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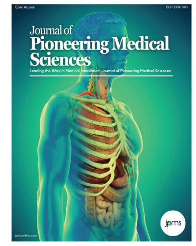

How Accurate is the Fit of Additive 3D-Printed Implant-Supported Restorations and Partial Coverage Posterior Restorations? A Systematic Review

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Abstract **Background:** Accuracy of fit is a critical determinant of the clinical success and longevity of dental restorations, particularly for implant-supported and partial coverage posterior restorations. Although subtractive milling techniques have been widely used in dentistry, additive manufacturing technologies have emerged as promising alternatives, offering the potential for greater accuracy, customization and cost-efficiency. This systematic review aimed to compare the accuracy of fit of additive 3D-printed implant-supported and partial coverage posterior restorations with subtractive milling and conventional techniques. **Methods:** The review followed PRISMA guidelines. A comprehensive electronic search was conducted across PubMed, Cochrane Library, Web of Science, Embase and Scopus to identify relevant studies. Studies were included if they evaluated the accuracy of fit of additive 3D-printed implant-supported restorations and partial coverage posterior restorations, compared to subtractive milling or conventional techniques. The modified CONSORT checklist for *in vitro* studies was used to assess methodological quality and risk of bias. **Results:** A total of 1,913 records were identified and after removing duplicates and screening for eligibility, eight *in vitro* studies were included. The studies evaluated 322 samples across a range of implant-supported frameworks, inlays and onlays. Technologies assessed included Selective Laser Melting (SLM), stereolithography (SLA), Digital Light Processing (DLP) and multijet 3D printing, alongside CAD/CAM milling and conventional casting. The findings consistently demonstrated that additive manufacturing achieved accuracy of fit comparable to subtractive milling in simple designs, while three-dimensional printed restorations exhibited better marginal and internal adaptation, especially for complex geometries. Conventional casting and milling techniques showed larger discrepancies, particularly for multiunit frameworks. The risk of bias was generally low across all included studies, although variation in measurement techniques and the lack of sample size justification were noted as limitations. **Conclusion:** This systematic review indicates that additive manufacturing techniques offer improved accuracy of fit compared to subtractive milling and conventional methods for implant-supported restorations and partial coverage posterior restorations. However, the *in vitro* design of the studies limits the direct clinical applicability of the findings.

Key Words Additive Manufacturing, 3D Printing, Implant-Supported Restoration, Onlay, Inlay

INTRODUCTION

The accuracy of fit is a critical factor influencing the clinical success and longevity of dental restorations in the oral environment, particularly for implants and partial coverage posterior restorations [1]. Inadequate marginal or internal adaptation may lead to cement dissolution and microleakage, potentially causing secondary caries and compromising both function and aesthetics [2,3]. Therefore, achieving a precise fit between the restoration and the prepared tooth is essential to minimize complications and enhance the longevity of dental prostheses [4].

Conventional casting is a complex and time-intensive process that involves multiple steps and relies heavily on both the operator's skill and the quality of materials used. Due to its sensitivity and dependency on various factors, it is more susceptible to errors [5]. To overcome these limitations, digital workflows were introduced, marking a transition from traditional manual fabrication to computer-aided methods. Subtractive milling technique, commonly known as Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM), was introduced in dentistry nearly four decades ago and has been widely used for fabricating these restorations. This method involves carving the restoration from a prefabricated solid material block with the guidance of Computer Numerical Control (CNC), which can result in material wastage and limitations in creating intricate designs [6]. Additionally, the use of milling burs can restrict access to concave or complex geometries, leading to less-than-optimal marginal adaptation, notches or cracks [7].

Building on these digital workflows, recent advances have enabled additive manufacturing technologies, particularly 3D printing, to emerge as a promising alternative. Unlike subtractive methods, 3D printing builds restorations layer-by-layer, allowing for greater customization, detailed contouring and reduced material waste [8]. Among the various techniques, selective laser melting and multijet 3D Printing have shown significant potential in producing highly accurate and precise dental restorations [8]. These technologies are particularly advantageous for creating complex geometries and intricate designs with less material waste, which are challenging to achieve with traditional milling [9]. Selective laser melting has the ability to completely melt the metal powder, unlike selective laser sintering, which only partially fuses the powder particles [10-12].

Despite the growing interest in 3D-printed dental restorations, there remains a lack of consensus on whether they provide superior accuracy of fit compared to conventional subtractive milling methods. Previous research on dental restorations has often emphasized material properties and manufacturing efficiency, with less attention given to the direct comparison of accuracy of fit between additive 3D printing and subtractive milling techniques. In addition, much of the available literature has examined a wide range of restoration types and materials, rather than specifically focusing on implant-supported and partial coverage posterior restorations. Therefore, this systematic review aimed to provide a focused and up-to-date comparison of the accuracy of fit between additive manufacturing and subtractive milling methods for these specific types of restorations.

METHODS

Eligibility Criteria

This systematic review was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines and has been registered in the Open Science Framework database (https://osf.io/rq5ve).

The objective of this review was to address the research question: In implant-supported and partial coverage posterior restorations, how is the accuracy of fit of restorations fabricated with additive 3D printing compared with subtractive milling or conventional fabrication techniques in terms of marginal and internal adaptation? The selection criteria for the studies included in this review were established using the PICOS framework (Population, Intervention, Comparison, Outcome and Study Design) as follows:

- **Population:** Implant-supported restorations or partial coverage posterior restorations
- **Intervention:** Additive manufacturing (3D-printed restorations)
- **Comparison:** Subtractive milling or conventional fabrication techniques
- **Outcome:** The primary outcome is the accuracy of fit, assessed in terms of marginal and internal fit discrepancies (measured in microns). A secondary outcome is to compare and summarize the different assessment methods used across studies
- **Study Design:** Laboratory studies

Only original peer-reviewed studies published in English focusing on accuracy of fit measurements were eligible for inclusion. Studies were excluded if they were animal studies, case reports, case series, review articles, systematic reviews, meta-analyses, editorials or commentaries. Additionally, research that did not specifically assess accuracy of fit or did not compare additive manufacturing to subtractive or conventional methods was excluded.

Information Sources and Search Strategy

A comprehensive electronic search was performed across multiple databases, including PubMed, Cochrane Library, Web of Science, Embase and Scopus, to identify relevant studies published up to June 5, 2025. The primary objective of the search was to evaluate the accuracy of fit of additive 3D-printed implant-supported and partial coverage posterior restorations, as well as to compare it to subtractive milling and conventional fabrication techniques. The search strategy was developed using a combination of keywords and MeSH terms along with Boolean operators to ensure a comprehensive retrieval of relevant literature (Supplementary file 1).

Study Selection and Assessment

Two researchers carried out the initial screening of titles and abstracts. Following this, full-text articles were meticulously examined to confirm their eligibility for inclusion. Any discrepancies or uncertainties that happened during the selection process were resolved through discussion and consensus. Reference lists of the included studies were manually screened to identify any relevant articles.

Data Extraction

Two researchers independently extracted data using a structured extraction table, with any disagreements resolved through discussion. This rigorous methodology ensured that only studies directly relevant to the research question were included. Extracted information included the main author, year of publication, country of origin, study design, sample size and type of restoration. Details on intervention and comparison groups were recorded, specifically noting the manufacturing techniques used, including selective laser melting, stereolithography, CAD-CAM milling and conventional casting. Characteristics of samples, such as tooth type, cavity design and materials used, were documented. Outcome measures focused on methods of fit assessment, including Replica Technique and Micro-CT Scanning, as well as specific measurement points, such as marginal and internal gaps. Main findings related to fit accuracy were extracted, along with study limitations.

Quality Assessment

The methodological quality and risk of bias of the included studies were independently evaluated by two researchers using the modified CONSORT checklist for *in vitro* studies [13]. Each study was assessed based on its adherence to 10 relevant items from the original 14-item CONSORT checklist, excluding 4 items specific to clinical trials: randomization methods, allocation concealment, blinding and trial protocol access. The quality assessment covered essential aspects including structured summary, background and rationale, study objectives, intervention details, outcome measurements, sample size justification, statistical methods, results reporting, limitations and funding disclosure [14]. For each criterion, a determination of ‘Yes (Y)’ or ‘No (N)’ was made based on the fulfillment of the item’s requirements. Studies were then assigned an overall risk-of-bias rating, categorized as follows: low risk (minimal concern about bias influencing the results), moderate risk (potential bias that could introduce some uncertainty to the findings) and high risk (substantial risk of bias that may significantly impact the study outcomes). Any discrepancies between the assessments were resolved through discussion to ensure consistency and accuracy in the evaluation process.

RESULTS

Study Selection

A total of 1,913 records were identified through electronic database searches. After removing 290 duplicate records, 1,623 records were left for initial screening. Titles and abstracts were carefully reviewed to determine their relevance, resulting in the exclusion of 1,596 records that did not meet the inclusion criteria. As a result, 27 full-text articles were obtained and evaluated in detail for eligibility. Out of these, 19 articles were excluded for the following reasons: eight articles did not address accuracy of fit, six articles did not investigate implant-supported or partial coverage restorations, three articles reported ineligible study outcomes and two articles were not accessible in full text. In the end, 8 studies met all the inclusion criteria and were included in the systematic review [15-22]. Figure 1 provides an overview of the complete study selection process.

Study Characteristics

All eight *in vitro* experimental studies were included in this systematic review, each evaluating the accuracy of fit for implant-supported restorations and partial coverage posterior restorations fabricated using additive manufacturing compared to subtractive milling or conventional technique**s***,* with a total of 322 samples. The studies were conducted across six different countries: Turkey [15], Finland [16], USA [17-19], Spain [20], South Korea [21] and India [22]. The sample sizes varied across studies and ranged from 20 [19] to 90 [15] restorations, with all studies utilizing extracted human teeth or resin models (Table 1).

The restorations examined included implant-supported frameworks, inlays and onlays, with a focus on multiunit screw-retained frameworks, Class II inlays and partial coverage posterior onlays. Additive manufacturing methods varied across the studies, including selective laser melting, stereolithography and digital light processing. Comparison groups predominantly included CAD-CAM milling and conventional casting techniques. All studies measured marginal and internal fit discrepancies using various methods, such as replica technique, Micro-CT Scanning, digital microscopy and coordinate measurement machines. The measurement points differed among studies, with some focusing on marginal gaps, while others included internal gaps at occlusal, axial and proximal surfaces. The materials used for 3D printing included hybrid composite resins, photopolymer resins and cobalt-chromium alloys, whereas zirconia, PMMA and graphene-reinforced PMMA were commonly used for milling. Notably, graphene-reinforced PMMA and hybrid composite resins were exclusively utilized in onlay and inlay studies, whereas Co-Cr alloys were preferred for implant-supported frameworks (Table 2).

Quality Assessment

The risk of bias assessment using the modified CONSORT checklist for *in vitro* studies revealed that all included studies demonstrated a low risk of bias. Most studies adhered to key methodological standards, particularly in the areas of background and rationale, study objectives, intervention descriptions, outcome measurements, statistical methods and results reporting. However, a common limitation across the studies was the lack of sample size justification, with the exception of one study [15], which adequately reported this

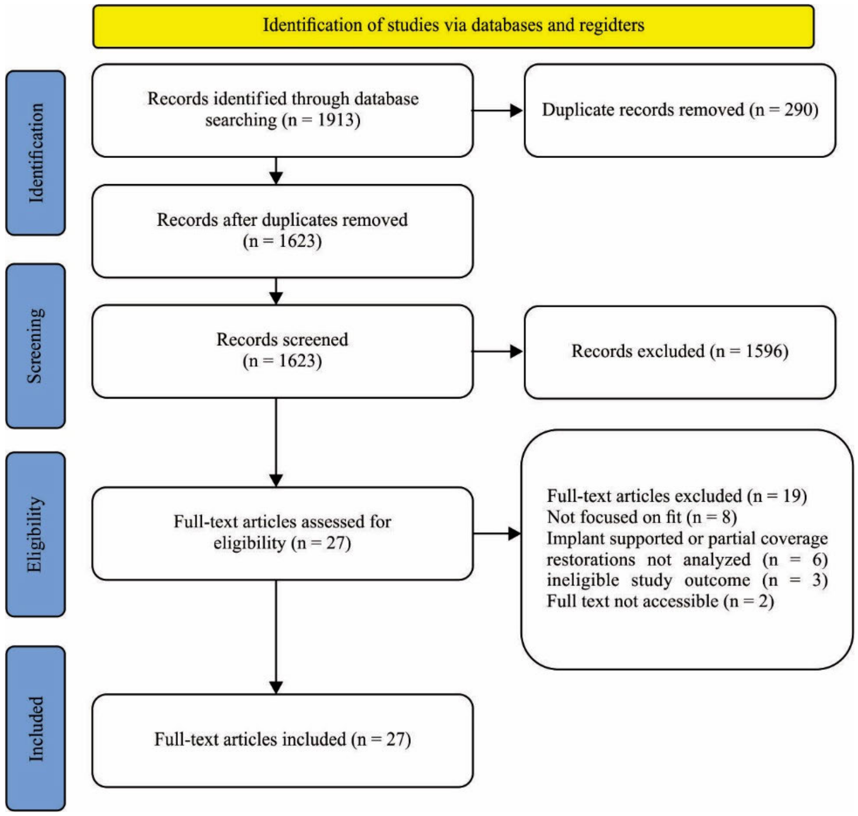

Figure 1: PRISMA flow diagram for included studies

Table 1: Demographic characteristics of the included studies

Authors and Year	Country	Study Design	Sample Size
Akçin *et al.* [15]	Turkey	*In vitro* study	N = 90
Ahlholm *et al.* [16]	Finland	*In vitro* study	N = 6
Revilla-León *et al.* [17]	USA	*In vitro* study	N = 40
Abu Ghofa and Önöral, [18]	Turkey	*In vitro* study	N = 50
Revilla-León *et al.* [19]	USA	*In vitro* study	N = 20
Cantó-Navés *et al.* [20]	Spain	*In vitro* study	N = 44
Lim *et al.* [21]	South Korea	*In vitro* study	N = 52
Pasha *et al.* [22]	India	*In vitro* study	N = 20

aspect. Additionally, one study Cantó-Navés *et al.* [20] received a slightly lower score due to the absence of a structured abstract, although the overall risk of bias was still categorized as low. No studies were rated as having a moderate or high risk of bias, indicating a generally high level of methodological quality across the included studies (Table 3).

Results of Individual Studies and Main Findings

A quantitative statistical meta-analysis was not conducted due to the substantial heterogeneity observed among the included studies. Variations were noted in study designs, manufacturing techniques, materials used and methods of fit assessment. Additionally, differences in sample types, measurement points and statistical analyses contributed to the heterogeneity. As a result, a narrative synthesis was deemed more appropriate to provide a comprehensive comparison of the accuracy of fit between additive manufacturing and conventional techniques. Akçin *et al.* [15] found that selective laser melting provided the best marginal fit for 3-unit and 4-unit Co-Cr frameworks, whereas the lost wax method showed superior fit for 5-unit frameworks. In contrast, CAD-CAM milling exhibited the poorest fit, particularly for 5-unit frameworks. Ahlholm *et al.* [16] reported that 3D-printed inlay and onlay restorations demonstrated significantly better marginal and internal fit compared to milled restorations. Revilla-León *et al.* [17] concluded that dynamic abutment scan bodies offered the most accurate mesiodistal and buccolingual positioning of implant replicas, while conventional methods showed better apicocoronal accuracy. Abu Ghofa and Önöral [18] revealed that selective laser melting produced the best passive fit with the lowest vertical marginal discrepancies

Table 2: Overview of study characteristics for the included studies

Authors and Year	Objective	Intervention and Comparison Groups	Characteristics of Samples	Outcome	Results	Limitations
Akçin *et al.* [15]	To compare the marginal and internal fit of Co-Cr implant-supported multiunit frameworks using Lost Wax, CAD-CAM Milling and SLM techniques	LW, CAD-CAM Milling, SLM	3-unit, 4-unit and 5-unit frameworks; Stock titanium abutments; 16 reference points per abutment; 3,360 total measurements	Silicone Replica Technique, Digital measurements with light microscope at ×45 magnification	• 3-unit: LW and SLM showed no significant differences; CAD-CAM Milling had the highest discrepancy • 4-unit: LW, CAD-CAM and SLM showed no significant differences • 5-unit: CAD-CAM Milling had the widest discrepancy, LW had the best fit. • Axial discrepancies were not influenced by unit number • Occlusal discrepancies were the highest across all groups	• Digital measurements at ×45 magnification might not capture micro-gaps smaller than the resolution limit • Results are based on three specific multiunit designs (3-unit, 4-unit and 5-unit), which may limit broader applicability
Ahlholm *et al.* [16]	To evaluate and compare the accuracy of inlay/onlay restorations fabricated using 3D printing (Multijet technology) and CAD/CAM milling techniques	• 3D Printing (3D Group): Composite restorations made using Multijet 3D printing technology • Milling (M Group): Nano-ceramic restorations manufactured using CAD/CAM milling	• Teeth Type: Six extracted and root canal treated human third molars • Cavity Type: Inlay and onlay cavities of different shapes prepared following CEREC guidelines • Digital Impressions: Captured using CEREC AC Omnicam© intraoral scanner	• Micro-CT Scans: Used to measure marginal and internal gaps • Replica Technique: A-silicone impressions were made to evaluate internal fit and weighed using an analytical balance	• 3D Printing Group showed significantly better marginal and internal fit compared to the Milling Group • Mean internal gap values of the 3D Group were 40-60% lower than those of the M Group, with statistically significant differences at most measuring points ($p<0.05$)	• Small Sample Size • The 3D printed material was not approved for permanent restorations • Micro-CT scans were taken from one mesio-distal section, which may not represent fit in other sections or planes

Revilla-León *et al.* [17]	To evaluate the influence of scan body designs and digital implant analogs on the accuracy of implant replica positions in AM casts compared to conventional stone casts	• Conventional (CNV) Group: Open-tray polyvinyl siloxane impressions poured with Type IV dental stone
		• AM Groups: Three subgroups based on different scan body and digital implant analog systems:
		  • AM-1: Elos Medtech
		  • AM-2: Nt-Trading
		  • AM-3: Dynamic Abutment
			• Typodont Model: Partially edentulous maxillary typodont with 3 implant replicas (Brånemark system; Nobel Biocare)
			• Implant Positions: Right and left canines and left second premolar
			• Scanning Method: Laboratory scanner (E3 scanner; 3Shape A/S)
			• 3D Printing: Polyjet AM technology using VeroDent MED670 polymer (Stratasys Eden 500V)
				• Coordinate Measuring Machine (CMM): Measured linear and angular discrepancies at x-, y- and z-axes	• 3D Discrepancy: CNV group showed the highest discrepancy, while AM groups showed lower values: Elos Medtech, Nt-Trading and Dynamic Abutment
					• Angular Discrepancies: The CNV group had significantly higher angular discrepancies on the x- and y-axes compared to AM-3 but showed lower discrepancies on the z-axis compared to AM-2 and AM-3
					• AM-3 Group: Exhibited the most accurate mesiodistal and buccolingual implant replica positions
						• CMM measurements were limited to one plane, potentially missing discrepancies in other orientations
						• Only a laboratory scanner was used, which may have different accuracy compared to intraoral scanners

Table 2: Continue

Abu Ghofa and Önöral [18]	To evaluate the passive fit of multiunit screw-retained implant frameworks fabricated using additive (Selective Laser Melting, Stereolithography) and subtractive (Soft Alloy Milling, PMMA Milling, Conventional Casting) manufacturing techniques	• Additive Manufacturing: • SLM • SLA • Subtractive Manufacturing: • SAM) • PMMA Milling • CT	• Framework Type: 3-unit Co-Cr screw-retained frameworks • Implant Sites: Right second premolar and second molar of a partially edentulous mandibular typodont model • Implant Analogs: Nobel Biocare multiunit implant analogs	• Sheffield Test: Used to assess passive fit by fixing the framework with one screw and measuring the VMD on the non-screw-retained side • Stereomicroscope: Digital images captured at ×40 magnification and analyzed using an image-analyzing software	• Manufacturing technique significantly influenced the passive fit • SLM showed the lowest mean VMD, followed by SLA, SAM. PMMA Milling and Conventional Technique • The SLM group had significantly lower VMD values compared to all other groups • No significant effect of the evaluation site or the interaction between manufacturing technique and evaluation site on VMD values	• Only vertical marginal gaps were measured; internal fit was not evaluated • Only Co-Cr alloy was tested, results may vary with other alloys • Frameworks were evaluated without veneering ceramic, which could influence the fit • Only 3-unit frameworks were tested; results might differ for longer-span frameworks
Revilla-León *et al.* [19]	To measure the linear and angular discrepancies at the implant abutment-prosthesis interface of complete-arch cobalt-chromium (Co-Cr) implant frameworks fabricated using additive - SLM and subtractive CNC milling technologies before and after ceramic veneering	• Additive Manufacturing (AM Group): Co-Cr frameworks fabricated using SLM technology • Subtractive Manufacturing (CNC Group): Co-Cr frameworks produced using CNC milling	• Framework Type: Complete-arch Co-Cr implant-supported frameworks • Implant Positions: Six implant abutment replicas (Multi-unit Abutment RP Replicas; Nobel Biocare) in an edentulous maxillary cast from the right first molar to the left first molar • Ceramic Veneering: Standardized protocol using Creation CC ceramic system	• CMM: Used to assess linear and angular discrepancies at the implant abutment-prosthesis interface before and after ceramic veneering	• Ceramic veneering significantly increased both linear and angular discrepancies in both groups • XZ Angle Discrepancy: The AM Group showed a significantly higher discrepancy on the x-axis compared to the CNC Group • No significant differences were found between the groups before ceramic veneering	• Ceramic veneering procedures were found to cause significant distortions, which may limit clinical applicability • CMM measurements were limited to linear and angular discrepancies and did not assess internal fit
Cantó-Navés *et al.* [20]	To compare the internal and marginal adaptation of graphene-reinforced PMMA milled onlays and hybrid composite 3D-printed onlays, fabricated using the same CAD design	• Group 1 (Milled Onlays): Fabricated using 5-axis milling from a graphene-reinforced PMMA disc (Acrylgraph; Nuprodent SL) • Group 2 (3D-Printed Onlays): Produced using SLA 3D printing with a hybrid composite resin (Permanent Crown Resin; Bego GmbH)	• Tooth Type: Upper-right first resin molar with a standardized onlay preparation maintaining distal cusps and reducing mesial cusps by 3 mm • Scanning and CAD Design: Prepared tooth was scanned using Trios3 Move+ intraoral scanner and designed using Exocad Galway • Post-Processing: 3D-printed onlays underwent post-polymerization at 60°C for two cycles of 20 minutes	• Digital Gap Measurement: Gaps were measured using Limaguide 1.9.1 software at predefined points (marginal, inner and central) by aligning the STL files of the prepared tooth and the onlays	• Printed onlays demonstrated significantly better internal and marginal adaptation compared to milled onlay • Printed onlays showed higher gap reproducibility with smaller standard deviations, particularly at the marginal and central points • Milled Onlays exhibited larger gaps at the central part compared to printed onlays	• Only graphene-reinforced PMMA and hybrid composite resin were tested • Gaps were measured only at predetermined points, not over the entire interface • Onlays were evaluated without any finishing or polishing, which could affect the adaptation

Table 2: Continue

Lim *et al.* [21]	To compare the marginal and internal fitness as well as the 3D accuracy of Class II inlays fabricated using TS, LU, ZR and 3D printing (NextDent C&B)	• TS Group: Conventional method using Tescera resin • LU Group: Milling with hybrid composite resin blocks (Lava Ultimate) • ZR Group: Milling with multilayer zirconia blocks (Zolid Fx) • 3D Group: 3D printing with hybrid composite resin (NextDent C&B)	• Tooth Type: Class II mesio-occlusal cavities prepared on mandibular right first molar resin teeth • Cavity Design: Standardized cavity with occlusal box depth of 2.5 mm and proximal box depth of 4.0 mm • Digital Impressions and CAD Design: Master dies were scanned using Trios 3 intraoral scanner and inlays were designed using Ceramill Mind software	• Replica Technique: Light body silicone impressions were made to evaluate marginal gap (MG) and internal gap (IG) at six points (cervical margin, occlusal margin, cervical floor, axial wall, pulpal wall and axial wall of occlusal box) • 3D Accuracy: Measured using Geomagic Verify software by superimposing STL files of reference and fabricated inlays to calculate trueness and precision as Root Mean Square (RMS) values	• ZR and 3D groups showed significantly better marginal and internal fitness than TS and LU groups • 3D-printed inlays exhibited the smallest internal gap and marginal gap • LU Group showed the largest internal gap and marginal gap • ZR demonstrated the highest trueness and 3D showed the best precision • Statistically significant discrepancies between MG and IG were observed in LU, ZR and 3D groups	• Marginal and internal gaps were measured at six predetermined points, potentially missing discrepancies in other areas • TS inlays were fabricated without cement space, which may have influenced the fitness and accuracy results
Pasha *et al.* [22]	To evaluate and compare the internal adaptation and marginal fit o f onlays fabricated using CAD CAM and 3D Printing techniques	• Group 1 (CAD-CAM Onlays): Fabricated using Amanngirrbach CAD-CAM machine with Aidite superperfect zirconia full ceramic • Group 2 (3D-Printed Onlays): Produced using Shinning 3D printer with photopolymer resin (Shining 3D bio clear resin SG01)	• Tooth Type: Extracted mandibular first molars without caries • Onlay Preparation: Involved the mesiobuccal cusp with standardized dimensions (2 mm cusp reduction and 2.5 mm gingival floor depth) • Digital Impressions: Taken using Shinning 3D scanner for both groups	• Replica Technique: Used light body addition silicone impression to assess internal adaptation and marginal fit • Stereomicroscope (Zeiss Discovery 20): Used at ×20 magnification to measure internal adaptation at proximal margins, inner axial wall and occlusal cavosurface area • Micro-CT Scan (GE X-ray): Used to measure marginal fit at the same points with high resolution (5-50 µm voxel)	• 3D-Printed Onlays showed significantly better internal adaptation and marginal fit compared to CAD-CAM onlays • Stereomicroscope Results: Mean thickness of 3D-Printed Group at occlusal cavosurface was significantly lesser than CAD-CAM Group • Micro-CT Results: 3D-Printed Group showed better marginal fit • 3D-Printed Group exhibited consistently lower thickness values in proximal and axial surfaces as well	- Only zirconia and photopolymer resin were tested - Gaps were measured at predetermined points, potentially overlooking discrepancies at other locations. - Onlays were assessed without cementation, which could influence the fit in clinical scenarios.

LW: Lost Wax; SLM: Selective Laser Melting; SLA: Stereolithography; AM: Additive Manufacturing; CNC: Computer Numerical Control; SAM: Soft Alloy Milling; PMMA: Polymethyl Methacrylate; CT: Conventional Technique; MG: Marginal Gap; IG: Internal Gap; VMD: Vertical Marginal Discrepancy; CMM: Coordinate Measuring Machine; 3D: Three-Dimensional; TS: Tescera Resin; LU: Lava Ultimate; ZR: Zolid Fx Multilayer

Table 3: Risk of bias assessment for included studies using Modified CONSORT

Author and Year	Structured Summary	Background and Rationale	Objectives and Hypotheses	Interventions Description	Outcome Measures	Sample Size Determination	Statistical Methods	Results Reporting	Limitations	Funding and Support	Overall Risk of Bias
Akçin *et al.* [15]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Low
Ahlholm *et al.* [16]	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Low
Revilla-León *et al.* [17]	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Low
Abu Ghofa and Oñoral [18]	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Low
Revilla-León *et al.* [19]	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Low
Cantó-Navés *et al.* [20]	N	Y	Y	Y	Y	N	Y	Y	Y	Y	Low
Lim *et al.* [21]	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Low
Pasha *et al.* [22]	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Low

Y: Yes, N: No

among multiunit screw-retained implant frameworks, whereas conventional casting showed the highest discrepancies. In another study, Revilla-León *et al.* [96] found that ceramic veneering caused significant distortions in both selective laser melting and CNC-milled complete-arch frameworks, with selective laser melting showing higher x-axis discrepancies after veneering. Cantó-Navés *et al.* [20] observed that 3D-printed onlays demonstrated better internal and marginal adaptation with higher gap reproducibility compared to milled onlays. Lim *et al.* [21] found that 3D-printed Class II inlays exhibited the best internal and marginal fit with high accuracy and precision, while Lava Ultimate milled inlays showed the poorest fit. Pasha *et al.* [22] concluded that 3D-printed onlays had significantly better internal adaptation and marginal fit than CAD-CAM onlays (Table 4).

DISCUSSION

While conventional and subtractive milling techniques have long been the standard for fabricating implant-supported and partial coverage posterior restorations, recent advancements in additive manufacturing technologies have introduced new possibilities for dental restoration. Subtractive milling, in particular, remains a robust and reliable technique, with strengths that include standardized manufacturing protocols, high repeatability across laboratories and a well-documented long-term clinical track record. Techniques such as selective laser melting and multijet 3D printing offer the potential for greater accuracy of fit, enhanced customization and improved cost-efficiency compared to traditional methods. However, to gain widespread acceptance among dental professionals, these new techniques must demonstrate superior accuracy, reliable clinical performance and material durability. In this systematic review, we aimed to evaluate the accuracy of fit of additive 3D-printed implant-supported restoration compared to conventional subtractive milling techniques, with the goal of determining whether these emerging technologies provide a clinically viable alternative. The findings consistently demonstrated that additive manufacturing provides equal or superior accuracy of fit compared to traditional milling methods. These results suggest that 3D printing is a viable alternative for producing highly accurate restorations, potentially enhancing clinical outcomes. The included studies showed that 3D-printed restorations generally exhibited better marginal and internal fit compared to subtractive milling. Akçin *et al.* [15] found that SLM provided the best fit for 3-unit and 4-unit frameworks, while milling exhibited the poorest fit, particularly for 5-unit frameworks. This finding was consistent with the results of Pompa *et al.* [23], who also reported superior accuracy with SLM. Furthermore, studies comparing conventional casting with selective laser melting technology reported that the latter achieves superior marginal fit for metallic copings and fixed partial dentures compared to traditional casting methods [24-26]. However, it contrasted with the findings of other studies Kim *et al.* [27] and Nesse *et al.* [28], in which traditional and

Table 4: Key findings from the included studies

Author and Year	Main Findings
Akçin *et al.* [15]	• SLM showed the best fit for 3-unit and 4-unit frameworks, while LW had the best fit for 5-unit frameworks • CAD-CAM Milling had the poorest fit for 5-unit frameworks • Number of units did not affect fit for LW frameworks • Occlusal discrepancies were the highest among all internal fit measurements
Ahlholm *et al.* [16]	• Multijet 3D printing demonstrated equal or superior accuracy compared to CAD/CAM milling for inlay and onlay restorations • 3D printing showed potential for higher accuracy and better fit for complex cavity forms • Further research is recommended to optimize 3D printing processes and identify suitable materials for permanent restorations
Revilla-León *et al.* [17]	• AM technology demonstrated higher accuracy in 3D implant replica position transference compared to conventional methods • Dynamic Abutment (AM-3) showed the best accuracy in mesiodistal and buccolingual positioning • Conventional method had better accuracy for the apicocoronal implant replica position • Scan body and digital implant analog design primarily influenced angular discrepancies
Abu Ghofa and Oñöral [18]	• Selective Laser Melting (SLM) produced frameworks with the best passive fit, showing the lowest vertical marginal discrepancies • Additive manufacturing techniques (SLM and SLA) demonstrated better accuracy compared to subtractive methods and conventional casting • All manufacturing techniques produced VMD values within the clinically acceptable limit of <150 μm
Revilla-León *et al.* [19]	• Ceramic veneering caused significant distortions at the implant abutment-prosthesis interface, increasing both linear and angular discrepancies • Additive Manufacturing (SLM) and Subtractive Manufacturing (CNC milling) showed comparable discrepancies before ceramic application • SLM exhibited a higher x-axis discrepancy after ceramic veneering compared to CNC milling • Both manufacturing techniques produced clinically acceptable fits before ceramic veneering
Cantó-Navés *et al.* [20]	• Printed onlays adapted significantly better than milled onlays at all measured points (marginal, inner and central) • Higher gap reproducibility was observed within the printed onlay group, indicating more consistent manufacturing • 3D printing showed potential for superior fit and predictability compared to milling for onlay restorations
Lim *et al.* [21]	• 3D-printed inlays showed superior marginal and internal fitness compared to conventional and milled restorations • ZR and 3D groups exhibited clinically acceptable fitness and accuracy, indicating high potential for use in routine clinical practice • LU Group showed the poorest internal fitness and accuracy, possibly due to greater material removal during milling • 3D printing demonstrated better precision and predictability due to consistent manufacturing and fewer errors
Pasha *et al.* [22]	• 3D-Printed onlays demonstrated significantly better internal adaptation and marginal fit than CAD-CAM onlays at all measurement points • 3D Printing showed higher accuracy and better reproducibility due to consistent layer-by-layer manufacturing • CAD-CAM onlays exhibited larger internal gaps and less accurate marginal fit, likely due to material removal during milling • 3D Printing proved to be a more predictable and accurate manufacturing technique for onlays compared to CAD-CAM milling

SLM: Selective Laser Melting, LW: Lost Wax, CAD-CAM: Computer-Aided Design and Computer-Aided Manufacturing, 3D: Three-Dimensional, AM: Additive Manufacturing, VMD: Vertical Marginal Discrepancy, CNC: Computer Numerical Control, SLA: Stereolithography, ZR: Zolid Fx Multilayer, LU: Lava Ultimate

subtractive techniques were superior, suggesting that framework complexity and design variations may influence the fit outcomes. A potential explanation for the enhanced dimensional accuracy and consistency of frameworks produced using selective laser melting technology is the complete material density achieved during the final printing stage [29].

The fit of an indirect restoration to the prepared tooth is crucial for its long-term durability [30]. Inadequate marginal or internal adaptation can result in cement dissolution, leading to microleakage which in turn induce secondary caries or even fracture of the restoration [31,32]. Consequently, achieving optimal adaptation between the indirect restoration and the tooth preparation is essential to minimize the risk of these complications. Ahlholm *et al.* [16] reported that 3D printing showed superior accuracy for inlay and onlay restorations compared to CAD/CAM milling. Interestingly, their findings revealed that additive manufacturing techniques are capable of producing more accurate restorations with complex geometries compared to conventional subtractive milling methods. This enhanced precision is likely due to the layer-by-layer fabrication process of additive manufacturing, which allows for greater customization and detailed contouring, particularly in intricate designs [33,34]. The reduced adaptation of the milled onlays could be due to the sharp contours of the prepared tooth, which may pose challenges during the milling process. This is likely because the milling burs are unable to effectively access concave areas, resulting in less accurate fitting. These findings align with the hypothesis that additive manufacturing allows for more precise and consistent layer-by-layer fabrication, reducing material waste and inaccuracies associated with milling [35-37]. Previous studies have similarly demonstrated that stereolithography showed superior accuracy for inlays [38]. Additionally, printed fixed dental prostheses exhibited better internal fit and greater predictability and repeatability in manufacturing compared to milled restorations [39]. Similarly, 3D-printed resin-composite crowns demonstrated a better marginal fit than milled crowns, as assessed by sectioning and laser microscopy [40-42]. However, some discrepancies were observed in specific scenarios. Revilla-

León *et al.* [17] found that dynamic abutment scan bodies provided the best accuracy for mesiodistal and buccolingual positioning, while conventional methods were more accurate for apicocoronal positions. This suggests that although 3D printing excels in overall accuracy, specific geometric aspects may still be better managed with conventional techniques.

CONCLUSIONS

Within the evidence presented in this systematic review, it was found that 3D printing provides superior accuracy of fit compared to subtractive milling and conventional techniques. Selective laser melting consistently showed the best accuracy for implant-supported frameworks, while 3D-printed restorations exhibited excellent fit and reproducibility for inlays and onlays. Conversely, conventional casting and milling techniques generally showed larger discrepancies, particularly for complex geometries. However, the *in vitro* design of the included studies limits direct clinical applicability and variations in measurement techniques contributed to heterogeneity. Future research should focus on validating these findings in clinical settings and exploring the long-term performance of 3D-printed restorations.

Limitations

This review followed PRISMA guidelines with prior registration, applied strict eligibility focused on implant-supported and partial coverage posterior restorations and used independent data extraction with a structured tool. Despite the promising results, several limitations were noted among the included studies. The *in vitro* design of all included studies limits the direct translation of results to clinical settings, as factors such as salivary contamination, occlusal forces and patient-specific anatomical variations were not accounted for. Additionally, the review did not assess the long-term clinical performance of the included restorative materials, as all studies were conducted in controlled laboratory settings without evaluating clinical outcomes such as prosthesis longevity, patient satisfaction or biological compatibility. A major limitation across most studies was the lack of sample size justification. Another limitation was the variation in measurement techniques and outcome reporting among the included studies. Different methods, such as micro-CT scanning, silicone replica techniques and coordinate measuring machines, were used to assess accuracy of fit, leading to potential inconsistencies in measurement precision and data interpretation. The lack of standardized outcome reporting also hindered the ability to perform a meta-analysis, as the heterogeneity in study designs and measurement points precluded quantitative synthesis. Moreover, the studies predominantly focused on specific materials and manufacturing techniques, such as selective laser melting and 3D printing, limiting the generalizability of the findings to other additive manufacturing methods and materials. Despite the rigorous and comprehensive review process, the search strategy was restricted to studies published in English, potentially excluding relevant studies published in other languages. Another limitation was the exclusion of two potentially relevant studies that could not be retrieved despite attempts to contact the authors. Although unlikely to alter the main findings, their absence should be noted as a source of potential publication bias.

The superior accuracy of fit observed with 3D-printed restorations has significant clinical implications, including improved marginal integrity, reduced risk of microleakage and enhanced long-term survival rates. These benefits are particularly relevant for implant-supported restorations, where precise fit is essential for load distribution. The ability of 3D printing to produce complex geometries with minimal material distortion is particularly advantageous for implant-supported restorations, where precise fit is crucial for load distribution and osseointegration. Furthermore, the reduced manufacturing time and cost-efficiency associated with additive manufacturing make it an appealing option for both dental laboratories and clinicians. However, widespread adoption of additive manufacturing may be limited by practical barriers, including the cost of equipment and materials, as well as the need for specialized training and workflow adaptation in clinical and laboratory settings. Future research should prioritize conducting clinical trials to validate the *in vitro* findings in real-world scenarios. Additionally, providing detailed sample size justifications would enhance the generalizability of the results. Further studies are needed to explore the long-term clinical performance of 3D-printed restorations, including their impact on periodontal health and prosthesis longevity. It is also important to investigate the influence of different printing parameters, such as layer thickness, post-processing techniques and material composition, on the accuracy of fit. Addressing these areas will contribute to a better understanding of the clinical applicability and durability of additive manufacturing in restorative dentistry.

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