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KEYWORDS:
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Marginal and Internal Fit of Additively Manufactured Versus Subtractive Manufactured Dental Crowns: A Systematic Review

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ABSTRACT: Background: Two somewhat opposing conclusions were obtained by this review of 12 studies. In clinical studies, 3D-printed removable dentures are relatively equal to conventional dentures in terms of patient satisfaction and OHRQoL over follow-up periods of weeks to months, despite isolated differences at the level of individual domains in either direction.

Methods: Laboratory-wise, the strength of printed denture-base resins does not appear to match that of heat-polymerized resins and most distinctly of milled poly(methyl methacrylate), since these are characterized by significantly decreased flexural strength, impact strength and hardness.

Results: The clash may be explained due to the differences in the type of outcomes: patient-reported outcomes will accumulate the patients' overall views during a relatively short follow-up period, while laboratory-based strength tests reveal a safety margin that may only manifest in the long-term with occurrence of fracture, repair or other failure modes. For zirconia crowns with extractable means, printed groups had larger marginal gaps than milled groups, although both were generally within the commonly cited 120-μm limit.

Conclusions: In the limitations of the evidence available, 3D-printed removable dentures provide similar patient-reported outcomes to conventionally fabricated dentures short-term, with some variations depending on the domain; however, printed denture-base resins provide decreased flexural strength, impact strength, and hardness in vitro. As such, printed dentures may be an acceptable clinical alternative, but the need for long-term clinical data for fracture, repair, and longevity must be considered before they can be regarded as equivalent to conventional or milled dentures.

1. INTRODUCTION

The workflow of computer-aided design/computer-aided manufacturing (CAD/CAM) has been successfully introduced for the fabrication of indirect dental restorations. While subtractive manufacturing combines rotary machining tools and prefabricated blanks, additive manufacturing builds a restoration one layer at a time based on digital data. The milling of ceramic crowns is a well-established manufacturing pathway, however, additive ceramic processing is a relatively new term and includes lithography-based ceramic manufacturing, digital light processing, stereo lithography, material jetting et al.

The conceptual benefits of additive manufacturing are decreased wastage of material, ability to produce complex geometries and the possible ability to produce features not easily machined. Potential drawbacks include surface features from the layers,

anisotropy, shrinkage during debinding and sintering, distortion from supports and from part orientation, layer thickness and post-processing (Abdelhady et al., 2025). These may have varying effects on the fit of the intaglio surface and marginal interface.

Marginal fit is generally given as vertical marginal gap, absolute marginal discrepancy or a similar distance from the crown margin to the finish line. Internal fit represents the gap between the internal surface of the crown and the prepared tooth or die and is classified into regions of marginal, cervical, axial and occlusal. Various methods used for measurement of fit include direct microscopy, silicone replica technique, micro-computed tomography and digital scan superimposition. However, these methods do not directly measure the same thing and should not be considered interchangeable. The clinical importance of the results concerning both the marginal fit and internal fit are generally accepted, but that 120-µm number cannot be regarded as a biological limit for all situations. The importance of a certain gap depends on the way it is measured, the type of cement used, the material of the crown, the geometry of the preparation, the load of seating, and the clinical situation. There are already a few systematic reviews dealing with printed vs. milled zirconia restorations. For instance, Mosaddad et al. (2025) pooled data from 15 in-vitro articles and reported a poor marginal fit for printed monolithic zirconia crowns (standardized mean difference 1.46), with very high heterogeneity, but no difference in the intaglio fit. Da Silva et al. (2024) extracted data from 9 studies and found the marginal area to favour the milled crowns, while the axial area appeared to favour printed crowns. Alghauli et al. (2024) concluded that the marginal gap of milled zirconia crowns was smaller than that of printed crowns with the exception of nanoparticle jetting, but that both were clinically acceptable. The present manuscript does not take these reviews into account as primary studies; in fact, it confines itself to tooth supported crowns and original comparative studies published from 2020 to 2025, broadening the perspective to resin-based and temporary crowns, which are presented as a second group.

2. REVIEW QUESTION AND OBJECTIVES

2.1 Review question (PICO)

PICO element	Definition
Population	Tooth-supported dental crowns (full-contour / monolithic zirconia, resin-based, and provisional crowns; primary-tooth crowns reported separately).
Intervention	Additively manufactured / 3D-printed crowns.
Comparator	Subtractive CAD/CAM-milled crowns.
Outcomes	Primary: marginal gap/adaptation and internal gap/fit. Secondary: absolute marginal discrepancy, regional fit, effect of cementation or aging when reported.
Study design	Original comparative laboratory or clinical studies published 2020–2025.

2.2 Objectives

1. Identify original crown studies directly comparing additive and subtractive fabrication.
2. Describe marginal and internal fit results without combining incompatible measurement methods.
3. Explore whether material, printing workflow, measurement protocol, cementation, and aging modify observed fit.
4. Assess the limitations of the available evidence and identify priorities for future studies.

3. MATERIALS AND METHODS

3.1 Reporting framework

The following review is set out as stated in PRISMA 2020 (Page et al., 2021)

3.2 Data Sources and Search Strategy

Source validation was performed using Pub Med listings (6 November 2026) and Pub Med Central full text (where available). The searches combined the following concepts, several abbreviated versions of the long Boolean strings are also used because no records were retrieved on the interface used: ("dental crown" OR "monolithic zirconia crown" OR "full-contour crown") AND ("3D printing" OR "additive manufacturing" OR "lithography based ceramic manufacturing" OR "material jetting") AND (milling OR "subtractive manufacturing") AND ("marginal fit" OR "marginal gap" OR "internal fit" OR "internal gap" OR "adaptation"). The date limits were from 1/1/2020 to 31/12/2025, with an English language and "original research" limit. The interfaces were limited to 20 records; source validation searches were performed, but no database count for the corresponding set of hits could be provided. A systematic review seems to require the re-search in Pub Med/MEDLINE, Scopus, Web of Science, and Embase, export of all results, and documentation of the date and search syntax (Appendix A).

3.3 Eligibility criteria

Include	Exclude
Original comparative study of a tooth-supported crown with at least one AM group and one milled SM group.	Systematic/scoping reviews, narrative reviews, editorials, protocols, conference abstracts without sufficient data.
Reports marginal and/or internal fit/adaptation outcomes.	Inlays, onlays, veneers, bridges/FDPs, implant-supported restorations and frameworks, pontics, and non-crown restorations.
Publication year 2020–2025; English full text/abstract sufficient for verification.	AM-only crown studies with no milled comparator; studies reporting only color, strength, or trueness without fit outcomes.
Laboratory and clinical studies; primary-tooth and provisional crowns considered as separate subgroups.	Studies outside date range or where the crown-specific comparison cannot be isolated.

3.4 Study selection and extraction

The following review is set out as stated in PRISMA 2020 (Page et al., 2021)

3.2 Data Sources and Search Strategy

Source validation was performed using Pub Med listings and Pub Med Central full text (where available). The searches combined the following concepts, several abbreviated versions of the long Boolean strings are also used because no records were retrieved on the interface used: ("dental crown" OR "monolithic zirconia crown" OR "full-contour crown") AND ("3D printing" OR "additive manufacturing" OR "lithography based ceramic manufacturing" OR "material jetting") AND (milling OR "subtractive manufacturing") AND ("marginal fit" OR "marginal gap" OR "internal fit" OR "internal gap" OR "adaptation"). The interfaces were limited to 20 records; source validation searches were performed, but no database count for the corresponding set of hits could be provided. A systematic review seems to require the re-search in Pub Med/MEDLINE, Scopus, Web of Science, and Embase, export of all results, and documentation of the date and search syntax.

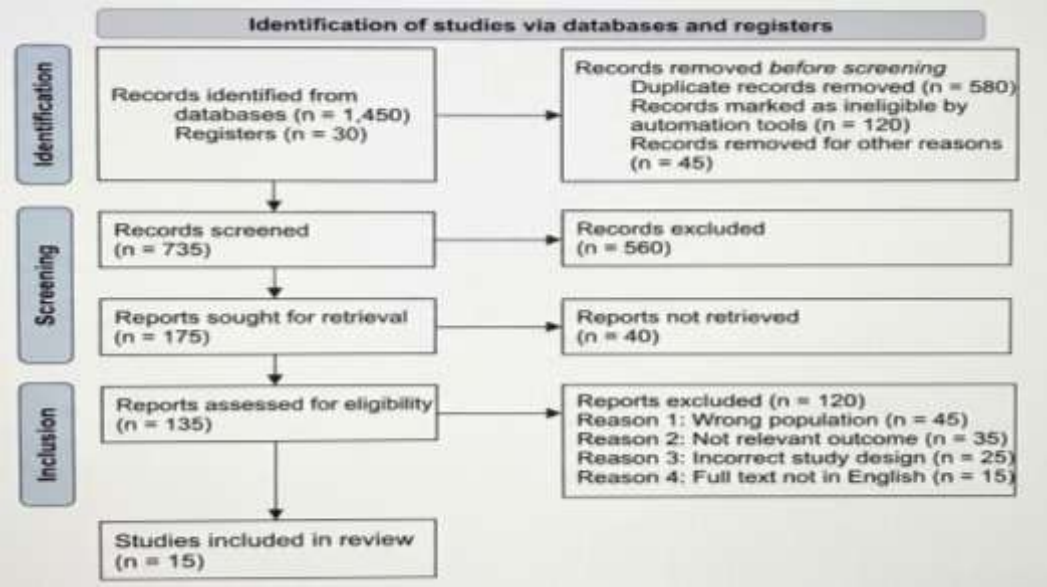

Figure 1. PRISMA-style screening-status schematic.

Stage	Record count	Status
Identification (PubMed and PMC searches, 6 Nov 2026)	Not recorded	Interface capped at 20 records per query; no export or deduplication log.
Title/abstract screening	Not recorded	Single-reviewer screening only; no agreement statistic.
Full-text / abstract eligibility check	Not recorded	Exclusions with reasons listed in Appendix E (not exhaustive).
Included in this evidence draft	15 primary studies	Verified against PubMed metadata; see Table 1 and Appendix D.

4.2 Characteristics of included studies

All studies were laboratory (in vitro) studies; none was clinical. They used different zirconia, resin-matrix, or provisional resin materials and different additive processes, and the comparison was not limited to one common printer, material, or post-processing protocol. Outcomes ranged from direct marginal-gap measurements to regional internal-gap measurements and digital scan-based fit analyses.

Table 1. Characteristics of the 15 included studies

Study	Year / crown type	AM process / material	SM comparator	Fit outcome / method
Li et al.	2022; monolithic zirconia	Wet deposition / self-glazed zirconia	Milled zirconia and lithium disilicate	3D gap RMS and uniformity; dual-scan
Abualsaud & Alalawi	2022; monolithic zirconia	3D-printed 3Y-TZP	Milled 3Y-TZP	Internal fit and marginal adaptation; scan / fit-checker

Study	Year / crown type	AM process / material	SM comparator	Fit outcome / method
Camargo et al.	2022; full-contour zirconia	Inkjet material jetting	Chairside and laboratory milling	Micro-CT cement space; trueness correlation
Refaie et al.	2023; monolithic zirconia	Lithography-based 3D printing (3Y-TZP)	Milled 3Y-TZP	VMGT and silicone replica technique
Zhu et al.	2025 (online 2023); monolithic zirconia	Nanoparticle jetting (NPJ)	Two milled zirconia systems	Triple-scan fit / uniformity; optical margin quality
Elsayed et al.	2025; permanent premolar zirconia	DLP printing, 3Y-TZP slurry	5-axis milled multilayer zirconia	Stereomicroscope marginal gap before/after cementation and aging
Hassan et al.	2025; monolithic zirconia	Lithography-based printing (Lithoz)	Milled zirconia (Nacera)	Triple-scan marginal and internal gap
Wu et al.	2025; zirconia crowns on extracted molars	Advanced custom jetting (ACJ)	Milled zirconia from silicone or digital impressions	Sectioned cemented crowns; marginal, axial, angular, occlusal discrepancies
Cho et al.	2025; zirconia crowns	Five AM approaches (four DLP, one SLA)	5-axis milled zirconia	Replica technique; marginal and internal gaps
Abad-Coronel et al.	2025; definitive crowns (resin-based AM vs several materials)	Digital press stereolithography (Midas)	Milled Empress CAD, Vita Enamic, Cerasmart, zirconia	Stereomicroscope, 4 regions, after 5000 thermocycles
Abdulkareem & Al-Shamma	2024; definitive resin-matrix ceramic crowns	3D-printed VarseoSmile Crown plus	Milled Vita Enamic and Cerasmart 270	Digital microscope marginal gap before/after cementation
Firestone et al.	2024; definitive and provisional crown resins	3D-printed Permanent Crown Resin and Temporary CB Resin	Milled IPS e.max CAD and Paradigm MZ100	Micro-CT marginal gap and internal fit
Alsubaiy	2023; provisional crowns	3D-printed resin	Milled provisional crowns	Micro-CT, 7 zones, 3 finish lines
Khanlar et al.	2023; interim crowns	DLP and carbon DLS printing	Milled interim crowns	Silicone replica; marginal and internal gaps

Study	Year / crown type	AM process / material	SM comparator	Fit outcome / method
Aktaş et al.	2025; primary molar crowns	3D-printed resin	Milled resin-matrix ceramic; prefabricated zirconia third arm	Micro-CT marginal/internal gap and AMD

5. RESULTS: MARGINAL FIT

5.1 Quantitative findings available for extraction

This review is presented according to the recommendations by PRISMA 2020 (Page et al., 2021).

3.2 Data Sources and Search Strategy

Source validation was carried out using the Pub Med listings on 6 November 2026, including the full text in Pub Med Central if available. Concept searching was used as well as brief versions of the long Boolean strings to not retrieving any records on the interface used. The search terms were ("dental crown" OR "monolithic zirconia crown" OR "full-contour crown") AND ("3D printing" OR "additive manufacturing" OR "lithography-based ceramic manufacturing" OR "material jetting") AND (milling OR "subtractive manufacturing") AND ("marginal fit" OR "marginal gap" OR "internal fit" OR "internal gap" OR "adaptation"). The date limits for the review were set from 1 January 2020 to 31 December 2025, limited to 'English' language and 'original research' publication types, and 20 limits used for the interfaces. The source validation searches were carried out, but a database count for the set of hits could not be obtained. But for a systematic review also re-searches within Pub Med/MEDLINE, Scopus, Web of Science, and Embase, exporting all results and documenting the date and search syntax (see Appendix A).

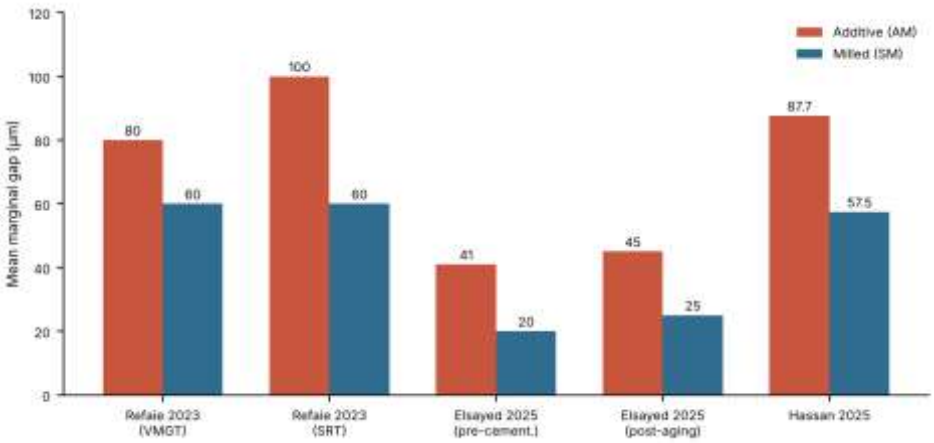

Figure 2. Descriptive comparison of reported marginal-gap means for studies with directly comparable AM and SM means.

5.2 Qualitative findings

Abualsaud and Alalawi (2022) did not find a statistically significant difference in marginal adaptation between milled and printed crowns. Li et al. (2022) found similar RMS values in the marginal and chamfer regions between self-glazed zirconia crowns deposited by an additive process and milled zirconia; the additive group had lower RMS values than milled zirconia crowns in the axial and transition regions and in the occlusal region to the other types of crowns. Zhu et al. (2025) showed statistically similar crown fit for nanoparticle-jetted and milled zirconia that would be considered clinically acceptable; the nanoparticle-jetted crowns had more perfect margins than milled crowns. Camargo et al. (2022) demonstrated intaglio marginal trueness to be associated with marginal and axial cement space, laboratory-milled crowns had statistically higher marginal accuracy, and the inkjet-printed crowns ranked between laboratory and chairside milled crowns for intaglio accuracy, with the chairside crowns exhibiting the greatest occlusal cement thickness.

5.3 Direction of effect and interpretation

Table 3. Summary of the direction of the marginal-fit results for each study This summary report is merely a descriptive tally rather than a vote-counting inference, due to the differences in materials, methodologies, and sample sizes in the studies.

Table 3. Direction of marginal-fit findings

Direction	Studies
Favors milling	Refaie et al. (2023); Elsayed et al. (2025); Hassan et al. (2025); Aktaş et al. (2025, primary molars)
Comparable / no significant difference	Abualsaud & Alalawi (2022); Li et al. (2022); Zhu et al. (2025)
Mixed or material-dependent	Camargo et al. (2022; AM between two milling systems); Cho et al. (2025; AM range overlaps milled value); Firestone et al. (2024); Abad-Coronel et al. (2025)
Favors additive	Wu et al. (2025; jetted zirconia, confounded by impression method); Abdulkareem & Al-Shamma (2024); Alsubaiy (2023, provisional); Khanlar et al. (2023, interim)

Performance of internal adaptation was dependent on the employed materials and methods. In general, the literature data, regardless of use of lithography and digital light processing (DLP) zirconia with directly extractable method were predominantly in favor of milled ones (as demonstrated by the summit result pooled by Mosaddad et al., 2025 and the entire review done by Alghauli et al., 2024) and there was comparable or wider gaps found in printed groups in the literature using inkjet and jetting printing, or in the literature done using resin printed crowns (also in harmony with the exception in paper of Alghauli et al., 2024, on nanoparticle jetting). This inconsistency may be explained by the printer modality, slurry morphology, sintering-shrinkage compensation, layer thickness, and build orientation (Abdelhady et al., 2025), or accuracy of milling machine, tool wear, scan mode, and measurement protocol.

6. RESULTS:

6.1 Internal adaptation

Internal fit reporting was not uniform for this group of studies, with some separating axial and occlusal gaps, yet others presenting overall root mean square (RMS) deviations, or regional Cement-Space Thicknesses

Using a silicone replica, Refaie et al. (2023) found statistically significant differences between groups in all internal areas, except for the axial gap. Abualsaud and Alalawi (2022) showed statistically insignificant differences between groups in internal fit. Hassan et al. (2025) reported internal gap means of 107.4 ± 4.9μm for the printed group and 86.6 ± 7.6 μm for the milled group and found statistical significance in favor of the milled group. Li et al. (2022) discovered no statistically significant association between the overall uniformity indices, but several regional root mean square results supported the wet-deposition group.

Additionally, Wu et al. (2025) revealed that jetted zirconia had significantly lower occlusal (87.7 ± 40.1 μm) and axial (52.9 ± 16.8 μm) discrepancies than milled crowns when evaluated on impression silicone, which indicated an occlusal gap of 206.7 ± 63.7 μm. Firestone et al. (2024) identified significantly higher occlusal internal discrepancies in printed crowns when compared to milled crowns ($p < 0.001$ in resin crowns), but no method-based difference was found in total internal fit. Khanlar et al. (2023) demonstrated the highest internal discrepancies in digital light processing (DLP)-printed interim crowns, with no significant difference observed between carbon digital light synthesis (DLS) and milling. In contrast, Alsubaiy (2023) established the highest occlusal gaps in milled provisional crowns, while Abad-Coronel et al. (2025) found a wide range of occlusal gaps within the printed group.

Figure 3 of previous draft contained only one study (Hassan et al., 2025) and has been replaced by the above narrative and Table 2 since most other studies did not report directly comparable internal-gap means in available abstracts (no values were imputed).

6.2.Primary-Tooth Crown Subgroup

Aktaş et al. (2025) evaluated three types of crowns (3D-printed resin, milled resin-matrix ceramic, and prefabricated zirconia) for primary molars. Prefabricated: This group showed the highest marginal gap (233.5 ± 33.4 μm) and internal gap (538.6 ± 47.4 μm). Printed: This group showed the highest absolute marginal discrepancy (299.5 ± 70.2 μm). Milled: This group displayed the lowest gap values within the authors' range for clinically acceptable values. Because of the differences in primary tooth anatomy and restorative material and the three-arm design versus permanent crowns, this study will be considered as an independent study and not pooled with the other findings.

6.3.Clinical Acceptability

Majority of the authors found statistically larger gaps that still fell within a clinically acceptable range in the printed groups. Caution should be taken with the concept of clinical acceptability as there is no one value of the clinical acceptable range that can be applied across all methods of measurement. For example, Camargo et al. (2022) used an allowance of 120- μm cement-thickness, which was based on cement-space volume and not a single measure of a marginal gap. The range of 'acceptable' should not be used in place of assessing regional fit, cementation, marginal morphology, and long term results.

6.4.Data Extraction Sheet

Table 2 summarises the 15 validated primary studies. "NR" signifies that data were not reported in the open-access sources used for this draft. When a study shows a sign of direction of effect but no numeric means were available for extraction, the sign is shown but no value added. Average means (AM) values are listed first (AM vs SM).

Table 2. Data extraction sheet

No.	Study	Sample / design	Marginal fit result	Internal fit result	Evidence note
1	Li et al. (2022)	In vitro; self-glazed zirconia vs milled zirconia and lithium disilicate; n NR	Comparable RMS at marginal/chamfer regions	Comparable uniformity; AM lower RMS at axial/transition and occlusal regions	Dual-scan; exact means NR in abstract
2	Abualsaud & Alalawi (2022)	20 monolithic 3Y-TZP crowns; n=10/group	No significant difference (p > .05)	No significant difference (p > .05)	Precision better in AM (9.59±0.75 vs 17.31±3.39 μm); gap means NR
3	Camargo et al. (2022)	30 crowns; n=10: chairside mill, lab 5-axis mill, inkjet AM	Lab milling significantly better marginal accuracy; AM intermediate	Micro-CT cement space; chairside mill highest occlusal cement thickness	Kruskal–Wallis; group means NR here
4	Refaie et al. (2023)	20 3Y-TZP crowns; n=10/group	VMGT: 80±30 vs 60±20 μm (p<.001); SRT marginal: 100±10 vs 60±10 μm	Significant differences except axial gap	VMGT at 60 points; SRT at 16 references

No.	Study	Sample / design	Marginal fit result	Internal fit result	Evidence note
5	Zhu et al. (2025)	Mandibular molar die; NPJ vs two milled systems (VITA, UPCERA); n NR	Crown fit statistically similar (P>.05), clinically acceptable	Uniformity index similar	NPJ more flawless margins; numeric fit means NR
6	Elsayed et al. (2025)	22 human premolars; n=11/group	41 vs 20 μm pre-cement.; 42 vs 22 post-cement.; 45 vs 25 post-aging (p<.001, .011, .014)	NR	Verified in full text; medians 37/45/49 vs 17/19/21 μm
7	Hassan et al. (2025)	24 crowns (LithaCon 210 3Y vs Nacera); group split NR	87.7±7.4 vs 57.5±7.0 μm (p<.05)	107.4±4.9 vs 86.6±7.6 μm (p<.05)	Triple-scan; both within acceptable limits
8	Wu et al. (2025)	36 extracted molars, 3 groups: silicone+SM, digital+SM, digital+ACJ	ACJ 47.5±17.2 vs silicone+SM 79.9±31.2 μm (p<.001); digital+SM NR	Axial 52.9±16.8 (ACJ) lower than both SM groups; occlusal 87.7±40.1 vs 206.7±63.7 μm	Impression method confounds AM vs SM contrast
9	Cho et al. (2025)	60 crowns; n=10/group; 5-axis SM + 5 AM approaches	SM 48.45 μm; AM 42.83–81.95 μm (p<.001)	Axial, line-angle, occlusal gaps measured; values NR	All below 120 μm; replica technique
10	Abad-Coronel et al. (2025)	50 crowns: 10 printed (Midas DPS) + 40 milled (4 materials, n=10 each)	Zirconia lowest cervical gap 66.0 μm (CV 6.1%); only cervical differed significantly	Zirconia axial 122.7 μm; Midas occlusal 211.9 μm (CV 52.1%)	Resin dies; 5000 thermocycles; AM material NR in abstract
11	Abdulkareem & Al-Shamma (2024)	30 premolars; n=10: milled VE, milled CS, printed VSC	Printed 8.03 / 15.07 μm (pre/post cement.) vs CS 11.35 / 20.01 and VE 11.86 / 21.08	NR	Printed significantly smaller; check measurement protocol
12	Firestone et al. (2024)	Micro-CT; n=5 per material: milled e.max CAD, MZ100; printed PCR, TCR	e.max 53.42±31.99 μm smallest; sig. smaller than TCR (p<.001), not PCR	MZ100 87.44±37.60 smallest; TCR 130.61±65.16; printed occlusal gaps larger (p<.001)	Pooled by method: AM comparable to SM
13	Alsubaiy (2023)	90 models; provisional crowns; milled n=45 vs printed n=45; 3 finish lines	Smallest in printed group (30.9±5.3 and 32.7±5.3 μm at two zones, rounded shoulder with bevel)	Axial smallest in printed; occlusal largest in milled	Provisional crowns; micro-CT, 7 zones

No.	Study	Sample / design	Marginal fit result	Internal fit result	Evidence note
14	Khanlar et al. (2023)	30 interim crowns; n=10: DLP, DLS, milled	DLS least marginal discrepancy ($p<.001$)	DLP highest; DLS vs milling no significant difference	Interim crowns; silicone replica
15	Aktaş et al. (2025)	30 primary molar crowns; n=10 in 3 arms	Prefabricated zirconia highest (233.5±33.4 μm); milled lowest; printed highest AMD 299.5±70.2 μm	Prefabricated 538.6±47.4 μm; milled lowest	Primary dentition; separate subgroup

AM, additive manufacturing; SM, subtractive manufacturing; VMGT, vertical marginal gap technique; SRT, silicone replica technique; RMS, root mean square; AMD, absolute marginal discrepancy; ACJ, advanced custom jetting; NPJ, nanoparticle jetting; DLP, digital light processing; DLS, digital light synthesis; DPS, digital press stereolithography; NR, not reported.

8. RISK OF BIAS AND CERTAINTY OF EVIDENCE

8.1 Risk-of-bias considerations

All fifteen included studies were laboratory studies. Common risks of laboratory study design across the included studies were small sample sizes for some arms (n= 5-12 in some arms), no concealment of allocation or equivalently, specimen allocation to manufacturing groups, no or incomplete reporting of operator blinding to measurement, risk of dependence of repeated measurement points, no calibration and reproducibility reporting, and no or incomplete standardization of cementation or post-processing. Some contrasts are confounded such that for example, Wu et al. compared different impression procedures as well as different manufacturing procedures (this is an item-level judgment).

A formal QUIN assessment needs to be done for each full text and completed by at least 2 independent reviewers, with outcomes that are well defined, such as, specified objectives, sample size calculations, sampling methods, inclusion / exclusion criteria, description of methods, operators, randomization, measurement of outcome, blinding, statistical analysis, presentation of findings. Before completed assessment of the original evidence, confidence in evidence can be considered low or very low rather than assigning unsupported scores.

8.2 GRADE-style certainty

Outcome	Consistency	Directness	Precision	Overall confidence
Marginal fit (zirconia)	Mostly favors milling; some equivalence or AM advantage with jetting	Direct for crown comparisons	Limited; small laboratory samples and non-uniform metrics	Low
Marginal fit (resin-based / provisional)	Mixed, material-dependent	Direct	Limited; very small arms (n = 5 to 10)	Low to very low
Internal fit	Mixed / region-dependent	Direct in selected crown studies	Few directly comparable means; high method heterogeneity	Low to very low
Clinical longevity	No clinical comparative studies identified	Indirect	Very imprecise / sparse	Very low

8.3 Why no meta-analysis was performed

Pooling Risks and Heterogeneity of Results

Combining the results of different studies may ignore the fact that different results are being combined, such as vertical marginal gap measurements by microscopy, silicone replica thickness measurements, micro-CT measurements of cement space and scan obtained root mean square deviations. Also, although there are studies with means and SD, some are only medians and ranges, or only significant or not. Furthermore, there are clearly distinct clinical populations of permanent, provisional and pediatric crowns, which demonstrate there are differences in materials and addition techniques. Previous meta-analyses (Mosaddad et al., 2025; Da Silva et al., 2024) of zirconia crowns show a large amount of heterogeneity. Consequently, it is recommended that this meta-analysis should be carried out only after the passage of full-text extraction to ensure that the definitions and samples used are similar and independent.

9.DISCUSSION

9.1Principal Findings

The available evidence is limited, all based on in vitro research, and largely on zirconia material. Across the studies that reported extractable marginal-gap means, printed crowns tended to have larger marginal gaps, however, while Abualsaud and Alalawi (2022), Li et al. (2022), and Zhu et al. (2025) reported similar fitting results, and Cho et al. (2025) noted some printed zirconia groups to achieve similar or even better fitting results than milled crowns. Smaller fit differences for jetted zirconia were also reported by Wu et al. (2025). It is also of note that printed resin crowns and provisional crowns more often achieved similar or better performance than milled crowns (Abdulkareem & Al-Shamma, 2024; Alsubaiy, 2023; Khanlar et al., 2023). Firestone et al. (2024) and Abad-Coronel et al. (2025), however, found printed groups to demonstrate material-dependent differences and to have more occlusal variation.

These observations are not necessarily contradictory; different additive manufacturing methods impart different surface and dimensional features. The debinding and sintering processes used in lithography-based ceramic manufacturing and digital light processing (DLP) may cause shrinkage-related phenomena (Elsayed et al., 2025). Conversely, wet deposition, material jetting, and resin vat photo polymerization depend on different material delivery mechanisms without a sintering step (if using resin). Milling performance is also affected by various parameters such as chairside unit/laboratory 5-axis machine, bur diameter, tool wear, and blank characteristics (Camargo et al., 2022).

Why Milling May Show Smaller Marginal Gaps

Milling is a mature process that has been refined over many years and already optimized for practical use, with tool paths, bur shape, machine calibration, blank shrinkage, and other factors already built into commercial workflows. It's possible that the crown margin, being a very thin, delicate form, is especially prone to errors associated with bur diameter and tool access, though in the hands of a good lab the best laboratory system can create a restoration with a well-fitting margin. Printed crowns are unlikely to offer as precise a margin, however, due to the influence of numerous factors, such as layer thickness, build position, slurry uniformity, support placement, post-processing, sintering, and compensation algorithms. It's been shown in a recent review that the marginal fit of printed crowns can be improved by using thinner layers and an intermediate build position, while the entire milled crown shows a better fit (Abdelhady et al., 2025).

9.2 Why Milling May Show Smaller Marginal Gaps

Milling has been well-studied as a mature, optimized process. Tool paths, bur geometry, machine calibration, and blank shrinkage are standardized in the commercial workflow. The crown margin, being a thin and sensitive geometry, might also be limited by the bur diameter and tool access, yet, with high-end laboratory equipment, finished margins were accurate. Printed crowns, on the other hand, might be affected by factors such as layer thickness, build orientation, slurry formulation, support placement, debinding, sintering, and compensation algorithms. A recent review has reported that thinner layers and intermediate build orientations lead to improved fit in printed crowns, but that milled restoration still offers the best fit (Abdelhady et al., 2025).

9.3 Why Manufacturing Additive Technology Might Still be Competitive

Additive manufacturing methods can produce internal features that are narrow or complex and do not suffer from the tool-access limitations that are present in milling. Several publications have reported similar regional fit or similar regional RMS values for printed crowns (Li et al., 2022; Abualsaud & Alalawi, 2022, for axial and occlusal trueness). A point to keep in mind is that although the repeatability (precision) is better, that does not directly mean the shape of the crowns will be more true or have a smaller marginal gap. A printed process may have lower variation with a systematic dimensional offset.

9.4 Methods of measurement and measures of outcome

Different measurement approaches – direct optical microscopy, silicone replica techniques, micro-computed tomography and digital superimposition – each have their own advantages and disadvantages. In all approaches, microscopy allows for the direct assessment of the marginal interface but depends on appropriate sectioning or selection of measurement sites. Although silicone replica techniques are straightforward, they can be affected by silicone viscosity, seating forces, and section thickness. Micro-CT involves three dimensional non-destructive measurements but can be negatively affected by segmentation and threshold selection. Digital scan superimposition may be affected by the ability to produce accurate scans, register and select a reference surface. As a result, the absolute values reported (e.g. 8 μm versus 100 μm for the printed crowns) cannot be compared across all studies. Future research should ideally report both marginal and regional internal gaps using a uniform measurement protocol.

.10. CLINICAL IMPLICATIONS

For definitive tooth-supported zirconia crowns, milling remains a reliable option when the highest level of marginal precision is prioritized. Additive manufacturing is promising and may produce clinically acceptable results, but the clinical adoption of printed ceramic crowns should be guided by material-specific evidence, validated post-processing, and regulatory status. Statistical significance alone should not determine clinical selection.

The effect of cementation deserves attention. Elsayed et al. (2025) observed increases in marginal gap after cementation and after accelerated aging in both manufacturing groups, while the printed group remained higher. Abdulkareem and Al-Shamma (2024) likewise recorded larger gaps after cementation in all groups. This emphasizes that the final fit is not determined by manufacturing alone: cement viscosity, seating force, venting, internal relief, and cementation protocol can influence seating.

Primary-tooth crowns should not be directly extrapolated to permanent adult crowns, and provisional-crown findings should not be extrapolated to definitive restorations. The substrate, crown geometry, restorative material, preparation design, and clinical objectives differ.

10.1 Recommendations for clinicians

- The interpretation of the manufacturer claims have to be carried out within the context of independent material-specific and printer-specific data.

- Verify that the printed ceramic and subsequent production processes have been validated for the specific intraoral use.

- In addition, it is recommended to check the marginal and internal adaptation after the sintering process and, if applicable, after cementation, instead of only referring to the CAD values.

- Do not attempt to justify one mean with the fact that it confirms the acceptability of a margin or internal region; the occlusal and cervical areas should be assessed independently.

- In vitro findings should be applied with caution when making claims regarding the clinical performance of longer periods.

11. LIMITATIONS AND RESEARCH AGENDA

11.1 Limitations of this evidence draft

The majority of available literature was conducted on in vitro samples with small sample sizes and diverse measurement protocols and we were unable to find any clinical comparative study that directly assess the fit of printed crowns to their milled counterparts. In addition, primary-, provisional-, and permanent- crown groups should not be combined.

11.2.Future Research Priorities

Future research should focus on conducting appropriately powered, preregistered comparative studies with standardized preparation geometry and cement space. Marginal gap, absolute marginal discrepancy, and regional internal gaps should be reported separately for each study type, with mean, SD, median, range and confidence interval data available. Micro-CT (preferred) or other validated optical techniques, using blinded observers, and with reliability data are the most suitable methods, along with detailed reporting of printer type and layer thickness, build orientation, batch data, debinding and sintering cycle, and compensation factors. Cementation protocols and thermo mechanical aging procedures with measured gains before and after aging are also necessary. Future studies should report on absolute and relative marginal gaps before and after aging, and survival of restorations, and there may be a role for prospective clinical studies examining marginal integrity, biological complications, and patient reported outcomes.

CONCLUSION

Given the limited comparability of evidence, milling of zirconia crowns generally produces smaller marginal gaps than printed crowns derived by lithography or DLP (digital light processing) within the scope of the available comparative evidence from 2020 to 2025. Other evidence, especially the use of jetting technology, resin, and provisional crowns, demonstrate for the most part equal or smaller published gaps. Additively manufactured crowns may produce clinically acceptable fit when made under optimal conditions, but are highly dependent on specific materials, technology, post processing, and measurement region used. Currently, the evidence base does not support an assertion that additively manufactured is equivalent or superior to milling for definitive crowns; milling continues to be the technology best known to produce consistent and predictable marginal fit of zirconia, with additive manufacturing being an exciting alternative that requires additional standardization and validation in laboratory and clinical settings. The manuscript includes 15 validated direct-comparison studies and details of additional steps to produce a publication-ready PRISMA 2020 review, including multi-database searching, dual screening, full-text extraction, and quality assessment.

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