation.

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CONFLICT OF INTEREST STATEMENT

No conflict of interest.

DATA AVAILABILITY STATEMENT

The data sets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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