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The Effect of Different Framework Fabrication Techniques on Marginal Adaptation in All-on-4 Implant-Supported Fixed Prostheses

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Abstract

Background

The durability of implant-supported prosthetic structures is closely related to the attainment of precise marginal sealing at the connection among the prosthesis, implant fixture, and abutment. Traditionally, implant-supported metal frameworks have been produced using conventional wax patterning and casting approaches; nevertheless, these procedures can result in variable manufacturing outcomes and are susceptible to a range of process-dependent inaccuracies. To overcome these limitations, digital manufacturing approaches such as Selective Laser Melting (SLM) and three-dimensional (3D) printing technologies have been introduced for framework fabrication.

Materials and methods

Frameworks for 12-unit maxillary fixed prostheses planned according to the All-on-4 concept were designed using digital data obtained from a clinical case. Four different fabrication techniques were evaluated: conventionally cast Co-Cr frameworks, Co-Cr frameworks produced by Selective Laser Melting (SLM), 3D-printed resin frameworks, and Co-Cr frameworks obtained by casting the 3D-printed resin patterns (n = 6 per group). Marginal fit was assessed under a stereomicroscope using the Sheffield single-screw test. The obtained data were statistically analyzed.

Results

Marginal gap measurements differed across the evaluated groups. The 3D-printed resin frameworks exhibited the greatest marginal gap values; however, a marked improvement in marginal fit was observed following their conversion into Co–Cr frameworks through the casting process. Variability in marginal fit was observed among Co-Cr frameworks fabricated using the SLM technique, Co-Cr frameworks obtained by casting resin patterns, and Co-Cr frameworks produced by conventional casting methods, depending on the measurement regions. In certain regions, SLM-fabricated Co-Cr frameworks exhibited lower marginal gap values, whereas in other regions, Co-Cr frameworks obtained through resin pattern casting or those produced by conventional casting demonstrated lower marginal discrepancies.

Conclusions

Considering the methodological boundaries of the present investigation, the framework fabrication technique was found to affect the marginal fit of All-on-4 implant-supported fixed prostheses. However, clear superiority could not be established among the fabrication techniques, and marginal adaptation varied according to both fabrication technique and measurement region.

INTRODUCTION

Tooth loss is a significant health problem with a multifactorial etiology that directly affects oral function and quality of life [1]. Progressive bone resorption of the alveolar ridges after tooth loss can result in severe maxillary and mandibular atrophy. Patients with severe jaw atrophy and complete edentulism can be rehabilitated using various treatment modalities, including traditional full-arch prosthetic dentures, implant-retained fixed restorations, and implant-assisted removable prosthetic appliances [2]. In cases with severe posterior bone resorption in the maxilla and mandible, placement of standard implants often necessitates surgical bone augmentation procedures. However, augmentation increases treatment time and cost and is associated with higher morbidity and complication risk. The All-on-4 technique was developed to overcome these limitations by allowing posterior implant angulation, thereby reducing the need for extensive surgical interventions and enabling faster prosthetic rehabilitation [3]. In All-on-4 restorations, the attainment of a passive framework–implant fit is a decisive factor for long-term clinical stability, as it reduces biomechanical stress and supports the health of peri-implant tissues [4]. One of the clinical methods used to evaluate passive fit is the Sheffield single-screw test, which is based on fixing the framework only to a terminal implant and observing any lifting at the remaining implant sites [5]. Factors affecting passive fit include implant number and position, impression material, abutment type, restoration design and framework fabrication technique [6, 7].

Cobalt-chromium (Co-Cr) alloys are frequently utilized for implant-supported fixed prostheses and have demonstrated high survival rates in long-term clinical follow-ups [3]. Conventionally, Co-Cr frameworks are fabricated using wax patterning and lost-wax casting techniques. However, this multistep laboratory workflow may lead to dimensional inaccuracies and inconsistencies in production quality. To minimize these limitations and improve standardization, digital manufacturing technologies have become increasingly prevalent in dentistry. Recently, metal frameworks can be produced using CAD/CAM systems and additive manufacturing methods such as Selective Laser Melting (SLM) [8].

CAD/CAM systems predominantly rely on subtractive manufacturing processes, in which material is removed from a solid block through milling. Although production time is relatively short, excessive material waste remains a major disadvantage [9]. As defined by the American Society for Testing and Materials (ASTM), additive manufacturing involves the layer-by-layer construction of objects from three-dimensional digital data and offers a substantial reduction in material waste [9].

Selective Laser Melting (SLM) is a powder bed fusion-derived manufacturing method in which metal powders are fully melted through a high-intensity laser beam, allowing the production of dense and structurally uniform metal frameworks [10]. By allowing direct production from CAD data, SLM provides a more controlled and standardized workflow compared to conventional casting techniques [11, 12].

Another additive approach, 3D printing, involves layer-by-layer bonding of powder materials using binding agents and may require subsequent infiltration or surface hardening procedures [13–15]. This technique offers advantages such as low cost and rapid prototyping [13].

Studies comparing conventional casting, SLM and CAD/CAM techniques remain limited in the literature [16, 17]. More recent investigations indicate that 3D printing technologies may also serve as alternative fabrication methods; however, the biomechanical properties of polymer-based frameworks produced by these techniques remain insufficiently understood [18].

The present study was designed to assess and compare the marginal adaptation of All-on-4 implant-based fixed prosthetic frameworks produced using four distinct manufacturing approaches-conventional cast Co-Cr, SLM-produced Co-Cr, 3D-printed resin, and Co-Cr frameworks obtained by casting 3D-printed resin patterns-by means of the single-screw test.

Null Hypothesis (H_0):

No statistically significant differences are expected in the marginal adaptation of All-on-4 prosthetic frameworks manufactured using traditional casting approaches, Selective Laser Melting (SLM), 3D-printed resin methods, or by casting patterns obtained from 3D-printed resin.

MATERIALS AND METHODS

In this study, a completely edentulous maxillary case planned according to the All-on-4 concept was used. Four dental implants (Nobel Biocare, Sweden) were inserted into the maxillary arch. Two implants were inserted in the anterior region parallel to the alveolar crest axis, whereas the other two were positioned posteriorly with angulation in alignment with the planned prosthetic axis. Following completion of the osseointegration period, 0° multi-unit abutments were tightened onto the anterior straight implants with a torque of 35 N·cm, while 30° multi-unit abutments were connected to the posterior implants and torqued to 15 N·cm, in accordance with the manufacturer's guidelines.

An open-tray impression technique was employed. A custom tray compatible with the open-tray method was fabricated. Open-tray impression copings suitable for multi-unit abutments were placed intraorally and splinted together with dental floss to ensure stabilization. Pattern resin (Motif Pattern Resin LC, DETAX GmbH, Ettlingen, Germany) was applied at the connection points to create a rigid assembly and prevent displacement during impression taking. After complete polymerization of the resin, the impression was made using a polyvinyl siloxane material (Variotime® Easy Putty, Kulzer, Hanau, Germany). Upon polymerization, the tray was removed and correct positioning of the copings within the impression was verified. The impression was preserved for subsequent laboratory procedures.

Model Fabrication and Digital Scanning

A working cast was produced from the impression using polyurethane-based casting material to accurately reproduce implant positions (Fig. 1). Implant analogs were inserted into the impression prior to pouring, and their stability was confirmed after polymerization.

Scan bodies (IOS scan abutment, Nobel Biocare, Sweden) were manually tightened onto the implant analogs on the polyurethane cast. The model was digitized using a laboratory optical 3D scanner. The resulting data were transferred into Exocad (Exocad GmbH, Darmstadt, Germany), where a 12-unit fixed prosthesis framework compatible with the All-on-4 concept was digitally designed. The design was exported in STL format for fabrication.

Framework Fabrication Methods

Using the STL data, frameworks were produced with four different techniques (n = 6 per group; total = 24).

1. Conventional Casting

Wax patterns were prepared directly on UCLA abutments. After confirming their fit, the patterns were cast in a Co-Cr alloy (Magnum Ceramic, MESA, Italy) using the lost-wax casting method. The prepared wax patterns were connected to sprues, embedded in a phosphate-bonded investment material (Nanovest, Şirin Dental, Ankara, Turkey), and subsequently subjected to burnout in a preheating furnace (Mikrotek MFX-1025). Casting was completed in an induction centrifugal casting machine (Mikrotek Inf-2010). After divesting, sprues were removed and frameworks were sandblasted with 50 μm Al_2O_3. Finishing procedures were completed (Figs. 2–3).

2. Selective Laser Melting (SLM)

The same STL files were used to fabricate Co-Cr frameworks via SLM (VM120 PBF-LB, Vulcan Technology, Germany) using 200 W fiber laser. Metal powder was fused layer by layer to obtain final frameworks (Fig. 4).

3. 3D Printed Resin Frameworks

The same CAD datasets were used to fabricate resin-based frameworks using a 3D printer (HALOT-SKY 2022, Shenzhen Creality 3D Technology Co., Ltd., Shenzhen, China) and a photopolymer resin material (Model Resin; Alias 3D Resin, Turkey). After printing, the frameworks were separated from the manufacturing platform, and the auxiliary support elements were manually detached without damaging the surface. This group represents the additive manufacturing method. Using this technique, a total of six 12-unit resin-based frameworks were produced. (Figs. 5–6).

4. Cast-from-3D Resin Frameworks

The printed resin frameworks were used as casting patterns and cast in Co-Cr alloy following the same lost-wax workflow (Fig. 7).

Marginal Fit Evaluation-Single Screw Test

Marginal gaps between frameworks and multi-unit abutments were evaluated using the Sheffield single screw test. Implant positions were labeled L1-L4. First, only the L1 screw was tightened to 15 N·cm, and then the same procedure was repeated for L4.

Each abutment surface was divided into mesial, mid-mesial and distal areas on both buccal and palatal sides. Five measurements were obtained per region, yielding 30 measurements per screw position. (Fig. 8–9)

For each fabrication group:

Buccal surface → 6 frameworks × 15 measurements = 90

Palatal surface → 6 frameworks × 15 measurements = 90

Total per group = 180 measurements.

All measurements were performed under a stereomicroscope at 200× magnification (Carl Zeiss Stemi 305, Göttingen, Germany) with an integrated digital camera (Zeiss ERC5). Marginal gap values were analyzed from high-resolution images.

Data obtained from L1 and L4 tightening conditions were comparatively analyzed to determine passive framework adaptation.

RESULTS

The minimum sample size needed to evaluate the study hypothesis was calculated with the aid of G*Power software (version 3.1.9.7), with a 95% confidence level, a significance threshold of $\alpha = 0.05$, and a target statistical power of 95% ($1- \beta = 0.95$). The analysis indicated that a minimum of 280 measurement points was required, corresponding to at least 35 points per cell. Within this study, 90 measurement points were obtained for each group, yielding an overall dataset of 720 measurements.

Data analyses were carried out using the Statistical Package for the Social Sciences (SPSS) for Windows, version 27 (SPSS Inc., Chicago, IL, USA), in combination with R statistical software (version 4.4.1, Vienna, Austria). Descriptive analyses were conducted to summarize the dataset, including the minimum, median, maximum, mean, and standard deviation values. The distribution of the data was assessed for normal distribution through the Shapiro-Wilk test. For data that deviated from normal distribution, intergroup differences between two distinct groups were assessed using the Mann-Whitney U test, whereas analyses involving three or more separate groups were evaluated with the Kruskal-Wallis test. When significant differences were identified, pairwise comparisons were carried out using Bonferroni-adjusted post hoc analyses. The threshold for statistical significance was defined as $\alpha = 0.05$ for all analyses.

Vertical misfit in the conventional casting, SLM, 3D resin, and cast-from-3D resin framework groups was evaluated by tightening a single screw first at the most distal multi-unit abutment on the right side (L1 region), followed by repeating the same procedure on the left side (L4 region).

The mean marginal gap values (μm) and standard deviations of the fabrication groups according to screw tightening positions (L1 and L4) are presented in Table 1.

With the L1 screw tightened, the minimum marginal misfit value was found in the cast-from 3D-printed resin group at the L1 buccal site (56.54 ± 31.68 μm), while the highest marginal discrepancy was noted among the 3D-printed resin group at the L4 buccal site (3637.28 ± 699.53 μm). When the L4 screw was tightened, the minimum marginal misfit value was recorded in the SLM group at the L4 buccal region (70.7 ± 39.6 μm), whereas the greatest marginal discrepancy was identified among the 3D-printed resin specimens at the L1 buccal region (1917.98 ± 503.66 μm).

Across all fabrication groups,
-With L1 screw tightening, the greatest marginal discrepancy occurred at L4 buccally.
- With L4 screw tightening, the greatest marginal discrepancy occurred at L1 buccally.

The regional comparison of marginal gap values obtained when tightening either the L1 or L4 screw for each fabrication method is presented in Table 2. Since the dataset showed a non-normal distribution pattern, the Mann-Whitney U test was employed to determine the statistical significance of differences in marginal gap values between L1 and L4 screw tightening for each region.

Based on the statistical analysis, marginal discrepancies increased toward the terminal end opposite the tightened screw in all specimens. Buccal and palatal marginal gaps differed within each implant region. For all fabrication groups, tightening the L1 screw resulted in lower marginal gap values at the L1 and L2 buccal and palatal regions, whereas tightening the L4 screw produced lower marginal gap values at the L3 and L4 buccal and palatal regions. The marginal gap values among fabrication groups according to screw position (L1 or L4) and surface (buccal/palatal) were evaluated using the Kruskal-Wallis test (Tables 3 and 4).

According to Table 3 (L1 screw tightening)

A statistically significant difference among groups was detected at the L1 buccal surface (KW = 229.369, $p < 0.001$). Post hoc multiple comparisons using Bonferroni correction indicated that the conventional casting group presented significantly greater marginal gap values than both the cast-from-3D-printed resin and SLM groups ($p < 0.05$). The 3D-printed resin group demonstrated significantly greater marginal gap values compared with all other groups ($p < 0.05$). Similarly, marginal gap values at the L1 palatal surface differed significantly among groups (KW = 209.034, $p < 0.001$). Bonferroni correction analysis indicated that the conventional casting group showed markedly greater marginal discrepancies compared with the cast-from-3D resin and SLM groups ($p < 0.05$). Furthermore, the resin-based 3D-

printed group demonstrated significantly increased marginal gap values compared with all other fabrication groups ($p < 0.05$).

A significant statistical variation between the study groups was detected at the L2 buccal surface (KW = 204.993, $p < 0.001$). Bonferroni-corrected multiple comparisons indicated that the 3D-printed resin specimens showed significantly greater marginal gap values compared with the conventional casting, cast-from-3D-printed resin, and SLM groups ($p < 0.05$).

Marginal discrepancy values recorded at the L2 palatal surface differed significantly among the fabrication groups (KW = 218.873, $p < 0.001$). Multiple comparison analyses with Bonferroni correction indicated that the SLM group presented significantly greater marginal gap values compared with both the cast-from-3D-printed resin and conventional casting groups ($p < 0.05$). Furthermore, the 3D-printed resin specimens demonstrated significantly greater marginal discrepancies compared with all remaining groups ($p < 0.05$).

At the L3 buccal surface, marginal discrepancy values differed significantly among groups (KW = 222.797, $p < 0.001$). Bonferroni-corrected multiple comparison evaluation indicated the conventional casting group showed significantly greater marginal discrepancy values compared with both the cast-from–3D-printed resin and SLM groups ($p < 0.05$). Moreover, the resin-based 3D-printed specimens presented significantly increased marginal discrepancies compared with all remaining fabrication groups ($p < 0.05$).

Similarly, statistically significant variations between the groups were detected in marginal discrepancy values at the L3 palatal surface (KW = 214.647, $p < 0.001$). Multiple comparison testing with Bonferroni correction indicated the SLM group showed significantly greater marginal discrepancy values compared with the cast-from–3D-printed resin specimens. Consistently, the resin-based 3D-printed specimens presented markedly increased marginal discrepancies compared with the remaining groups ($p < 0.05$).

Marginal discrepancy measurements recorded at the L4 buccal surface revealed significant statistical variation between the fabrication groups (KW = 204.094, $p < 0.001$). Multiple comparison analysis using Bonferroni correction indicated the 3D-printed resin specimens presented significantly greater marginal discrepancy values compared with the remaining groups ($p < 0.05$).

Similarly, marginal discrepancy values at the L4 palatal surface showed statistically significant variation between the groups (KW = 203.211, $p < 0.001$). Bonferroni-corrected evaluation indicated the 3D-printed resin specimens presented markedly increased marginal discrepancies in comparison with the remaining study groups ($p < 0.05$).

Based on the mean and standard deviation values, the cast-from–3D-printed resin group showed the lowest level of marginal discrepancy relative to the conventional casting as well as the SLM groups. The resin-based additively manufactured group exhibited the greatest extent of marginal discrepancy across all evaluated regions.

According to Table 4 (L4 screw tightening)

Significant statistical variation was detected between the groups in marginal discrepancy assessments at the L1 buccal surface (KW = 178.678, $p < 0.001$). Bonferroni-corrected multiple comparison testing indicated the cast-from–3D-printed resin specimens showed significantly greater marginal discrepancy measurements relative to the conventional casting and SLM groups. The 3D-printed resin group showed a significantly greater degree of marginal misfit relative to the remaining study groups ($p < 0.05$).

At the L1 palatal surface, statistically significant differences were also observed (KW = 157.311, $p < 0.001$). Bonferroni analysis demonstrated that the cast-from-3D-printed resin group exhibited significantly greater marginal discrepancy levels relative to the conventional casting and SLM groups. Again, the 3D-printed resin group showed a significantly greater degree of marginal misfit relative to the remaining study groups ($p < 0.05$).

Marginal gap values measured at the L2 buccal surface differed significantly among groups (KW = 207.634, $p < 0.001$). Bonferroni-corrected multiple testing indicated the cast-from–3D-printed resin specimens demonstrated significantly greater marginal discrepancies relative to the conventional casting and SLM groups. The 3D-printed resin specimens presented significantly increased values compared with all remaining groups ($p < 0.05$).

Likewise, statistically significant variation between the groups was identified at the L2 palatal surface (KW = 199.633, $p < 0.001$). Bonferroni-corrected analysis demonstrated that the cast-from-3D resin group exhibited higher marginal gaps than the conventional casting and SLM groups, whereas the 3D-printed resin group presented the most elevated values ($p < 0.05$).

At the L3 buccal surface, significant differences among groups were detected (KW = 210.332, $p < 0.001$). Bonferroni-corrected multiple comparison evaluation indicated the SLM group demonstrated significantly improved marginal adaptation relative to the conventional casting and cast-from–3D-printed resin groups ($p < 0.05$). The 3D-printed resin group presented a significantly greater degree of marginal misfit relative to the remaining study groups ($p < 0.05$).

Significant statistical variation between the study groups was additionally identified in marginal discrepancy measurements at the L3 palatal surface (KW = 180.376, $p < 0.001$). Bonferroni-corrected analysis indicated the 3D-printed resin specimens were associated with a significantly greater degree of marginal discrepancy relative to the remaining fabrication groups ($p < 0.05$).

Marginal discrepancy values measured at the L4 buccal surface demonstrated significant statistical variation between the fabrication groups (KW = 177.687, $p < 0.001$). Multiple comparison testing with Bonferroni correction indicated the conventional casting group exhibited significantly greater marginal discrepancy levels relative to the cast-from–3D-printed resin and SLM groups ($p < 0.05$). The 3D-printed resin group presented significantly greater marginal discrepancies compared with the remaining groups in the study ($p < 0.05$).

Likewise, significant statistical variation in marginal gap measurements was detected between the groups at the L4 palatal surface (KW = 147.325, $p < 0.001$). Bonferroni analysis demonstrated that the conventional casting group exhibited significantly greater marginal discrepancies than the cast-from–3D-printed resin and SLM groups ($p < 0.05$). In addition, the 3D-printed resin group demonstrated significantly greater marginal discrepancies compared with the remaining fabrication groups ($p < 0.05$).

Among the conventional casting, SLM, and resin pattern-cast groups, the resin pattern-cast group showed the greatest marginal discrepancies across all regions, with the exception of the L4 buccal and L4 palatal surfaces. Across all regions, the 3D-printed resin group consistently demonstrated the greatest marginal discrepancies. Overall, the SLM group showed marginal gap values similar to or lower than those observed in the conventional casting group.

Based on all analyses obtained following tightening of either the L1 or L4 screw

3D-printed resin frameworks exhibited higher marginal gap values than all other fabrication groups in every measurement region.

Casting of the 3D-printed resin patterns into Co-Cr resulted in a marked reduction in marginal gap values.

When the cast-from-3D resin Co-Cr frameworks were compared with the conventional casting group, superior marginal adaptation was observed in some regions for the cast-from-3D resin group, whereas the conventional casting group demonstrated better results in other regions.

Similarly, comparison between the cast-from-3D resin Co-Cr frameworks and the SLM group revealed region-dependent variations, with each method showing lower marginal gap values in different areas. Overall, SLM-fabricated frameworks demonstrated superior marginal adaptation compared with those manufactured using conventional casting.

DISCUSSION

In this study, the marginal fit accuracy of frameworks fabricated using different production techniques on implants placed in a completely edentulous maxilla according to the All-on-4 concept was compared by means of the single screw test under stereomicroscopic evaluation. The material groups included Co-Cr frameworks produced by conventional casting, Co-Cr frameworks fabricated using Selective Laser Melting (SLM), 3D-printed resin frameworks, and Co-Cr frameworks obtained by casting the 3D-printed resin patterns. Based on the results obtained, since the production method was found to affect the marginal adaptation of the restorations, the null hypothesis (H_0) was rejected.

The All-on-4 approach was introduced to enable more efficient use of the available bone in the prosthetic rehabilitation of completely edentulous patients with anatomical constraints, while minimizing the need for further surgical intervention. The sustained clinical performance of All-on-4 restorations is strongly associated with the attainment of a passive and stress-free adaptation of the prosthetic framework. [4]. Achieving complete passive fit in implant-supported prostheses is highly challenging, and a certain level

of misfit is often unavoidable. Therefore, from a clinical perspective, the critical factor is not absolute perfection but maintaining discrepancies within acceptable limits. The multistep nature of implant framework fabrication complicates the attainment of passive fit, and each production technique may influence restoration accuracy differently due to technique-specific procedures and material properties [16]. In the present study, all variables other than fabrication technique were controlled to isolate its effect on marginal fit. All specimens were prepared using a single digital design and standardized casting protocol to minimize variability.

Metal-ceramic restorations fabricated through conventional casting remain widely used in the production of implant-supported complete-arch fixed prosthetic restorations. However, the technique-sensitive and multistage nature of casting increases the risk of dimensional distortion and misfit, particularly in multi-unit structures [19]. CAD/CAM technologies have been introduced as an alternative to conventional workflows, eliminating many thermal and mechanical influences associated with impression taking, model fabrication, investing, and casting, thereby enabling more standardized and accurate restorations [20–22]. Although most CAD/CAM systems rely on subtractive milling and demonstrate high success rates in metal framework fabrication, disadvantages such as material waste, bur wear, and prolonged processing times increase overall cost [9, 23, 24]. In recent years, additive manufacturing techniques such as SLM/SLS have enabled the high-precision fabrication of complex and customized prosthetic frameworks by selectively fusing metal powders layer by layer using laser technology, reducing manual intervention and improving production efficiency [24].

In the present study, in addition to Co-Cr frameworks fabricated using conventional casting and SLM techniques, resin frameworks produced by 3D printing and Co-Cr frameworks obtained by casting these resin patterns were also compared in terms of marginal fit in order to contribute to the current literature.

Microscopic and sectioning-based methods are commonly used in the literature for marginal fit evaluation [25–29]. In this study, a stereomicroscope was employed to allow clear determination of measurement boundaries and to directly assess vertical discrepancies at the micrometer level. Although no definitive consensus exists regarding acceptable misfit limits in implant-supported superstructures, several studies report that values within the range of approximately 150–200 μm may be considered clinically acceptable [4]. One of the earliest thresholds related to passive fit was proposed by Brånemark [30], who reported that vertical misfit in implant-supported frameworks should not exceed 10 μm. Zervas *et al*. [31] suggested that a discrepancy of approximately 30 μm at the implant-abutment interface could be clinically acceptable provided that it does not affect more than 10% of the circumferential fit. More recently, Jemt and Book [32] stated that even vertical misfits up to 150 μm might still fall within clinically acceptable limits. Moldovan *et al.* [33] reported that discrepancies around 100 μm could be regarded as good, whereas values between 200 and 300 μm remained clinically acceptable. Considering contemporary fabrication technologies and materials, previous in vitro findings and the findings of this study similarly indicate that a certain degree of accuracy loss and vertical misfit is unavoidable [34]. Therefore, the vertical marginal discrepancies measured in this study may reasonably reflect clinical reality.

A review of the literature reveals no standardized consensus regarding sample size, number of measurements per specimen, or reference points used for marginal fit evaluation [35, 36]. Groten *et al.* [36], in their in vitro study using scanning electron microscopy (SEM), emphasized that the number of measurements cannot be defined by a fixed formula and should instead be empirically determined according to the study design, recommending at least 20 measurement points per crown to ensure reliable results. Kokubo *et al*. [37] assessed the adaptation of 90 all-ceramic crowns by examining both marginal and internal discrepancies through the silicone replica method, using a total of 16 reference points. Pimenta et al. [38] assessed the marginal and internal fit of zirconia, lithium disilicate, and nickel–chromium restorations using micro-CT analysis, based on 13 reference points, including four at the margins and nine within the internal regions. In the present study, a total of 30 measurement points were defined for each implant region, comprising 15 on the buccal surface and 15 on the palatal surface. Since six specimens were produced for each fabrication technique, marginal fit was evaluated using datasets consisting of 90 measurement points for each surface per technique. Overall, 720 measurement points were analyzed.

Several studies have reported the use of the Sheffield (single-screw) test for evaluating the fit of implant-supported full-arch fixed frameworks [39–42]. Begoña Ormaechea *et al.* [43] recommended this method and demonstrated that vertical discrepancies become more pronounced at the terminal abutment opposite the tightened screw. Singh et al. [34] similarly reported increased marginal misfit at terminal implant regions in full-arch screw-retained prostheses. Mahmoud *et al.* [4] evaluated vertical marginal fit in All-on-4 full-arch prostheses using the Sheffield test and stereomicroscopy and reported higher discrepancies at terminal multi-unit abutment regions, consistent with the present findings. Yilmaz *et al.* [44] assessed marginal fit in All-on-4 full-arch screw-retained prostheses and demonstrated that frameworks fabricated from high-density polymers with lower elastic modulus exhibited lower marginal gaps than titanium and zirconia, emphasizing the influence of framework rigidity. Likewise, marginal fit differences among Co-Cr frameworks observed in this study may be associated with variations in structural rigidity and production-related biomechanical effects.

He *et al*. [45], in a comprehensive review of laboratory investigations evaluating 3D-printed Co-Cr implant-supported prostheses, reported that marginal adaptation varies depending on fabrication technique and restoration type. They concluded that 3D-printed Co-Cr frameworks generally show better marginal fit than conventional casting but lower accuracy than milled frameworks. These findings support the present results, where SLM-fabricated Co-Cr frameworks demonstrated lower marginal gap values than conventionally cast frameworks. Abu Ghofa and Önöral [46] reported that SLM demonstrated the lowest vertical marginal misfit values in multi-unit implant-supported Co-Cr frameworks fabricated using different techniques. However, their study was limited to three-unit restorations. The absence of consistent superiority of SLM frameworks in All-on-4 prostheses in the present study may be attributed to the different biomechanical conditions associated with full-arch prosthetic designs and angled distal implants. Akçin *et al.* [19] compared traditional casting, CAD/CAM milling methods, and SLM techniques in implant-supported Co-Cr frameworks and observed that SLM exhibited lower marginal gap values in three- and four-unit restorations, whereas conventional casting provided better marginal fit in five-unit

restorations. Presotto *et al.* [47] demonstrated that SLM-fabricated Co-Cr frameworks showed lower marginal discrepancies and reduced stress and strain values compared to conventional casting and soft metal milling techniques. Similarly, Zhou *et al.* [48] reported that marginal fit varied according to fabrication technique and became more pronounced as the number of units increased; CAD/CAM milling showed the best marginal adaptation, followed by SLM, while conventional casting exhibited the highest marginal gaps. Pompa *et al.* [49] also found significantly lower marginal gap values in four-unit prostheses fabricated using SLM compared to those produced by conventional casting.

Nesse *et al.* [50] compared conventional casting, CAD/CAM subtractive manufacturing methods, and Selective Laser Melting (SLM) approaches in three-unit Co–Cr fixed dental restorations and evaluated marginal adaptation by direct observation under optical magnification. Their findings demonstrated statistically significant differences among the fabrication methods. Among the fabrication methods, milling showed the most precise marginal adaptation, whereas the SLM group presented larger marginal gaps than the conventional casting group. Nesse *et al.* [50] also showed that metallic surface irregularities (metal pearls) formed during the SLM process may hinder complete seating of the framework and negatively affect marginal adaptation. In contrast, the results of this study indicated the SLM group exhibited superior marginal adaptation compared with the conventional casting group.These findings may be explained by variations in study design, since the investigation by Nesse *et al.* [50] focused on tooth-supported three-unit restorations and assessed marginal adaptation exclusively through direct visual examination.

Following the findings related to metal frameworks, studies evaluating the marginal adaptation of 3D-printed resin restorations indicate that manufacturing-related factors significantly influence marginal fit [51–55].

Park *et al.* [51] reported that marginal fit in implant-supported 3D-printed resin restorations may vary based on printing direction and selected layer thickness. Osman *et al.* [52] demonstrated that printing angle and support structure configuration are critical determinants affecting dimensional accuracy and marginal deviations in DLP-fabricated resin restorations. Similarly, Yang *et al.* [53] evaluated three-unit implant-supported resin prostheses produced by stereolithography (SLA) and reported regional variations in marginal fit associated with printing direction, particularly in areas adjacent to the pontic region. Higher marginal gap values were observed near the pontic areas and were attributed to polymerization shrinkage. Alharbi *et al.* [54] also showed that printing angle and the proximity of support structures to marginal areas may lead to increased marginal deformation in SLA-fabricated restorations.

These findings explain the increased marginal discrepancy values detected in the 3D-printed resin frameworks in the present study. In addition, the use of the Sheffield single-screw test for marginal fit evaluation is an important factor in interpreting the discrepancies between resin and metal frameworks. The lower elastic modulus and dimensional instability inherent to resin materials may have resulted in greater deformation during single-screw testing, thereby contributing to increased marginal gap values.

Conversely, the marked reduction in marginal discrepancies after casting the resin frameworks into Co-Cr may be associated with the increased rigidity and improved seating stability of the metal frameworks.

Bani-Younes *et al.* [56] compared Co-Cr metal frameworks produced via Selective Laser Melting (SLM) and the castable pattern (CP) technique based on 3D-printable casting resins, and evaluated marginal fit by examining silicone replica sections under a stereomicroscope. Marginal adaptation was found to be comparable between the two fabrication techniques, with no meaningful statistical separation detected. This finding indicates that digitally designed and 3D-printed castable resin patterns can provide marginal fit comparable to SLM frameworks. Within this study, Co-Cr frameworks obtained from casting 3D-printed resin patterns demonstrated lower marginal gap values than SLM frameworks in certain regions. The standardized and reproducible nature of the digital design phase in the cast-from-resin workflow, compared with conventional wax patterning, may have contributed to improved marginal adaptation. However, in some regions, marginal discrepancies within the cast-from–3D resin group were greater than those detected in the SLM group, which may be attributed to casting-related factors such as resin burnout, metal shrinkage, and interactions with the investment material. These findings suggest that although the cast-from-3D resin technique benefits from digital standardization, it cannot entirely eliminate the inherent limitations associated with the casting process. Dikova et *al.* [57] investigated the marginal fit of four-unit Co-Cr bridges fabricated using conventional casting, casting of 3D-printed patterns, and SLM, and reported that fabrication technique significantly influenced fit accuracy. Their results demonstrated superior marginal adaptation in Co-Cr frameworks obtained from cast 3D-printed patterns compared to both SLM and conventional casting methods. Pekkan *et al.* [58] compared marginal, internal, and occlusal adaptation of three-unit posterior tooth-supported Co-Cr fixed dental prostheses fabricated using conventional casting, 3D-printed pattern casting, CAD/CAM wax casting, SLM, and DMLS, using the silicone replica technique under stereomicroscopy. They reported that the SLM and DMLS groups generally exhibited better marginal fit than the conventional casting and 3D-printed pattern casting groups. No meaningful difference was identified between the conventional and 3D-printed pattern casting groups in the premolar area; however, in the molar area, the conventional group demonstrated higher marginal gap values. Kim *et al.* [59] examined marginal and internal fit of Co–Cr single crowns produced through conventional casting, casting from SLA-generated resin patterns, and milling using optical microscopy. They reported that SLA-derived cast frameworks demonstrated marginal adaptation that did not differ in a clinically relevant manner from conventionally cast frameworks, and that both fabrication methods remained within acceptable clinical thresholds. Kalsekar *et al.* [60] evaluated the vertical marginal accuracy of single-unit Co–Cr crowns produced through conventional casting, casting of 3D-printed resin patterns, and direct metal laser sintering (DMLS) in an in vitro study. Marginal adaptation was assessed under a stereomicroscope. The authors reported that marginal gap values were highest in the conventional casting group, whereas frameworks fabricated from 3D-printed resin patterns exhibited lower marginal discrepancies. The most favorable marginal adaptation was identified within the DMLS group [60].

Since this investigation evaluated marginal adaptation in All-on-4 prostheses under in vitro conditions only, direct extrapolation of the findings to clinical situations is limited and long-term clinical

investigations are warranted. Although the Sheffield single-screw test is widely used to detect passive misfit, its inability to fully simulate the clinical scenario in which all screws are tightened simultaneously represents an important limitation. Furthermore, only the All-on-4 configuration and the framework stage were examined; the effects of different implant distributions, varying prosthesis spans, and ceramic veneering procedures on marginal adaptation were beyond the scope of this study.

CONCLUSION

Considering the constraints of this investigation, in which the influence of various framework production methods on the marginal adaptation of All-on-4 implant-based fixed prostheses was assessed using the Sheffield single-screw test under stereomicroscopy, the following outcomes were obtained:

1. Significant differences in marginal fit were observed among frameworks fabricated using different production techniques (conventional casting, SLM, 3D-printed resin, and cast-from-3D-printed resin Co-Cr frameworks).
2. In all measurement regions, 3D-printed resin frameworks exhibited the highest marginal gap values compared to the other fabrication methods. However, a marked reduction in marginal discrepancies was observed in the Co-Cr frameworks obtained after casting these resin patterns.
3. The cast-from-3D-printed resin Co-Cr frameworks demonstrated marginal fit values comparable to those produced by conventional casting and SLM, and even showed lower marginal gaps in certain regions. Variations in marginal adaptation among fabrication techniques appear to be associated with technique-specific processing steps and the dimensional inaccuracies that may arise during each stage.
4. Co-Cr frameworks produced by casting from 3D-printed resin patterns may be considered a potential alternative to conventional and SLM-based production techniques for implant-supported restorations. Nevertheless, further clinical studies are required to validate these findings.

Abbreviations

ASTM
American Society for Testing and Materials
CAD
Computer Aided Design
CAM
Computer Aided Manufacturing
CEREC
Ceramic Reconstruction
Co-Cr
Cobalt-chrome
µm
micrometer

n
Number of samples
SLM
Selective Laser Melting
DMLS
Direct Metal Laser Sintering
3D
Three-dimensional

Declarations

Ethics approval and consent to participate: This study was reviewed and approved by the Non-Interventional Clinical Research Ethics Committee of Recep Tayyip Erdoğan University during the meeting held on July 29, 2025 (Decision No: 2025/341). All procedures performed in the study were in accordance with the ethical standards of the institutional and/or national research committee and the 1975 Declaration of Helsinki, revised in 2013. Informed consent was obtained from all participants included in the study.

Human ethics: The study does not include samples of human tissues.

Consent for publication: Not applicable

Availability of data and materials: All data generated or analysed during this study are included in this published article.

Competing interests: The authors declare that they have no competing interests.

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Authors' contributions: MÇ and MA contributed to the conceptualization of the study, writing, and preparation of the original draft. MA contributed to data curation, interpretation of the results, formal analysis, and critical revision of the manuscript. MÇ contributed to methodology design, data collection, literature review, and figure preparation. Both authors contributed to the review, editing, and final approval of the manuscript. All authors have read and approved the published version of the manuscript.

Clinical trial number: Not applicable

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Tables

Tables 1 to 4 are available in the supplementary files section

Figures



Figure 1

polyurethane model



Figure 2

Co-Cr metal frameworks fabricated by the conventional casting technique



Figure 3

Conventional cast Co-Cr frameworks positioned on the model



Figure 4

Co-Cr frameworks fabricated by the SLM technique positioned on the model

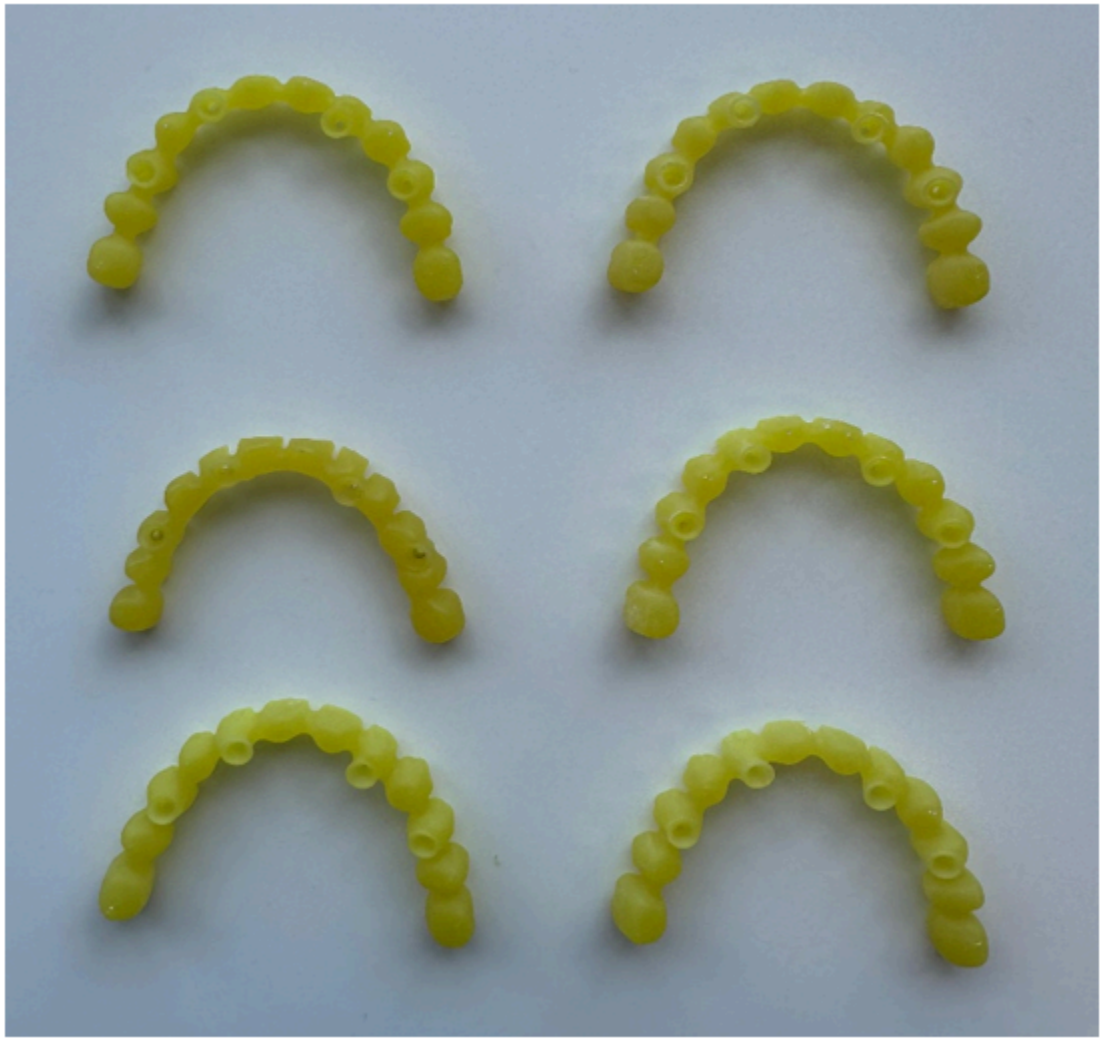


Figure 5

Resin-based frameworks fabricated using the 3D printing technique



Figure 6

3D-printed resin-based frameworks positioned on the model

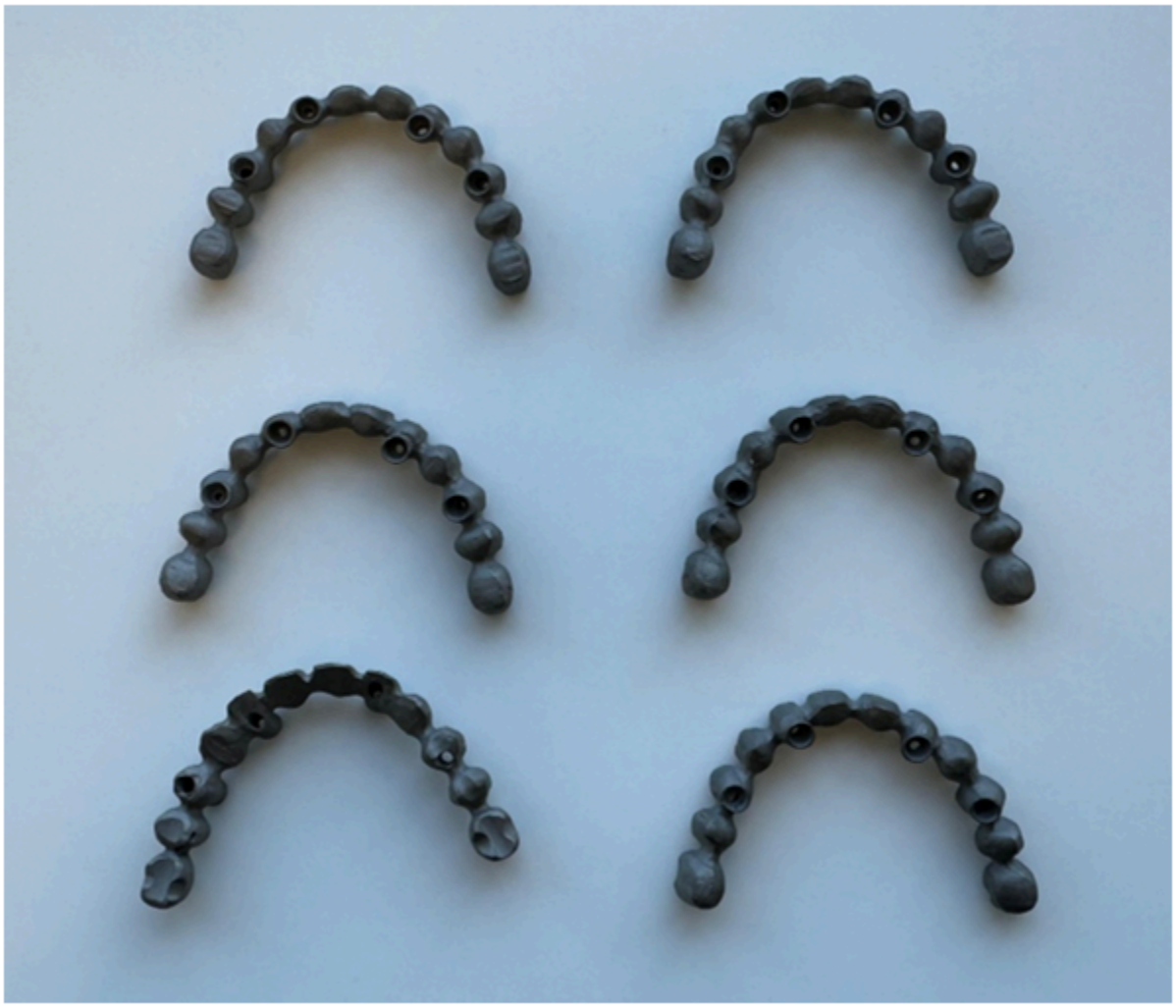


Figure 7

Co-Cr frameworks fabricated by casting of resin patterns



Figure 8

Marked regions on the polyurethane model

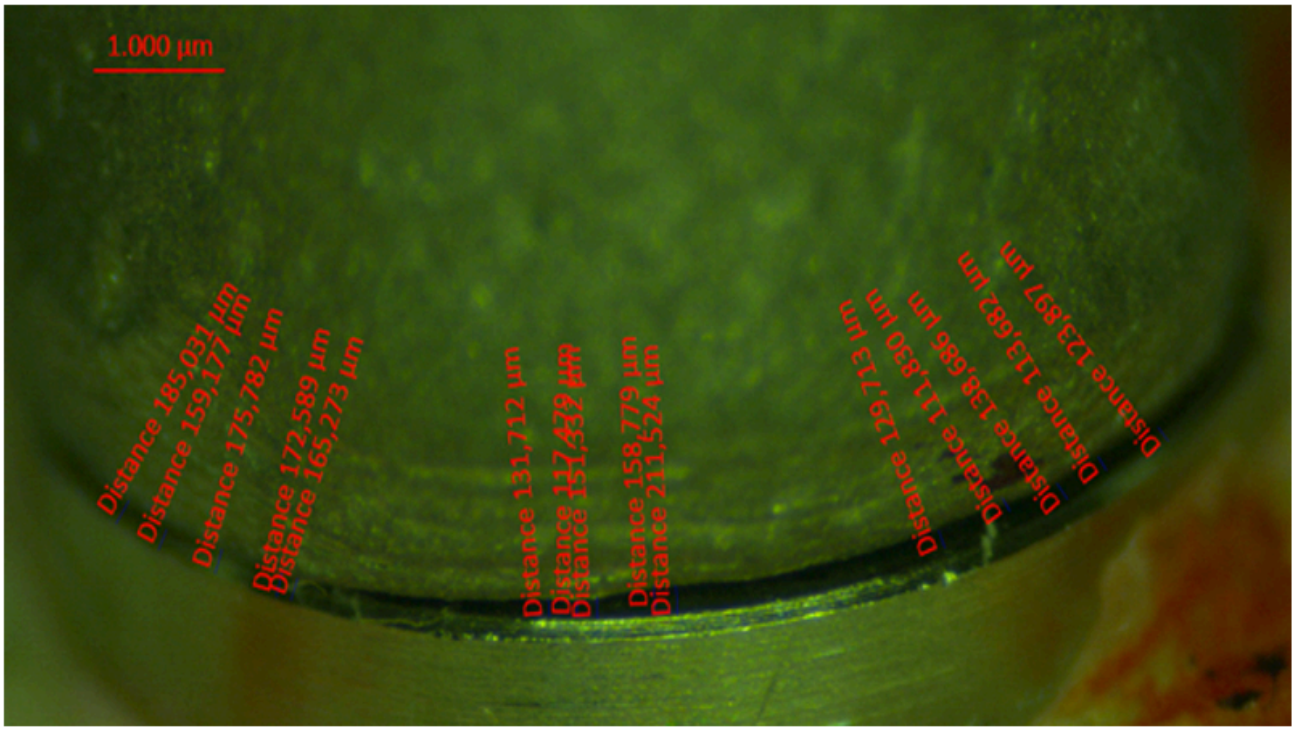


Figure 9

Stereomicroscopic examination of the specimens

Supplementary Files

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- MERVERTable.docx