

SYSTEMATIC REVIEW

Do 3D printed and milled tooth-supported complete monolithic zirconia crowns differ in accuracy and fit? A systematic review and meta-analysis of in vitro studies



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The popularity of ceramic restorations has increased recently, particularly of monolithic zirconia,¹ widely used for fabricating fixed restorations^{2,3} because of its esthetics, biocompatibility,⁴ and mechanical properties.⁵⁻⁷ Zirconia restorations have been conventionally fabricated through subtractive manufacturing (SM) using computer-aided design and computer-aided manufacturing (CAD-CAM).^{8,9} Raw materials are available as fully sintered zirconia for hard milling or as partially sintered porous ceramic blocks (presintered) for soft machining¹⁰⁻¹² followed by sintering. Presintered blocks are more popular for ease of restoration machining.¹³ Nevertheless, the resultant restorations undergo dimensional change associated with thermal shrinkage during sintering.¹⁴

ABSTRACT

Statement of problem. Additive (3-dimensional printing) and subtractive (milling) methods are digital approaches to fabricating zirconia restorations. Comparisons of their resultant fabrication accuracy and restoration fit are lacking.

Purpose. The purpose of this systematic review and meta-analysis was to evaluate the accuracy and fit of monolithic zirconia crowns fabricated by 3-dimensional printing and milling.

Material and methods. The PubMed (Medline), Scopus, Embase, Web of Science, Cochrane Library, and Google Scholar databases were searched up to August 2023. Eligible records were included, and the standardized mean difference (SMD) analyzed 4 outcomes: marginal fit, intaglio fit, trueness, and precision. Publication bias was analyzed with Trim-and-fill, the Egger regression test, and Begg funnel plot. Methodological quality was rated using the QUIN tool.

Results. A total of 15 publications were found eligible out of the initial 6539 records. The 3-dimensional printing group demonstrated a lower marginal fit (SMD=1.46, 95% CI=[0.67, 2.26], $P<.001$; $I^2=83\%$, $P<.001$) and trueness (SMD=0.69, 95% CI=[0.20, 1.18], $P=.006$; $I^2=88\%$, $P<.001$) and a significantly higher precision (SMD=-2.19, 95% CI=[-2.90, -1.48], $P<.001$; $I^2=56\%$, $P=.045$). The intaglio fit did not differ significantly across the study groups (SMD=0.77, 95% CI=[-0.22, 1.77], $P=.127$; $I^2=87\%$, $P<.001$).

Conclusions. Given the high degree of heterogeneity, it can be cautiously concluded that while 3-dimensional printing led to greater precision, the outcomes of the 2 accuracy and adaptation parameters most crucial to the longevity of the restorations—trueness and marginal fit—showed the superiority of the milling technique. (J Prosthet Dent 2025;133:383-393)

SM methods generate substantial material waste, raising production costs and environmental impact.¹⁵ Furthermore,

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Clinical Implications

Digital methods offer advantages in fabricating dental ceramics. However, further advancements and research in printing zirconia restorations are needed to ensure long-term clinical efficacy.

the shape and size of the milling instruments and the number of working axes impact the quality of the surface finish and replication of surface geometry.^{5,8,16,17}

Additive manufacturing (AM), or 3-dimensional (3D) printing with different technologies, has recently gained attention for fabricating dental ceramics, including zirconia.^{17–27} The advantages of AM include less material waste, the capability of manufacturing intricate objects, low residual stress, and lack of tool wear.^{18,28–30} However, its limitations³¹ include dimensional inaccuracies, extended printing times, the inconsistent postprocessing stages of available methods, layer-associated shrinkage, printing parameter-induced dimensional changes, and variations in both the physical and surface properties of the definitive restoration.^{28,32,33} The final quality of a 3D printed restoration can also be impacted by the printer brand, printing technology, parameter setting, layer thickness, amount of support material, build angle,^{28,34} staircase effect,³⁵ and postprocessing procedures.^{36,37}

The fit of a restoration is crucial for long-term clinical success.^{38,39} Marginal discrepancies can lead to cement dissolution,^{40,41} microleakage,^{42–45} pulpal damage,^{46,47} secondary caries,⁴⁴ or periodontal inflammation.³⁸ Moreover, an increased intaglio gap compromises retention,⁴⁸ rotational stability, and fracture resistance.⁴⁹ AM and SM techniques have been reported to achieve clinically acceptable marginal and intaglio adaptation.^{33,50,51} In the digital method, the accuracy is determined by trueness and precision,^{52,53} usually measured with the root mean square (RMS) value.^{15,54–56} However, a clear conclusion on the equivalence of 3D printed zirconia restorations to milled ones in terms of accuracy and fit is lacking.⁵⁷ Therefore, this systematic review and meta-analysis aimed to compare the accuracy and fit of tooth-supported monolithic zirconia crowns fabricated by AM and SM. The null hypothesis was that no differences would be found in adaptation and accuracy among the study groups.

MATERIAL AND METHODS

This study was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) and Cochrane Handbook for

Table 1. Study design

PICO Items	Study Design
Population	Tooth-supported complete monolithic zirconia crowns
Intervention	3D printing technology (AM)
Comparison	Subtractive manufacturing technique (SM)
Outcome	Accuracy and fit of the fabricated restorations (Marginal fit, intaglio fit, trueness, and precision)

systematic reviews.⁵⁸ The protocol was registered at the Open Science Framework (<https://doi.org/10.17605/OSF.IO/TSHKJ>). The primary research question formulated for this study based on the purposed population, intervention, comparison, and outcome (PICO) criteria was "Do 3D printed and milled zirconia tooth-supported single crowns differ in accuracy and fit?" (Table 1). Using established search strategies (Supplemental Table 1, available online), an electronic search was conducted up to August 2023 in the PubMed/Medline, Embase, Scopus, Web of Science, and the Cochrane Library databases. The search was limited to English-language publications without date restrictions. Reference lists of the selected articles and related prior studies were scrutinized and supplemented by a search in Google Scholar for additional qualifying studies.

The inclusion criteria involved in vitro studies published in peer-reviewed journals that compared the fit and accuracy of milled and 3D printed tooth-supported monolithic zirconia crowns. Articles that studied implant-retained or multiunit restorations, partial restorations, or materials other than zirconia, and other types of investigations, including ex vivo, clinical studies, pilot studies, case reports and case series, narrative and systematic reviews, expert opinions, analyses with insufficient or missing data, letters to the editor, editorial and commentary reports, and those that did not conform to the eligibility requirements were excluded from the study.

Two calibrated reviewers (S.A.M., M.A.) screened the studies based on their title and abstract, eliminating any duplicate entries. They cross-matched the full text of the remaining potentially eligible publications. Conflicts between the reviewers were resolved by reaching an agreement or consulting a third examiner (J.P.). The same reviewers retrieved the subsequent information from the included papers: first author, publication year, country, die material, abutment tooth, finish line design, impression technique, cement space, CAD software program, 3D printer brand and technology, layer thickness, build angle, milling machine brand and the number of axes, the type of zirconia material, post-processing technique, sample size, outcomes, measurement method, measured regions, fit and accuracy assessment criteria, and corresponding values for

marginal gap, intaglio gap (mean $\pm$ SD μ m), trueness, and precision (RMS $\pm$ SD μ m). The higher the mean or RMS values, the less the fit or accuracy of the restorations were. Conflicts in the data extraction were resolved with the assistance of a fourth reviewer (R.A.P.).

The interrater reliability between the assessors was calculated by using the Cohen kappa coefficient. The study groups were compared using a standardized mean difference (SMD) analysis, calculated by pooling the data using a random-effects model with the DerSimonian and Laird method.⁵⁹ The Cochran (Q) test and inconsistency score (I^2) were used to assess the heterogeneity of the effect-size estimates. Additionally, the pooled mean for each main study outcome was calculated in both groups to ascertain whether they fell within the clinically acceptable level. Potential publication bias was assessed using the Begg and Egger regression tests.⁶⁰ Furthermore, the Egger test was used to quantify the degree of asymmetry. Additionally, the trim-and-fill method was used to estimate any potentially missing studies that may have been omitted because of publication bias, thereby adjusting the overall effect estimate. In 1 study,⁶¹ the SD for marginal fit and intaglio fit was not reported quantitatively; therefore, after unsuccessful attempts to contact the corresponding author, a software program (PlotDigitizer 2.6.8) was used to retrieve the required data from the provided box plot. In 2 other studies,^{33,62} the required values were presented as the median and interquartile range (IQR), which were converted into SD using the formulas: $SD = \frac{IQR}{1.35}$ and $SD = \frac{Range}{4}$. In another study,⁶³ the additional data were retrieved by contacting the corresponding author. The methodological quality of the included records was assessed by using the Quality Assessment Tool For In Vitro Studies (QUIN Tool).⁶⁴

RESULTS

The initial search yielded 6539 records. In the title and abstract screening stage, duplicates ($n=2931$) and irrelevant reports ($n=3589$) were excluded ($\kappa=0.81$). After analyzing the full text of the remaining articles ($n=19$), 4 records^{65–68} were excluded (Table 2) ($\kappa=0.95$). Finally, 15 articles^{17,33,61–63,69–78} were selected for the meta-analysis (Fig. 1).

The selected studies were published between 2019 and 2023. Typodonts,^{69,71,72,74,76–78} extracted human teeth,⁶¹ gypsum,^{17,62,70} zirconia,^{33,73} and epoxy resin⁶³ were used as the die material. The finish line designs were mostly chamfer,^{33,61,63,70–74} followed by rounded shoulder,^{69,72} 90-degree shoulder,¹⁷ and knife-edge.⁷² Different 3D printing technologies comprised stereolithography (SLA),^{33,62,69,71–73,77,78} direct light processing (DLP),^{63,71,74–77} inkjet,^{61,74} lithography-based ceramic

Table 2. Records excluded with their reason

Study	Reason
Abduo et al ⁶⁵	Did not utilize 3D printing technology to fabricate zirconia crowns.
Li et al ⁶⁶	Lacked reference group.
Miura et al ⁶⁷	Only reported occlusal morphology reproductive trueness.
Marouki et al ⁶⁸	Using manufacturing 3D gel deposition approach.

manufacturing (LCM),¹⁷ and digital mask projection.⁷⁰ The mean assigned cement space was 56 μ m (range 25 to 80 μ m). All materials used for 3D printing were of 3 mol% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP), except for 3 studies^{74,76,77} which did not report the type of zirconia. The zirconia material used for the milling approach involved 3Y-TZP,^{61,63,69,70} partially stabilized zirconia (PSZ),^{72–74} 4Y-PSZ,⁷¹ and 5Y-PSZ.⁷¹ The specifics of the printing settings, such as the build angle, were infrequently detailed in the studies. However, the layer thickness data, sourced from the studies or directly from the authors, were integrated into the meta-analysis; studies used a 25 μ m-layer thickness for SLA,^{62,69,72,73,77} 10.5 μ m for inkjet,^{61,74} 25 μ m⁷⁷ and 30 μ m⁷⁴ for DLP, and 50 μ m for LCM.¹⁷ Postprocessing stages following 3D printing consisted of cleaning, debinding, and sintering without any finishing or polishing process. However, the documentation of postprocessing steps was deficient and displayed significant heterogeneity. Consequently, the build angle and postprocessing method were excluded from the meta-analysis. The characteristics of the included studies are detailed in Supplemental Table 2 (available online). For the meta-analysis, the selected studies were divided into 4 domains: marginal fit (MF), intaglio fit (IF), trueness, and precision.

Ten publications ($=21$ input studies) evaluated the MF using dual-scan,^{62,69,74} triple-scan,^{70,73} silicone replica,^{33,63,77} micro-CT,^{61,75} and stereomicroscopy methods.⁶³ Twenty-one input studies, including 362 observations, were combined in the analysis. According to the pooled effect size, the SMD of the marginal gap was significantly higher in the AM group (SMD=1.46, 95% CI=[0.67, 2.26], $P<.001$). Significant heterogeneity among the studies ($I^2=83\%$, $P<.001$) was found (Fig. 2), but the overall finding was not found to be sensitive to any of the included studies (Supplemental Fig. 1, available online). Additionally, a severe publication bias was noted because of the small study effect (Fig. 3A, Table 3). The results of the subgroup analysis on "marginal fit" are detailed in Supplemental Table 3 and Supplemental Figure 2 (available online).

The IF was investigated in 9 studies ($=29$ input studies) using dual-scan,^{62,69,74} triple-scan,⁷³ silicone replica,^{33,63,77} or micro-CT^{61,75} approaches. Twenty-nine input studies, including 534 observations, were combined in the analysis. No differences were observed

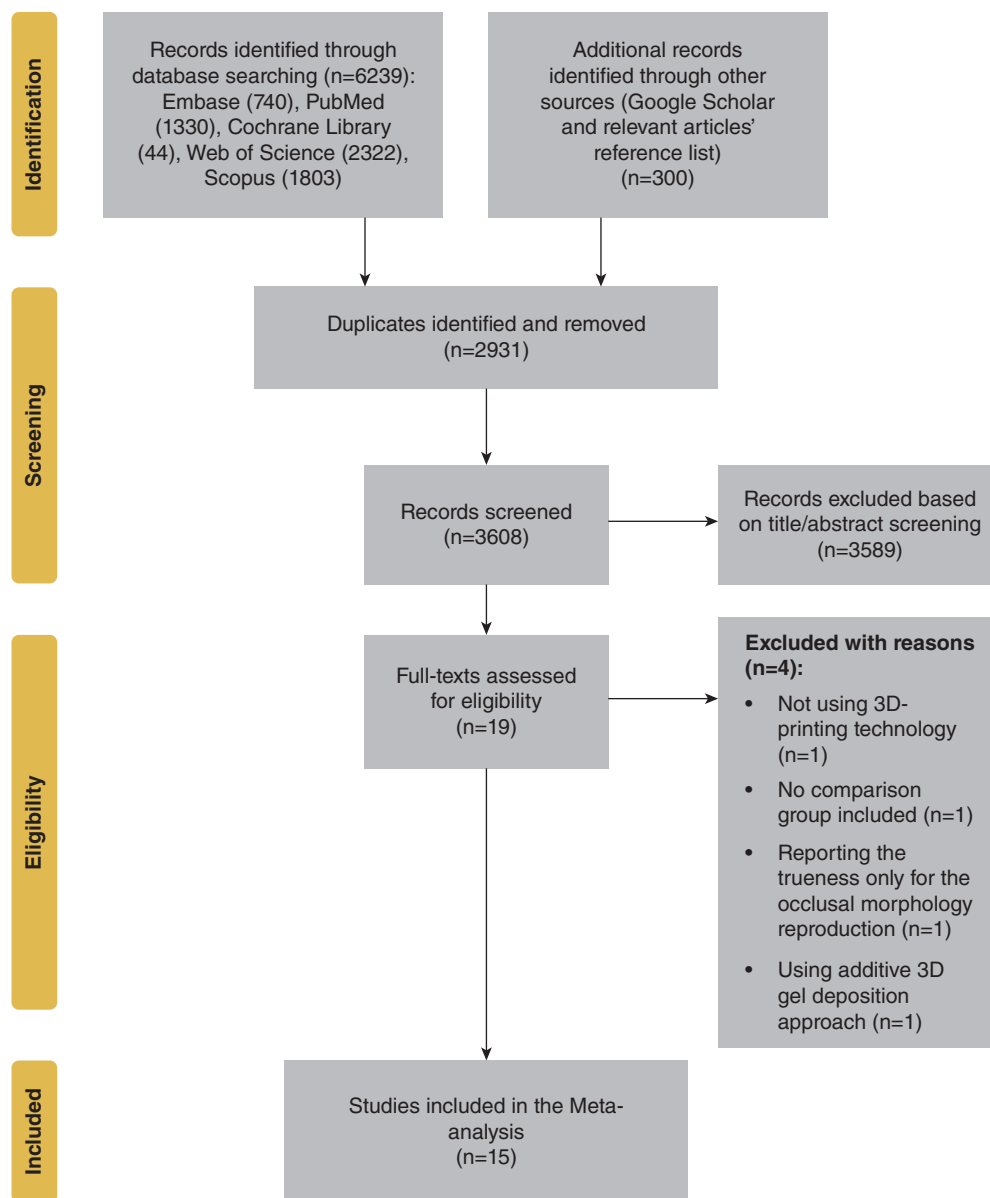


Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow diagram demonstrating information through different phases of systematic review.

among the intervention groups (SMD=0.77, 95% CI=[−0.22, 1.77], $P=.127$), although the SMD was higher in the AM group. In addition, there was significant heterogeneity among the studies ($I^2=87\%$, $P<.001$) (Fig. 4). However, the overall finding was sensitive to 2 of the input studies from 1 article,⁷⁷ so excluding them could have resulted in a significant difference among the intervention groups, still with a relatively high amount of heterogeneity among the studies (Supplemental Fig. 3, available online). Additionally, there seemed to be a severe publication bias because of the small study effect (Figure 3B and Table 3). The results of the subgroup analysis on intaglio fit are detailed in Supplemental Table 4 and Supplemental Figure 4 (available online).

Trueness was reported in 11 articles (=65 input studies) using digital 3D deviation analyses.^{17,61,62,69,71–74,76–78} Sixty-five input studies, including 1296 observations, were combined in the analysis. The SMD of trueness RMS values were significantly higher in the AM (SMD=0.69, 95% CI=[0.20, 1.18], $P=.006$). There was also significant heterogeneity among the studies ($I^2=88\%$, $P<.001$) (Fig. 5), and the overall finding was found not to be sensitive to any of the included studies (Supplemental Fig. 5, available online). Additionally, there seemed to be a severe publication bias because of the small study effect (Fig. 3C and Table 3). The results of the subgroup analysis on "trueness" are detailed in Supplemental Table 5 and Supplemental Figure 6 (available online).

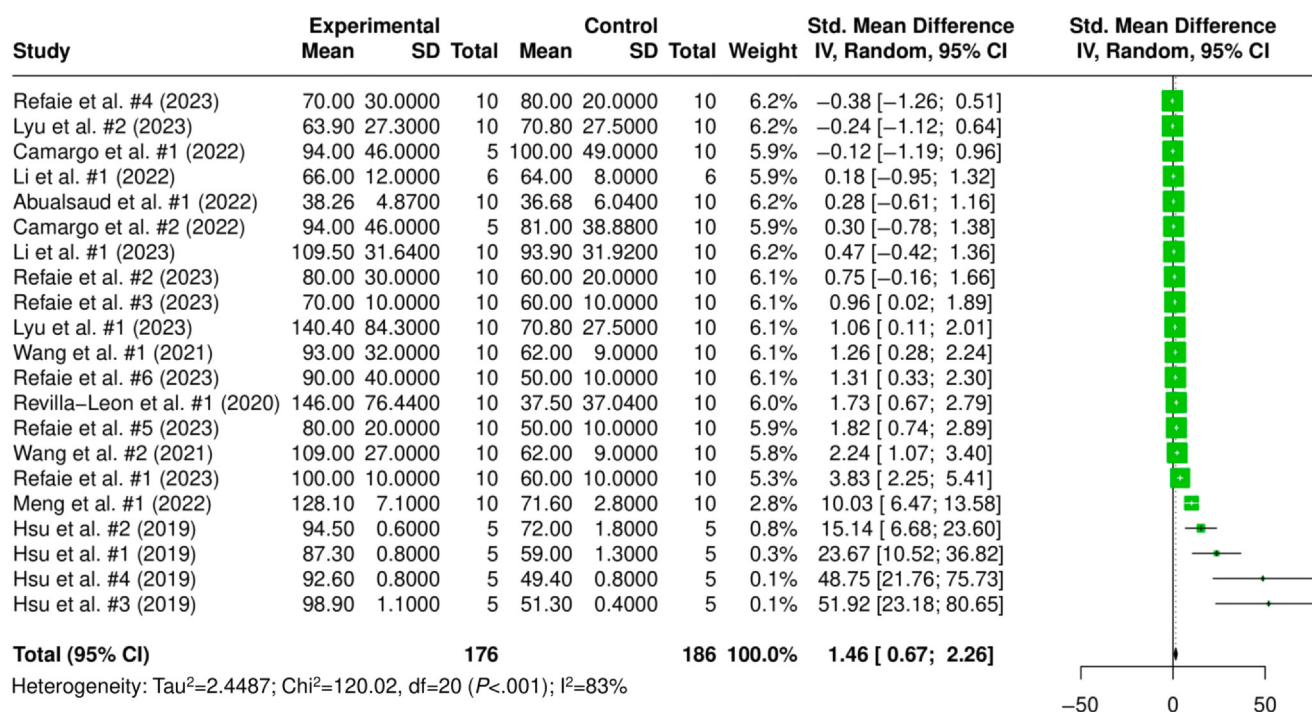


Figure 2. Forest plot comparing marginal fit between additively manufactured and subtractively manufactured restorations.

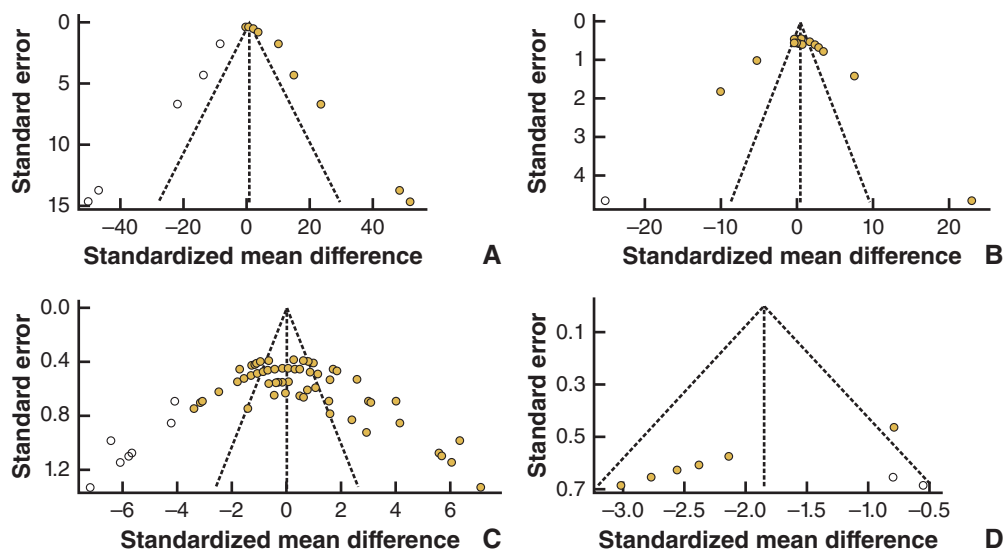


Figure 3. Funnel plot assessing publication of bias of studies included in meta-analysis. A, Marginal fit. B, Intaglio fit. C, Trueness. D, Precision outcomes.

Table 3. Results of publication bias analyses

Outcome	Egger	Begg	Trim Fill		
			N	SMD (95% CI)	I ²
Intaglio Fit	t=1.48, P=.151	z=2.93, P=.003	1	0.51 (-0.89, 1.91), P=.475	88%, P<.001
Marginal Fit	t=6.57, P<.001	z=4.23, P<.001	5	0.92 (-2.73, 4.57), P=.623	87%, P<.001
Precision	NA	NA	2	-1.85 (-2.53, -1.16), P<.001	61%, P=.011
Trueness	t=5.25, P<.001	z=3.78, P<.001	10	0.023 (-0.59, 0.63), P=.940	91%, P<.001

N, Number of added studies; NA, Not applicable

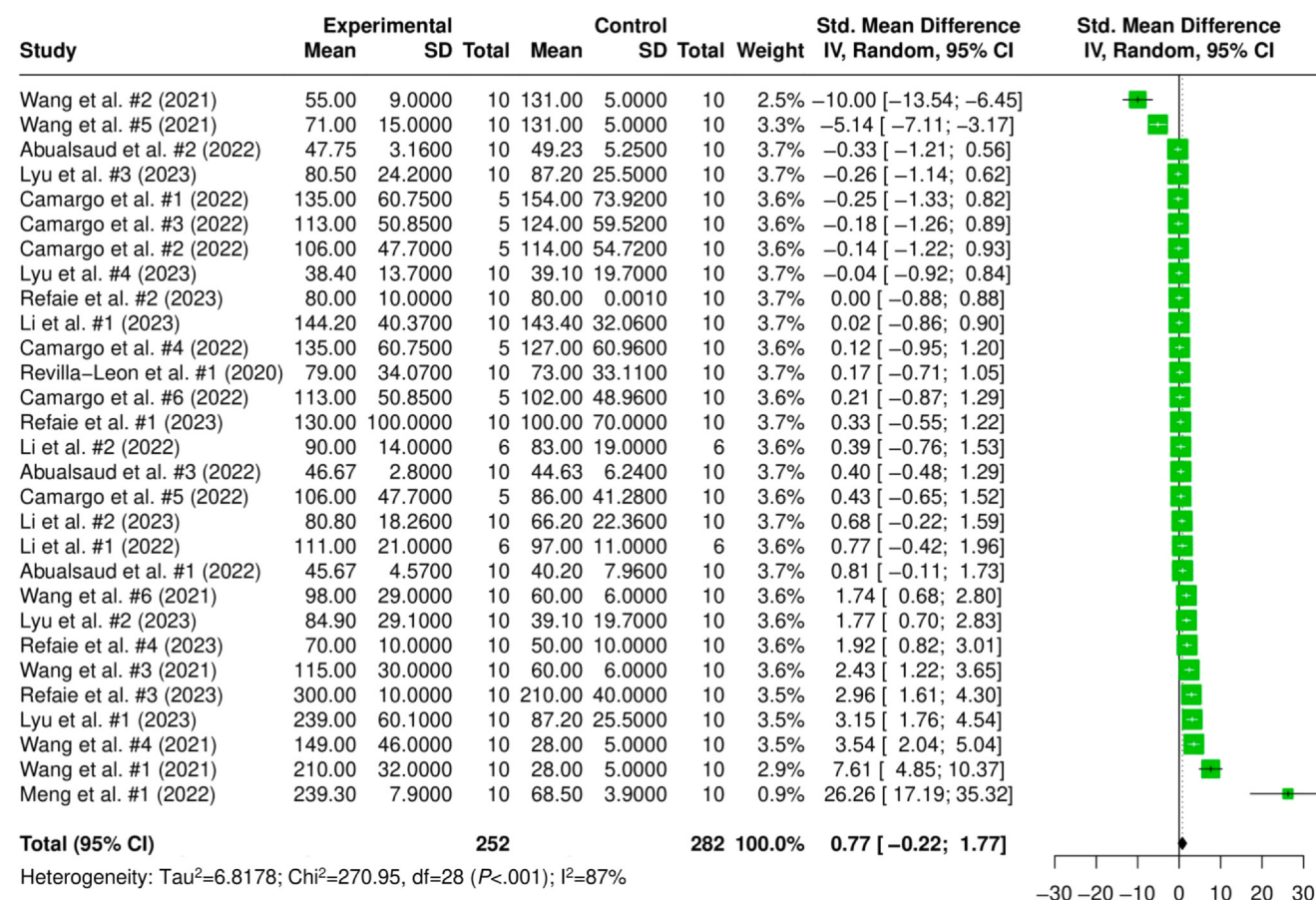


Figure 4. Forest plot comparing intaglio fit outcome between additively manufactured and subtractively manufactured restorations.

Precision was studied and reported in 2 papers (=6 input studies),^{62,69} measured by digital 3D deviation analyses. Six input studies, including 120 observations, were included in the analysis and were combined. The SMD of precision RMS values were significantly lower in the AM (SMD=-2.19, 95% CI=[-2.90, -1.48], *P*<.001) with significant heterogeneity among the studies (*I*²=56%, *P*=.045) (Fig. 6). Moreover, the overall finding was found not to be sensitive to any of the included studies except for 1 study⁶² which caused a significant drop in the heterogeneity (Supplemental Fig. 7, available online). Additionally, a moderate publication bias was found because of the small study effect (Fig. 3D) (Table 3). The results of the subgroup analysis on "precision" are detailed in Supplemental Table 6 and Supplemental Figure 8 (available online). Table 4 details the pooled mean (95% CI) associated with each principal study outcome between the 2 manufacturing technologies.

The results of the quality assessment (Supplemental Table 7, available online) showed 2 studies with a high risk of bias (RoB),^{70,75} 4 with a low RoB,^{63,71,77,78} and the remainder^{17,33,61,62,69,72-74,76} with a medium RoB. The QUIN criteria No. 7 (randomization) was considered

"not applicable" for all studies since identical samples were used for both the AM and SM techniques, reducing the potential for bias. The highest and lowest scores were 19/22⁷⁷ and 7/22,⁷⁵ respectively. The percentages of each assessed criterion are illustrated in Figure 7—none of the included studies used blinding.

DISCUSSION

The null hypothesis that no differences would be found in the adaptation and accuracy of the study groups was predominantly rejected because the studied digital fabrication methods significantly influenced the fit and accuracy of the crowns. However, the study showed that several confounders in the study designs could have affected the outcomes.

The results demonstrated a greater marginal discrepancy for the AM restorations than the SM group. Conversely, a previous study³⁷ reported comparable marginal discrepancies between AM and SM; however, it treated all prosthetic materials—including metals, polymers, and ceramics—collectively. The higher marginal discrepancy of the 3D printed restorations may

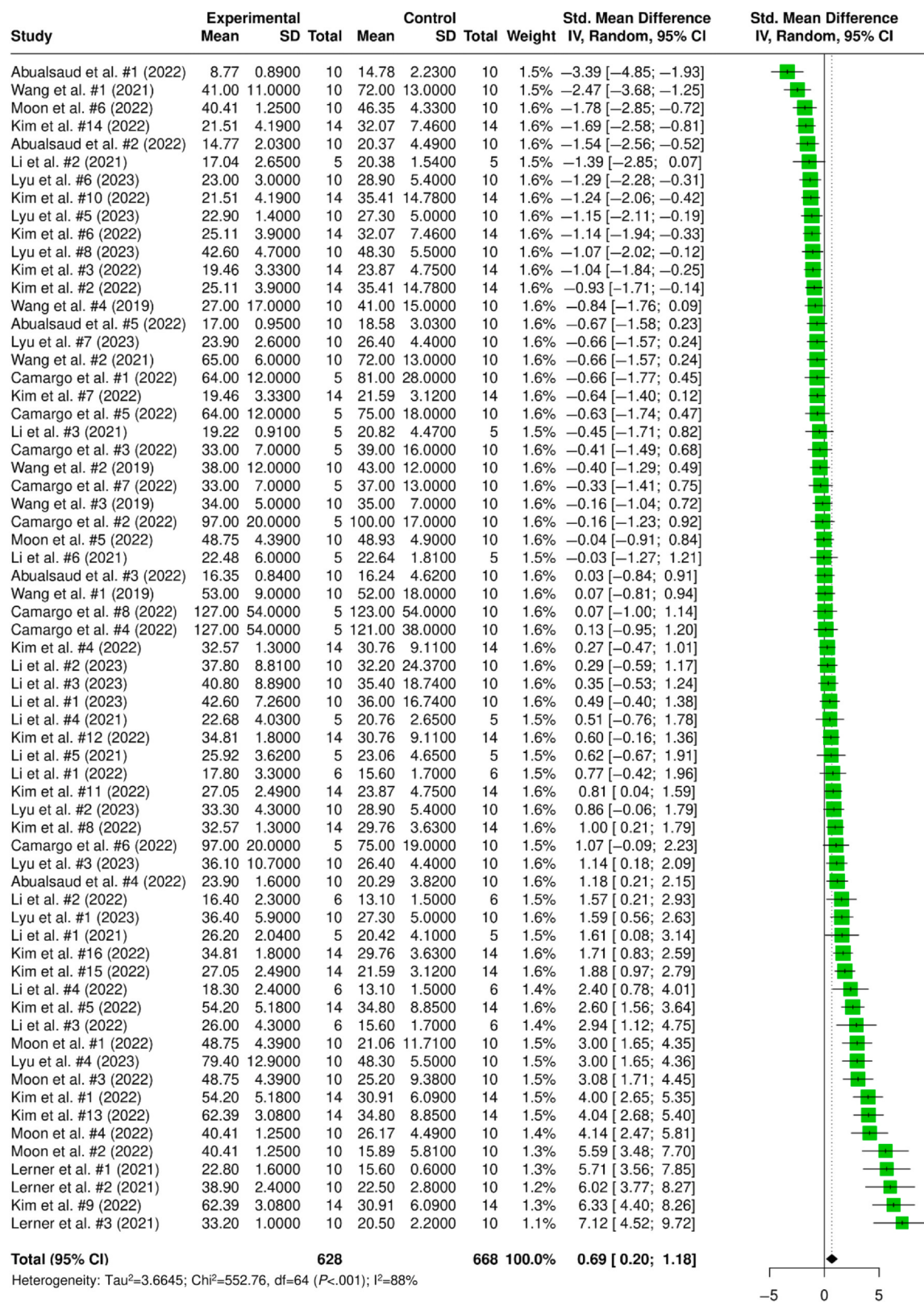


Figure 5. Forest plot comparing trueness outcome between additively manufactured and subtractively manufactured restorations.

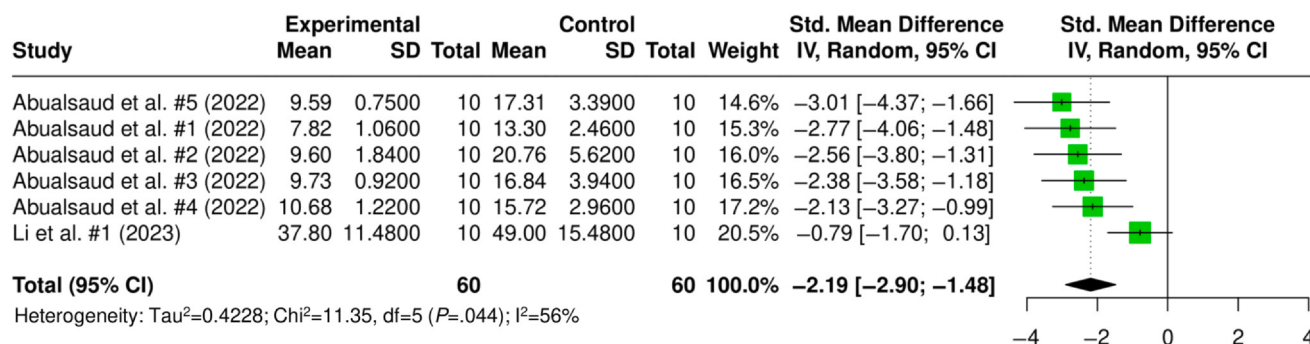


Figure 6. Forest plot comparing precision outcome between additively manufactured and subtractively manufactured restorations.

Table 4. Pooled mean values corresponding to each studied manufacturing approach in marginal fit, intaglio fit, trueness, and precision domains

Study Groups and Outcomes	3D Printing		Milling	
	Mean	95% CI	Mean	95% CI
Marginal fit (μm)	87.69	(82.78, 92.61)	60.85	(56.88, 64.82)
Intaglio fit (μm)	113.56	(89.35, 137.77)	84.44	(69.72, 99.15)
Trueness (RMS)	35.78	(32.75, 38.81)	32.36	(30.13, 34.59)
Precision (RMS)	10.41	(9.00, 11.82)	19.39	(15.74, 23.03)

RMS, Root Mean Square; 95% CI, 95% Confidence Interval.

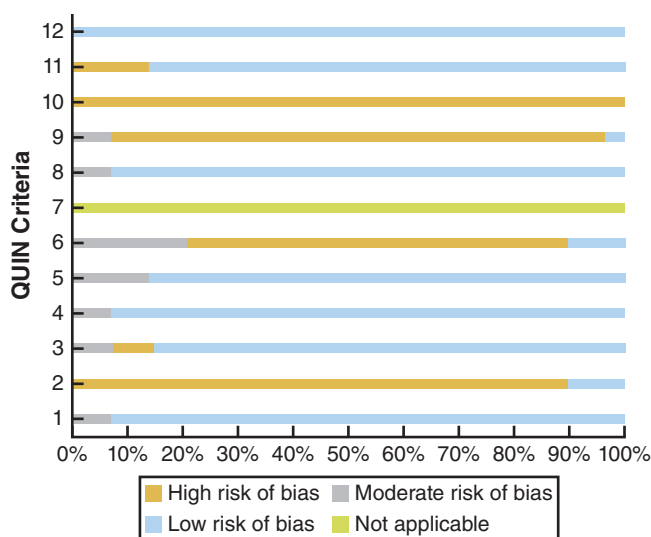


Figure 7. Risk of bias assessment based on Quality Assessment Tool For In Vitro Studies.

result from errors accumulated during various fabrication stages.^{33,63} In the AM group, zirconia particles were loosely stacked.⁷⁰ After printing, the workpiece underwent debinding to remove resin and was then sintered. This process led to primary volume reduction from resin removal and further shrinkage during sintering, resulting in distortion.⁷⁵ Thus, additional heat treatment phases inherent to AM entail more thermal shrinkage than with SM.⁷⁰ In SLA, metal particles have been reported to settle at the bottom of each suspension layer, decreasing their concentration at the top.³⁴ This settlement may cause more critical shrinkage and less

effective sintering, potentially causing a lower marginal fit in SLA.³⁴ The chamfer finish line's larger marginal discrepancy in AM may be related to its curved axioingival line angle, which increases the possibility of stair-stepping errors during the incremental layer printing.³⁹

The intaglio fit values between SM and AM were comparable. Conversely, another study⁵⁷ reported higher overall SM accuracy in fabricating dental ceramics, but the study did not distinguish between different types of ceramics, restorations, and accuracy outputs. The intaglio accuracy of the AM and SM can be impacted by limiting factors, with curved intaglio surfaces being difficult to reproduce in both approaches.³³ In SM, the axes' motion and bur diameter limitations affect the accurate recreation of the intaglio surfaces.⁹ However, the layer-by-layer printing mode increases the risk of errors on curved intaglio areas in AM.⁷⁸ The lower occlusal and axioocclusal intaglio fit in the AM crowns can be associated with the higher marginal discrepancy, which led to cascading effects that might reduce the intaglio fit at the occlusal and axial thirds.⁶¹ Furthermore, the additional sintering shrinkage of the horizontal plane can decrease the intaglio fit of the AM restorations.⁴¹ While an agreed-upon allowable marginal gap or intaglio gap for clinical success has not been established, values have been reported to range from 50 to 120 μm.^{42–45} Therefore, the marginal fit and intaglio fit pooled mean values for both SM and AM were within the clinically acceptable range.

Dimensional accuracy and clinical adaptability are closely correlated; the higher the dimensional accuracy, the better the clinical adaptation.⁷⁷ The trueness results

favored SM. The RMS values in AM could be impacted by printing modes, parameters, and postprocessing procedures.^{28,35,36} The higher error vulnerability of AM at curved surfaces affects trueness at corrugated and sloping surfaces.⁷⁸ Compared with AM, SM involves a bur-cutting orientation that results in milling lines on the interparallel plane distance, adjustable by controlling the machine's axis number, the geometry of the bur tip, and the width of the milling lines.⁵⁴ Postpolymerization processes in AM might also increase shrinkage, which cannot be compensated by adding further layers.⁵³ Additionally, the accuracy of the cusp replication in 3D printing is compromised by the presence of the printing supports. The width of the polymerization beam and the layer thickness also affect the accuracy of AM; the narrower the polymerization beam and the thinner the layers, the higher the accuracy.²² The RMS values were higher in the marginal and intaglio regions of the AM crowns, which could be associated with a failure to adequately counteract the effect of sintering shrinkage.⁷⁸ Reduced intaglio surface trueness in AM can narrow the axial space, cause early contact between the abutment and the restoration's intaglio surface, and enlarge the occlusal and axial gaps.⁴⁸ Lower trueness was found for DLP and LCM. In DLP, lens distortion influences the laser beam's straightness and reduces accuracy.²³ The LCM also has difficulties in accurately reproducing narrow and deep grooves.¹⁷ A reference RMS value is lacking, indicating a clinically admissible trueness. However, some studies^{55,56} specified 50 µm as the reference tolerance; therefore, the results indicate an acceptable trueness for both groups.

The AM group showed better precision. In AM, the same zirconia material, printing device, and production steps are used to print restorations simultaneously. In the SM group, following the initial milling, changes in the milling burs occur,¹⁰ deteriorating the milling burs' surface integrity and increasing the crowns' surface roughness.¹¹ The precision deviation can also be increased because of the inconsistency in terms of the location of zirconia workpieces within the blank and their link to the milling spindle (bur).¹⁵ The better precision of SLA can be explained by its layer-by-layer mechanism, which augments the reproducible nature of the printing.⁶²

The diverse manufacturing parameters used in the reviewed studies made obtaining definitive results challenging,³¹ so the results should be cautiously interpreted because of considerable heterogeneity. With most articles having a moderate risk of bias, the evidence synthesis findings should be cautiously interpreted. Notably, this study compiled precementation in

vitro data, which poses challenges to clinical extrapolation. Further research is necessary to advance additive manufacturing for zirconia restorations.

CONCLUSIONS

Based on the findings of this systematic review and meta-analysis of in vitro studies, the following conclusions were drawn:

1. Milling showed better trueness and marginal fit, while 3D printing had greater precision.
2. The intaglio fit of both techniques was comparable.

APPENDIX A. SUPPORTING INFORMATION

Supplemental data associated with this article can be found in the online version at [doi:10.1016/j.prosdent.2024.04.010](https://doi.org/10.1016/j.prosdent.2024.04.010).

REFERENCES

1. Alqutaibi AY, Ghulam O, Krsoum M, et al. Revolution of current dental zirconia: A comprehensive review. *Molecules*. 2022;27:1699.
2. Cinquini C, Alfonsi F, Marchio V, et al. The use of zirconia for implant-supported fixed complete dental prostheses: A narrative review. *Dent J (Basel)*. 2023;11:144.
3. Alfawaz Y. Zirconia crown as single unit tooth restoration: A literature review. *J Contemp Dent Pract*. 2016;17:418–422.
4. Manicone PF, Rossi Iommetti P, Raffaelli L. An overview of zirconia ceramics: Basic properties and clinical applications. *J Dent*. 2007;35:819–826.
5. Komine F, Blatz MB, Matsumura H. Current status of zirconia-based fixed restorations. *J Oral Sci*. 2010;52:531–539.
6. Soylemez B, Sener E, Yurdakul A, Yurdakul H. Fracture toughness enhancement of yttria-stabilized tetragonal zirconia polycrystalline ceramics through magnesia-partially stabilized zirconia addition. *J Sci: Adv Mater Devices*. 2020;5:527–534.
7. Turon-Vinas M, Anglada M. Strength and fracture toughness of zirconia dental ceramics. *Dent Mater*. 2018;34:365–375.
8. Guess PC, Att W, Strub JR. Zirconia in fixed implant prosthodontics. *Clin Implant Dent Relat Res*. 2012;14:633–645.
9. Abduo J, Lyons K, Bennamoun M. Trends in computer-aided manufacturing in prosthodontics: A review of the available streams. *Int J Dent*. 2014;2014:783948.
10. Payaminia L, Moslemian N, Younespour S, et al. Evaluating the effect of repeated use of milling burs on surface roughness and adaptation of digitally fabricated ceramic veneers. *Heliyon*. 2021;7:e06896.
11. Ceylan G, Emir F, Doğdu C, et al. Effect of repeated millings on the surface integrity of diamond burs and roughness of different CAD/CAM materials. *Clin Oral Investig*. 2022;26:5325–5337.
12. Xu J, Li L, Chen M, Paulo Davim J. An experimental investigation on milling features of fully-sintered zirconia ceramics using PCD tools. *Mater Manuf Process*. 2022;37:318–326.
13. Denry I, Kelly JR. State of the art of zirconia for dental applications. *Dent Mater*. 2008;24:299–307.
14. Uçar Y, Aysan Meriç İ, Ekren O. Layered manufacturing of dental ceramics: Fracture mechanics, microstructure, and elemental composition of lithography-sintered ceramic. *J Prosthodont*. 2019;28:e310–e318.
15. Al Hamad KQ, Al-Rashdan RB, Al-Rashdan BA, Baba NZ. Effect of milling protocols on trueness and precision of ceramic crowns. *J Prosthodont*. 2021;30:171–176.
16. Miyazaki T, Nakamura T, Matsumura H, et al. Current status of zirconia restoration. *J Prosthodont Res*. 2013;57:236–261.
17. Lerner H, Nagy K, Pranno N, et al. Trueness and precision of 3D-printed versus milled monolithic zirconia crowns: An in vitro study. *J Dent*. 2021;113:103792.

18. Methani MM, Revilla-León M, Zandinejad A. The potential of additive manufacturing technologies and their processing parameters for the fabrication of all-ceramic crowns: A review. *J Esthet Restor Dent*. 2020;32:182–192.
19. Zeng L, Zhang Y, Liu Z, Wei B. Effects of repeated firing on the marginal accuracy of Co-Cr copings fabricated by selective laser melting. *J Prosthet Dent*. 2015;113:135–139.
20. Xu D, Xiang N, Wei B. The marginal fit of selective laser melting-fabricated metal crowns: An in vitro study. *J Prosthet Dent*. 2014;112:1437–1440.
21. Gad MM, Fouda SM, Abualsaud R, et al. Strength and surface properties of a 3d-printed denture base polymer. *J Prosthodont*. 2022;31:412–418.
22. Wu J, Gao B, Tan H, et al. A feasibility study on laser rapid forming of a complete titanium denture base plate. *Lasers Med Sci*. 2010;25:309–315.
23. He R, Liu W, Wu Z, et al. Fabrication of complex-shaped zirconia ceramic parts via a DLP- stereolithography-based 3D printing method. *Ceram Int*. 2018;44:3412–3416.
24. Dehurtevent M, Robberecht L, Hornez J-C, et al. Stereolithography: A new method for processing dental ceramics by additive computer-aided manufacturing. *Dent Mater*. 2017;33:477–485.
25. Gibson I, Rosen D, Stucker B. Binder Jetting. In: Gibson I, Rosen D, Stucker B, editors. *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*. New York, NY: Springer New York; 2015:205–218.
26. Özkol E, Zhang W, Ebert J, Telle R. Potentials of the "direct inkjet printing" method for manufacturing 3Y-TZP based dental restorations. *J Eur Ceram Soc*. 2012;32:2193–2201.
27. Wang G, Wang S, Dong X, et al. Recent progress in additive manufacturing of ceramic dental restorations. *J Mater Res Technol*. 2023;26:1028–1049.
28. Osman RB, van der Veen AJ, Huijberts D, et al. 3D-printing zirconia implants; A dream or a reality? An in-vitro study evaluating the dimensional accuracy, surface topography and mechanical properties of printed zirconia implant and discs. *J Mech Behav Biomed Mater*. 2017;75:521–528.
29. Nakai H, Inokoshi M, Nozaki K, et al. Additively manufactured zirconia for dental applications. *Materials (Basel)*. 2021;14:3694.
30. Barazanchi A, Li KC, Al-Amlah B, et al. Additive technology: Update on current materials and applications in dentistry. *J Prosthodont*. 2017;26:156–163.
31. Konieczny B, Szczesio-Wlodarczyk A, Sokolowski J, Bociong K. Challenges of Co-Cr alloy additive manufacturing methods in dentistry-The current state of knowledge (systematic review). *Materials (Basel)*. 2020;13:3524.
32. Quan H, Zhang T, Xu H, et al. Photo-curing 3D printing technique and its challenges. *Bioact Mater*. 2020;5:110–115.
33. Revilla-León M, Methani MM, Morton D, Zandinejad A. Internal and marginal discrepancies associated with stereolithography (SLA) additively manufactured zirconia crowns. *J Prosthet Dent*. 2020;124:730–737.
34. Xiang D, Xu Y, Bai W, Lin H. Dental zirconia fabricated by stereolithography: Accuracy, translucency and mechanical properties in different build orientations. *Ceram Int*. 2021;47:28837–28847.
35. Halloran JW. Ceramic stereolithography: Additive manufacturing for ceramics by photopolymerization. *Annu Rev Mater Res*. 2016;46:19–40.
36. Çakmak G, Cuellar AR, Donmez MB, et al. Effect of printing layer thickness on the trueness of 3-unit interim fixed partial dentures. *J Prosthet Dent*. 2024;131:718–725.
37. Valenti C, Isabella Federici M, Masciotti F, et al. Mechanical properties of 3D-printed prosthetic materials compared with milled and conventional processing: A systematic review and meta-analysis of in vitro studies. *J Prosthet Dent*. 2024;132:381–391.
38. Hasanazade M, Aminikhah M, Afrashtehfar KI, Alikhasi M. Marginal and internal adaptation of single crowns and fixed dental prostheses by using digital and conventional workflows: A systematic review and meta-analysis. *J Prosthet Dent*. 2021;126:360–368.
39. Alharbi N, Alharbi S, Cuijpers V, et al. Three-dimensional evaluation of marginal and internal fit of 3D-printed interim restorations fabricated on different finish line designs. *J Prosthodont Res*. 2018;62:218–226.
40. Forberger N, Göhring TN. Influence of the type of post and core on in vitro marginal continuity, fracture resistance, and fracture mode of lithia disilicate-based all-ceramic crowns. *J Prosthet Dent*. 2008;100:264–273.
41. Mously HA, Finkelman M, Zandparsa R, Hirayama H. Marginal and internal adaptation of ceramic crown restorations fabricated with CAD/CAM technology and the heat-press technique. *J Prosthet Dent*. 2014;112:249–256.
42. Falahchai M, Babae Hemmati Y, Neshandar Asli H, Emadi I. Marginal gap of monolithic zirconia endocrowns fabricated by using digital scanning and conventional impressions. *J Prosthet Dent*. 2021;125:325. e1–e5.
43. Abduo J, Lyons K, Swain M. Fit of zirconia fixed partial denture: A systematic review. *J Oral Rehabil*. 2010;37:866–876.
44. Abdel-Azim T, Rogers K, Elathamna E, et al. Comparison of the marginal fit of lithium disilicate crowns fabricated with CAD/CAM technology by using conventional impressions and two intraoral digital scanners. *J Prosthet Dent*. 2015;114:554–559.
45. Goujat A, Abouelleil H, Colon P, et al. Marginal and internal fit of CAD-CAM inlay/onlay restorations: A systematic review of in vitro studies. *J Prosthet Dent*. 2019;121:590–597. e3.
46. Zarauz C, Valverde A, Martinez-Rus F, et al. Clinical evaluation comparing the fit of all-ceramic crowns obtained from silicone and digital intraoral impressions. *Clin Oral Invest*. 2016;20:799–806.
47. Dolev E, Bitterman Y, Meirowitz A. Comparison of marginal fit between CAD-CAM and hot-press lithium disilicate crowns. *J Prosthet Dent*. 2019;121:124–128.
48. Nakamura T, Dei N, Kojima T, Wakabayashi K. Marginal and internal fit of Cerec 3 CAD/CAM all-ceramic crowns. *Int J Prosthodont*. 2003;16:244–248.
49. Wettstein F, Sailer I, Roos M, Hämmerle CH. Clinical study of the internal gaps of zirconia and metal frameworks for fixed partial dentures. *Eur J Oral Sci*. 2008;116:272–279.
50. Papadichou S, Pissiotis AL. Marginal adaptation and CAD-CAM technology: A systematic review of restorative material and fabrication techniques. *J Prosthet Dent*. 2018;119:545–551.
51. Thakur J, Parlani S, Shivakumar S, Jajoo K. Accuracy of marginal fit of an implant-supported framework fabricated by 3D printing versus subtractive manufacturing technique: A systematic review and meta-analysis. *J Prosthet Dent*. 2023;129:301–309.
52. Renne W, Ludlow M, Fryml J, et al. Evaluation of the accuracy of 7 digital scanners: An in vitro analysis based on 3-dimensional comparisons. *J Prosthet Dent*. 2017;118:36–42.
53. Choi JW, Ahn JJ, Son K, Huh JB. Three-dimensional evaluation on accuracy of conventional and milled gypsum models and 3d printed photopolymer models. *Materials (Basel)*. 2019;12:3499.
54. Tapie L, Lebon N, Mawussi B, et al. Understanding dental CAD/CAM for restorations-accuracy from a mechanical engineering viewpoint. *Int J Comput Dent*. 2015;18:343–367.
55. Kim CM, Kim SR, Kim JH, et al. Trueness of milled prostheses according to number of ball-end mill burs. *J Prosthet Dent*. 2016;115:624–629.
56. Cho JH, Yoon HI, Han JS, Kim DJ. Trueness of the inner surface of monolithic crowns fabricated by milling of a fully sintered (Y, Nb)-TZP block in chairside CAD-CAM system for single-visit dentistry. *Materials (Basel)*. 2019;12:3253.
57. Al Hamad KQ, Al-Rashdan BA, Ayyad JQ, et al. Additive manufacturing of dental ceramics: A systematic review and meta-analysis. *J Prosthodont*. 2022;31:e67–e86.
58. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*. 2021;372:n71.
59. Deeks JJ, Higgins JPT, Altman DG. Chapter 10: Analysing data and undertaking meta-analyses (editors). In: Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page MJ, Welch VA, editors. *Cochrane Handbook for Systematic Reviews of Interventions version 6.4 (updated August 2023)* (Cochrane; 2023 (Available from). (www.training.cochrane.org/handbook).
60. Egger M, Smith GD, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. *BMJ*. 1997;315:629–634.
61. Camargo B, Willems E, Jacobs W, et al. 3D printing and milling accuracy influence full-contour zirconia crown adaptation. *Dent Mater*. 2022;38:1963–1976.
62. Li B, Jiang Q, Meng D. Evaluation of the trueness and adaptation of zirconia crowns fabricated with stereolithography. *Dent Mater J*. 2023;42:441–448.
63. Refaie A, Fouda A, Bourauel C, Singer L. Marginal gap and internal fit of 3D printed versus milled monolithic zirconia crowns. *BMC Oral Health*. 2023;23:448.
64. Sheth VH, Shah NP, Jain R, et al. Development and validation of a risk-of-bias tool for assessing in vitro studies conducted in dentistry: The QUIN. *J Prosthet Dent*. 2024;331:1038–1042.
65. Abduo J, Ho G, Centorame A, et al. Marginal accuracy of monolithic and veneered zirconia crowns fabricated by conventional and digital workflows. *J Prosthodont*. 2023;32:706–713.
66. Li R, Wang Y, Hu M, et al. Strength and adaptation of stereolithography-fabricated zirconia dental crowns: An in vitro study. *Int J Prosthodont*. 2019;32:439–443.
67. Miura S, Fujita T, Tsukada S, et al. Comparative evaluation of the reproductive trueness of zirconia crowns fabricated using additive manufacturing and conventional milling. *Int J Prosthodont*. 2022;35:410–413.
68. Marouki C, Shamon A, Svanborg P. Evaluation of fit and accuracy of single crowns fabricated from self-glazed zirconia compared with milled zirconia. *J Prosthet Dent*. 2024;331:1105–1110.
69. Abualsaud R, Alalawi H. Fit, precision, and trueness of 3d-printed zirconia crowns compared to milled counterparts. *Dent J ((Basel))*. 2022;10:215.
70. Hsu HJ, Lee SY, Jiang CP, Lin R. A comparison of the marginal fit and mechanical properties of a zirconia dental crown using CAM and 3DSP. *Rapid Prototyp J*. 2019;25:1187–1197.

71. Kim YK, Han JS, Yoon HI. Evaluation of intaglio surface trueness, wear, and fracture resistance of zirconia crown under simulated mastication: a comparative analysis between subtractive and additive manufacturing. *J Adv Prosthodont.* 2022;14:122–132.
72. Li R, Chen H, Wang Y, Sun Y. Performance of stereolithography and milling in fabricating monolithic zirconia crowns with different finish line designs. *J Mech Behav Biomed Mater.* 2021;115:104255.
73. Li R, Xu T, Wang Y, Sun Y. Accuracy of zirconia crowns manufactured by stereolithography with an occlusal full-supporting structure: An in vitro study. *J Prosthet Dent.* 2023;130:902–907.
74. Lyu J, Yang X, Li Y, et al. Dimensional accuracy and clinical adaptation of monolithic zirconia crowns fabricated with the nanoparticle jetting technique. *J Prosthet Dent.* 2024;332:985.e1–985.e7.
75. Meng J, Lian Q, Xi S, et al. Crown fit and dimensional accuracy of zirconia fixed crowns based on the digital light processing technology. *Ceram Int.* 2022;48:17852–17863.
76. Moon JM, Jeong CS, Lee HJ, et al. A comparative study of additive and subtractive manufacturing techniques for a zirconia dental product: An analysis of the manufacturing accuracy and the bond strength of porcelain to zirconia. *Materials (Basel).* 2022;15:5398.
77. Wang W, Sun J. Dimensional accuracy and clinical adaptation of ceramic crowns fabricated with the stereolithography technique. *J Prosthet Dent.* 2021;125:657–663.
78. Wang W, Yu H, Liu Y, et al. Trueness analysis of zirconia crowns fabricated with 3-dimensional printing. *J Prosthet Dent.* 2019;121:285–291.

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