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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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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)

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 machining followed by sintering.[10–12] 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] 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 limitations[31] 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 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.

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)

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, postprocessing technique, sample size, outcomes, measurement method, measured regions, fit and accuracy assessment criteria, and corresponding values for marginal gap, intaglio gap (mean ± SD µm), trueness, and precision (RMS ± SD µm). 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 (κ=0.81). After analyzing the full text of the remaining articles (n=19), 4 records[65–68] were excluded (Table 2) (κ=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 resin[63] 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 manufacturing (LCM),[17] and digital mask projection.[70] The mean assigned cement space was 56 µm (range 25 to 80 µm). 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 µm-layer thickness for SLA,[62,69,72,73,77] 10.5 µm for inkjet,[61,74] 25 µm[77] and 30 µm[74] for DLP, and 50 µm 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

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.

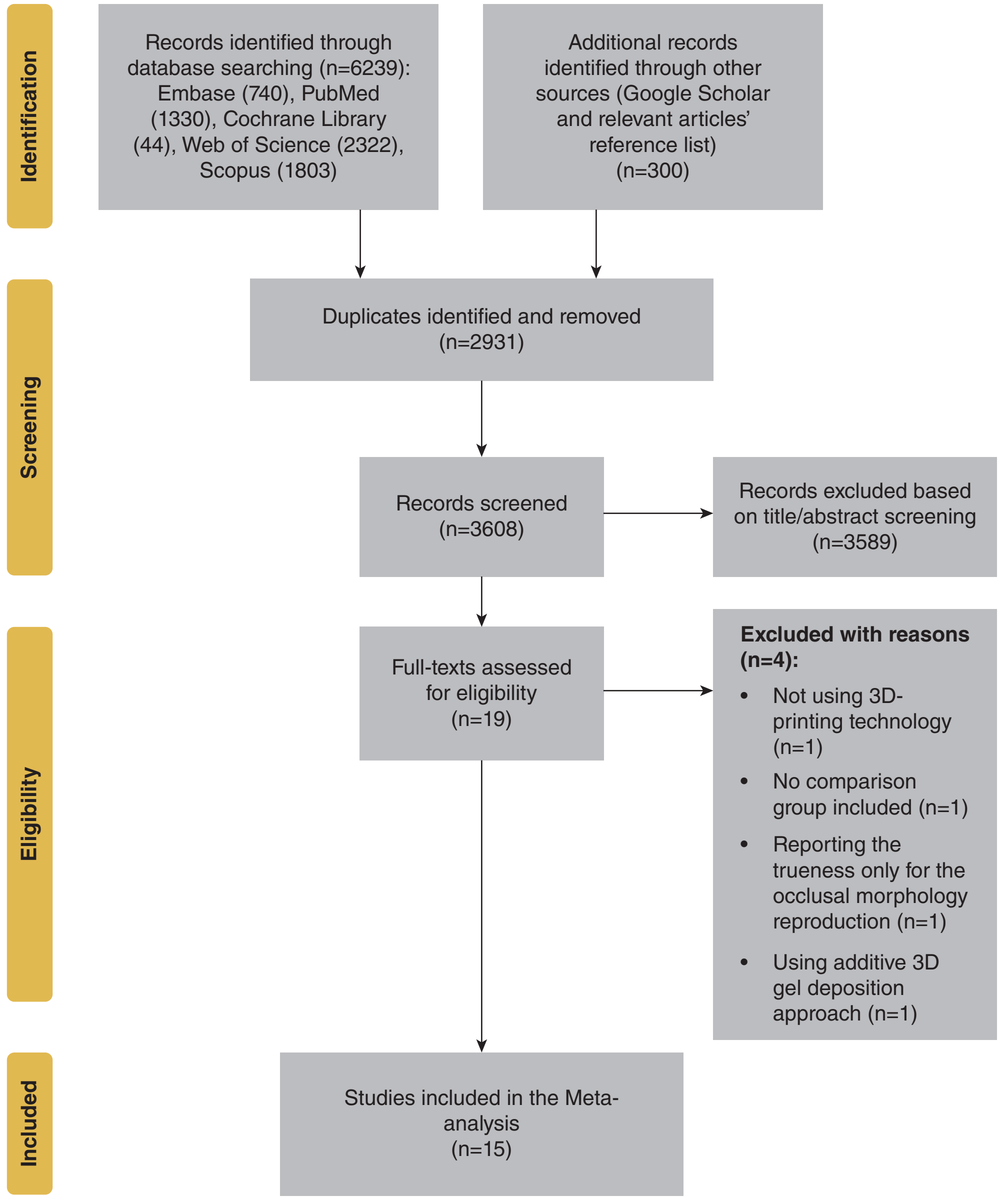

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow diagram demonstrating information through different phases of systematic review.

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).

Study	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Refaie et al. #4 (2023)	70.00	30.0000	10	80.00	20.0000	10	6.2%	−0.38 [−1.26; 0.51]
Lyu et al. #2 (2023)	63.90	27.3000	10	70.80	27.5000	10	6.2%	−0.24 [−1.12; 0.64]
Camargo et al. #1 (2022)	94.00	46.0000	5	100.00	49.0000	10	5.9%	−0.12 [−1.19; 0.96]
Li et al. #1 (2022)	66.00	12.0000	6	64.00	8.0000	6	5.9%	0.18 [−0.95; 1.32]
Abualsaud et al. #1 (2022)	38.26	4.8700	10	36.68	6.0400	10	6.2%	0.28 [−0.61; 1.16]
Camargo et al. #2 (2022)	94.00	46.0000	5	81.00	38.8800	10	5.9%	0.30 [−0.78; 1.38]
Li et al. #1 (2023)	109.50	31.6400	10	93.90	31.9200	10	6.2%	0.47 [−0.42; 1.36]
Refaie et al. #2 (2023)	80.00	30.0000	10	60.00	20.0000	10	6.1%	0.75 [−0.16; 1.66]
Refaie et al. #3 (2023)	70.00	10.0000	10	60.00	10.0000	10	6.1%	0.96 [0.02; 1.89]
Lyu et al. #1 (2023)	140.40	84.3000	10	70.80	27.5000	10	6.1%	1.06 [0.11; 2.01]
Wang et al. #1 (2021)	93.00	32.0000	10	62.00	9.0000	10	6.1%	1.26 [0.28; 2.24]
Refaie et al. #6 (2023)	90.00	40.0000	10	50.00	10.0000	10	6.1%	1.31 [0.33; 2.30]
Revilla–Leon et al. #1 (2020)	146.00	76.4400	10	37.50	37.0400	10	6.0%	1.73 [0.67; 2.79]
Refaie et al. #5 (2023)	80.00	20.0000	10	50.00	10.0000	10	5.9%	1.82 [0.74; 2.89]
Wang et al. #2 (2021)	109.00	27.0000	10	62.00	9.0000	10	5.8%	2.24 [1.07; 3.40]
Refaie et al. #1 (2023)	100.00	10.0000	10	60.00	10.0000	10	5.3%	3.83 [2.25; 5.41]
Meng et al. #1 (2022)	128.10	7.1000	10	71.60	2.8000	10	2.8%	10.03 [6.47; 13.58]
Hsu et al. #2 (2019)	94.50	0.6000	5	72.00	1.8000	5	0.8%	15.14 [6.68; 23.60]
Hsu et al. #1 (2019)	87.30	0.8000	5	59.00	1.3000	5	0.3%	23.67 [10.52; 36.82]
Hsu et al. #4 (2019)	92.60	0.8000	5	49.40	0.8000	5	0.1%	48.75 [21.76; 75.73]
Hsu et al. #3 (2019)	98.90	1.1000	5	51.30	0.4000	5	0.1%	51.92 [23.18; 80.65]
Total (95% CI)			**176**			**186**	**100.0%**	**1.46 [0.67; 2.26]**

Heterogeneity: Tau^2=2.4487; Chi^2=120.02, df=20 (*P*<.001); I^2=83%

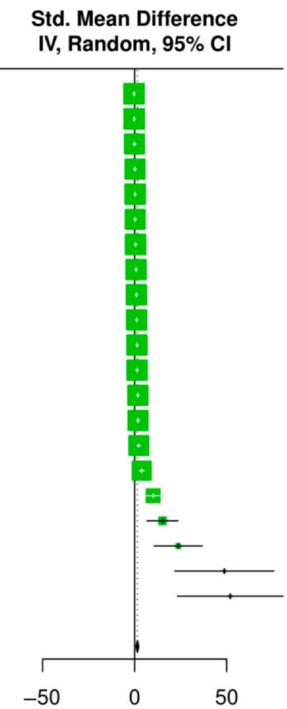

Figure 2. Forest plot comparing marginal fit between additively manufactured and subtractively manufactured restorations.

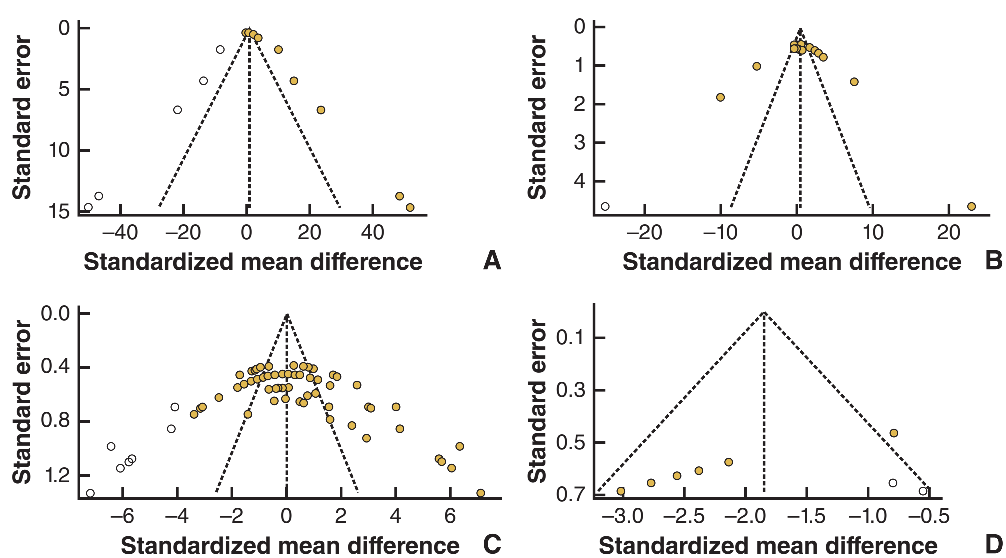

Figure 3. Funnel plot assessing publication of bias of studies included in meta-analysis. A, Marginal fit. B, Intaglio fit. C, Trueness. D, Precision outcomes.

Table 3. Results of publication bias analyses

Outcome	Egger	Begg	Trim Fill N	Trim Fill SMD (95% CI)	Trim Fill 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

Study	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
Wang et al. #2 (2021)	55.00	9.0000	10	131.00	5.0000	10	2.5%	−10.00 [−13.54; −6.45]
Wang et al. #5 (2021)	71.00	15.0000	10	131.00	5.0000	10	3.3%	−5.14 [−7.11; −3.17]
Abualsaud et al. #2 (2022)	47.75	3.1600	10	49.23	5.2500	10	3.7%	−0.33 [−1.21; 0.56]
Lyu et al. #3 (2023)	80.50	24.2000	10	87.20	25.5000	10	3.7%	−0.26 [−1.14; 0.62]
Camargo et al. #1 (2022)	135.00	60.7500	5	154.00	73.9200	10	3.6%	−0.25 [−1.33; 0.82]
Camargo et al. #3 (2022)	113.00	50.8500	5	124.00	59.5200	10	3.6%	−0.18 [−1.26; 0.89]
Camargo et al. #2 (2022)	106.00	47.7000	5	114.00	54.7200	10	3.6%	−0.14 [−1.22; 0.93]
Lyu et al. #4 (2023)	38.40	13.7000	10	39.10	19.7000	10	3.7%	−0.04 [−0.92; 0.84]
Refaie et al. #2 (2023)	80.00	10.0000	10	80.00	0.0010	10	3.7%	0.00 [−0.88; 0.88]
Li et al. #1 (2023)	144.20	40.3700	10	143.40	32.0600	10	3.7%	0.02 [−0.86; 0.90]
Camargo et al. #4 (2022)	135.00	60.7500	5	127.00	60.9600	10	3.6%	0.12 [−0.95; 1.20]
Revilla−Leon et al. #1 (2020)	79.00	34.0700	10	73.00	33.1100	10	3.7%	0.17 [−0.71; 1.05]
Camargo et al. #6 (2022)	113.00	50.8500	5	102.00	48.9600	10	3.6%	0.21 [−0.87; 1.29]
Refaie et al. #1 (2023)	130.00	100.0000	10	100.00	70.0000	10	3.7%	0.33 [−0.55; 1.22]
Li et al. #2 (2022)	90.00	14.0000	6	83.00	19.0000	6	3.6%	0.39 [−0.76; 1.53]
Abualsaud et al. #3 (2022)	46.67	2.8000	10	44.63	6.2400	10	3.7%	0.40 [−0.48; 1.29]
Camargo et al. #5 (2022)	106.00	47.7000	5	86.00	41.2800	10	3.6%	0.43 [−0.65; 1.52]
Li et al. #2 (2023)	80.80	18.2600	10	66.20	22.3600	10	3.7%	0.68 [−0.22; 1.59]
Li et al. #1 (2022)	111.00	21.0000	6	97.00	11.0000	6	3.6%	0.77 [−0.42; 1.96]
Abualsaud et al. #1 (2022)	45.67	4.5700	10	40.20	7.9600	10	3.7%	0.81 [−0.11; 1.73]
Wang et al. #6 (2021)	98.00	29.0000	10	60.00	6.0000	10	3.6%	1.74 [0.68; 2.80]
Lyu et al. #2 (2023)	84.90	29.1000	10	39.10	19.7000	10	3.6%	1.77 [0.70; 2.83]
Refaie et al. #4 (2023)	70.00	10.0000	10	50.00	10.0000	10	3.6%	1.92 [0.82; 3.01]
Wang et al. #3 (2021)	115.00	30.0000	10	60.00	6.0000	10	3.6%	2.43 [1.22; 3.65]
Refaie et al. #3 (2023)	300.00	10.0000	10	210.00	40.0000	10	3.5%	2.96 [1.61; 4.30]
Lyu et al. #1 (2023)	239.00	60.1000	10	87.20	25.5000	10	3.5%	3.15 [1.76; 4.54]
Wang et al. #4 (2021)	149.00	46.0000	10	28.00	5.0000	10	3.5%	3.54 [2.04; 5.04]
Wang et al. #1 (2021)	210.00	32.0000	10	28.00	5.0000	10	2.9%	7.61 [4.85; 10.37]
Meng et al. #1 (2022)	239.30	7.9000	10	68.50	3.9000	10	0.9%	26.26 [17.19; 35.32]
Total (95% CI)			**252**			**282**	**100.0%**	**0.77 [−0.22; 1.77]**

Heterogeneity: Tau^2=6.8178; Chi^2=270.95, df=28 (P<.001); I^2=87%

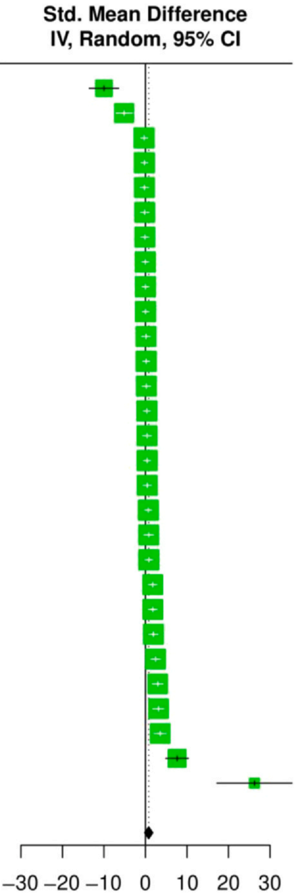

Figure 4. Forest plot comparing intaglio fit outcome between additively manufactured and subtractively manufactured restorations.

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 study[62] 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 19/22[77] 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 study[37] 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

Study	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Abualsaud et al. #1 (2022)	8.77	0.8900	10	14.78	2.2300	10	1.5%	−3.39 [−4.85; −1.93]
Wang et al. #1 (2021)	41.00	11.0000	10	72.00	13.0000	10	1.5%	−2.47 [−3.68; −1.25]
Moon et al. #6 (2022)	40.41	1.2500	10	46.35	4.3300	10	1.6%	−1.78 [−2.85; −0.72]
Kim et al. #14 (2022)	21.51	4.1900	14	32.07	7.4600	14	1.6%	−1.69 [−2.58; −0.81]
Abualsaud et al. #2 (2022)	14.77	2.0300	10	20.37	4.4900	10	1.6%	−1.54 [−2.56; −0.52]
Li et al. #2 (2021)	17.04	2.6500	5	20.38	1.5400	5	1.5%	−1.39 [−2.85; 0.07]
Lyu et al. #6 (2023)	23.00	3.0000	10	28.90	5.4000	10	1.6%	−1.29 [−2.28; −0.31]
Kim et al. #10 (2022)	21.51	4.1900	14	35.41	14.7800	14	1.6%	−1.24 [−2.06; −0.42]
Lyu et al. #5 (2023)	22.90	1.4000	10	27.30	5.0000	10	1.6%	−1.15 [−2.11; −0.19]
Kim et al. #6 (2022)	25.11	3.9000	14	32.07	7.4600	14	1.6%	−1.14 [−1.94; −0.33]
Lyu et al. #8 (2023)	42.60	4.7000	10	48.30	5.5000	10	1.6%	−1.07 [−2.02; −0.12]
Kim et al. #3 (2022)	19.46	3.3300	14	23.87	4.7500	14	1.6%	−1.04 [−1.84; −0.25]
Kim et al. #2 (2022)	25.11	3.9000	14	35.41	14.7800	14	1.6%	−0.93 [−1.71; −0.14]
Wang et al. #4 (2019)	27.00	17.0000	10	41.00	15.0000	10	1.6%	−0.84 [−1.76; 0.09]
Abualsaud et al. #5 (2022)	17.00	0.9500	10	18.58	3.0300	10	1.6%	−0.67 [−1.58; 0.23]
Lyu et al. #7 (2023)	23.90	2.6000	10	26.40	4.4000	10	1.6%	−0.66 [−1.57; 0.24]
Wang et al. #2 (2021)	65.00	6.0000	10	72.00	13.0000	10	1.6%	−0.66 [−1.57; 0.24]
Camargo et al. #1 (2022)	64.00	12.0000	5	81.00	28.0000	10	1.6%	−0.66 [−1.77; 0.45]
Kim et al. #7 (2022)	19.46	3.3300	14	21.59	3.1200	14	1.6%	−0.64 [−1.40; 0.12]
Camargo et al. #5 (2022)	64.00	12.0000	5	75.00	18.0000	10	1.6%	−0.63 [−1.74; 0.47]
Li et al. #3 (2021)	19.22	0.9100	5	20.82	4.4700	5	1.5%	−0.45 [−1.71; 0.82]
Camargo et al. #3 (2022)	33.00	7.0000	5	39.00	16.0000	10	1.6%	−0.41 [−1.49; 0.68]
Wang et al. #2 (2019)	38.00	12.0000	10	43.00	12.0000	10	1.6%	−0.40 [−1.29; 0.49]
Camargo et al. #7 (2022)	33.00	7.0000	5	37.00	13.0000	10	1.6%	−0.33 [−1.41; 0.75]
Wang et al. #3 (2019)	34.00	5.0000	10	35.00	7.0000	10	1.6%	−0.16 [−1.04; 0.72]
Camargo et al. #2 (2022)	97.00	20.0000	5	100.00	17.0000	10	1.6%	−0.16 [−1.23; 0.92]
Moon et al. #5 (2022)	48.75	4.3900	10	48.93	4.9000	10	1.6%	−0.04 [−0.91; 0.84]
Li et al. #6 (2021)	22.48	6.0000	5	22.64	1.8100	5	1.5%	−0.03 [−1.27; 1.21]
Abualsaud et al. #3 (2022)	16.35	0.8400	10	16.24	4.6200	10	1.6%	0.03 [−0.84; 0.91]
Wang et al. #1 (2019)	53.00	9.0000	10	52.00	18.0000	10	1.6%	0.07 [−0.81; 0.94]
Camargo et al. #8 (2022)	127.00	54.0000	5	123.00	54.0000	10	1.6%	0.07 [−1.00; 1.14]
Camargo et al. #4 (2022)	127.00	54.0000	5	121.00	38.0000	10	1.6%	0.13 [−0.95; 1.20]
Kim et al. #4 (2022)	32.57	1.3000	14	30.76	9.1100	14	1.6%	0.27 [−0.47; 1.01]
Li et al. #2 (2023)	37.80	8.8100	10	32.20	24.3700	10	1.6%	0.29 [−0.59; 1.17]
Li et al. #3 (2023)	40.80	8.8900	10	35.40	18.7400	10	1.6%	0.35 [−0.53; 1.24]
Li et al. #1 (2023)	42.60	7.2600	10	36.00	16.7400	10	1.6%	0.49 [−0.40; 1.38]
Li et al. #4 (2021)	22.68	4.0300	5	20.76	2.6500	5	1.5%	0.51 [−0.76; 1.78]
Kim et al. #12 (2022)	34.81	1.8000	14	30.76	9.1100	14	1.6%	0.60 [−0.16; 1.36]
Li et al. #5 (2021)	25.92	3.6200	5	23.06	4.6500	5	1.5%	0.62 [−0.67; 1.91]
Li et al. #1 (2022)	17.80	3.3000	6	15.60	1.7000	6	1.5%	0.77 [−0.42; 1.96]
Kim et al. #11 (2022)	27.05	2.4900	14	23.87	4.7500	14	1.6%	0.81 [0.04; 1.59]
Lyu et al. #2 (2023)	33.30	4.3000	10	28.90	5.4000	10	1.6%	0.86 [−0.06; 1.79]
Kim et al. #8 (2022)	32.57	1.3000	14	29.76	3.6300	14	1.6%	1.00 [0.21; 1.79]
Camargo et al. #6 (2022)	97.00	20.0000	5	75.00	19.0000	10	1.5%	1.07 [−0.09; 2.23]
Lyu et al. #3 (2023)	36.10	10.7000	10	26.40	4.4000	10	1.6%	1.14 [0.18; 2.09]
Abualsaud et al. #4 (2022)	23.90	1.6000	10	20.29	3.8200	10	1.6%	1.18 [0.21; 2.15]
Li et al. #2 (2022)	16.40	2.3000	6	13.10	1.5000	6	1.5%	1.57 [0.21; 2.93]
Lyu et al. #1 (2023)	36.40	5.9000	10	27.30	5.0000	10	1.6%	1.59 [0.56; 2.63]
Li et al. #1 (2021)	26.20	2.0400	5	20.42	4.1000	5	1.5%	1.61 [0.08; 3.14]
Kim et al. #16 (2022)	34.81	1.8000	14	29.76	3.6300	14	1.6%	1.71 [0.83; 2.59]
Kim et al. #15 (2022)	27.05	2.4900	14	21.59	3.1200	14	1.6%	1.88 [0.97; 2.79]
Li et al. #4 (2022)	18.30	2.4000	6	13.10	1.5000	6	1.4%	2.40 [0.78; 4.01]
Kim et al. #5 (2022)	54.20	5.1800	14	34.80	8.8500	14	1.6%	2.60 [1.56; 3.64]
Li et al. #3 (2022)	26.00	4.3000	6	15.60	1.7000	6	1.4%	2.94 [1.12; 4.75]
Moon et al. #1 (2022)	48.75	4.3900	10	21.06	11.7100	10	1.5%	3.00 [1.65; 4.35]
Lyu et al. #4 (2023)	79.40	12.9000	10	48.30	5.5000	10	1.5%	3.00 [1.65; 4.36]
Moon et al. #3 (2022)	48.75	4.3900	10	25.20	9.3800	10	1.5%	3.08 [1.71; 4.45]
Kim et al. #1 (2022)	54.20	5.1800	14	30.91	6.0900	14	1.5%	4.00 [2.65; 5.35]
Kim et al. #13 (2022)	62.39	3.0800	14	34.80	8.8500	14	1.5%	4.04 [2.68; 5.40]
Moon et al. #4 (2022)	40.41	1.2500	10	26.17	4.4900	10	1.4%	4.14 [2.47; 5.81]
Moon et al. #2 (2022)	40.41	1.2500	10	15.89	5.8100	10	1.3%	5.59 [3.48; 7.70]
Lerner et al. #1 (2021)	22.80	1.6000	10	15.60	0.6000	10	1.3%	5.71 [3.56; 7.85]
Lerner et al. #2 (2021)	38.90	2.4000	10	22.50	2.8000	10	1.2%	6.02 [3.77; 8.27]
Kim et al. #9 (2022)	62.39	3.0800	14	30.91	6.0900	14	1.3%	6.33 [4.40; 8.26]
Lerner et al. #3 (2021)	33.20	1.0000	10	20.50	2.2000	10	1.1%	7.12 [4.52; 9.72]
Total (95% CI)			**628**			**668**	**100.0%**	**0.69 [0.20; 1.18]**

Heterogeneity: $Tau^2=3.6645$; $Chi^2=552.76$, df=64 (*P*<.001); $I^2=88\%$

Std. Mean Difference IV, Random, 95% CI

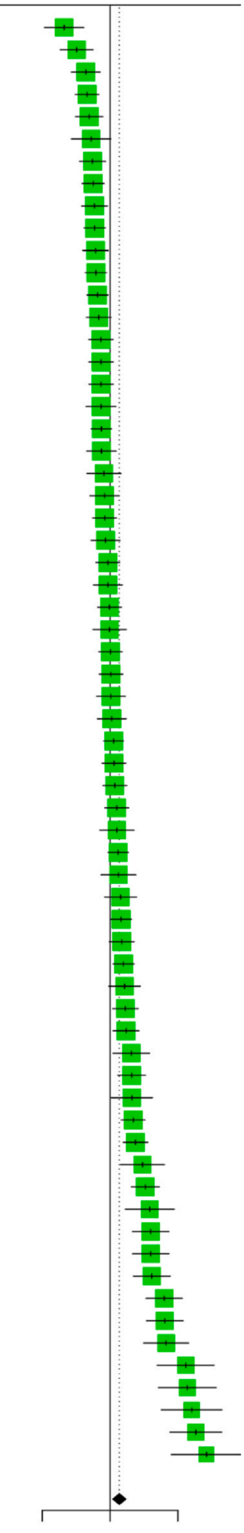

Figure 5. Forest plot comparing trueness outcome between additively manufactured and subtractively manufactured restorations.

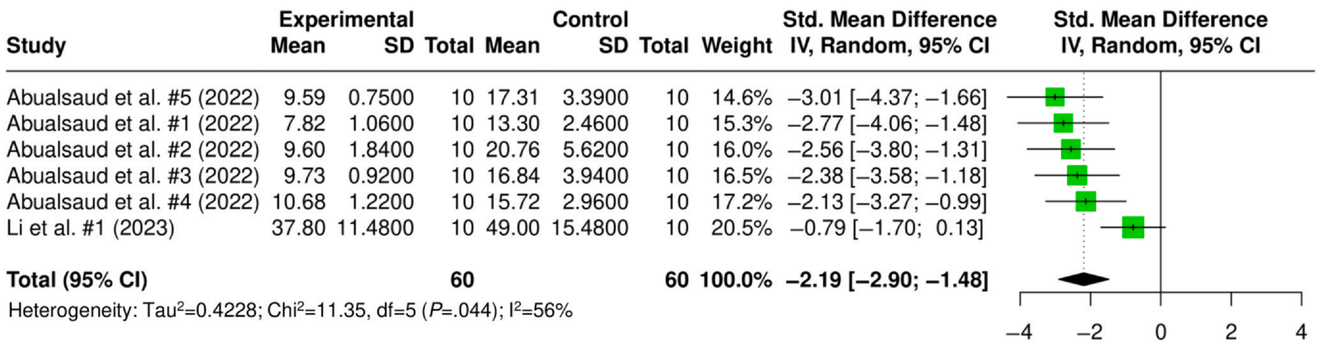

Figure 6. Forest plot comparing precision outcome between additively manufactured and subtractively manufactured restorations.

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.

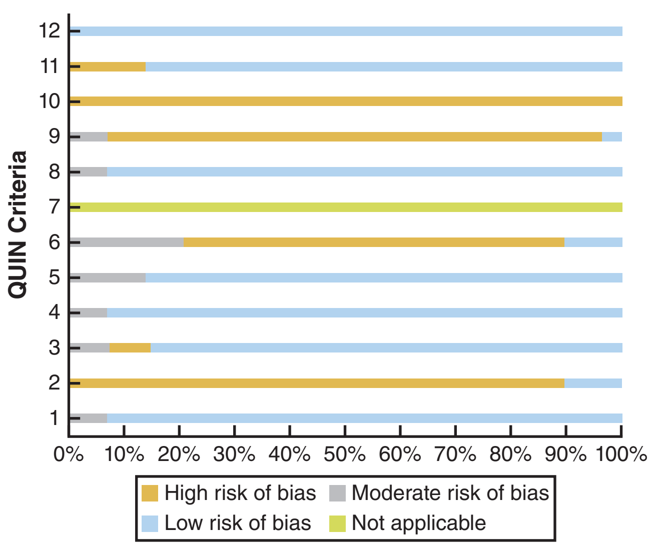

Figure 7. Risk of bias assessment based on Quality Assessment Tool For In Vitro Studies.

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 axiogingival 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 study[57] 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.

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