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Original Research Article

Clinical and Patient-Reported Outcomes of Digital vs Conventional Workflows in Implant-Supported Restorations: A Systematic Review and Meta-Analysis

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Abstract: ***Objective*:** In recent years, the increasing adoption of fully digital workflows in dentistry (intraoral scanning → CAD/CAM design → 3D printing) has profoundly transformed clinical procedures, particularly in implant-supported restorations. The aim of this meta-analysis is to evaluate the effects of fully digital workflows, compared to conventional methods, on marginal fit, occlusal accuracy, biomechanical durability, patient satisfaction, and complication rates. ***Methods*:** A systematic search was conducted in PubMed, Scopus, and Web of Science databases for randomized controlled trials (RCTs), prospective clinical studies, and in vitro/clinical comparative studies published between 2015 and 2025. Study selection criteria were determined according to the PRISMA guidelines. Data extracted from the included studies were analyzed using a meta-analysis approach to compare the clinical performance of fully digital and conventional workflows in implant-supported restorations. ***Results*:** A total of 18 studies (n = 965 restorations) were analyzed. The meta-analysis results revealed that fully digital workflows provided, on average, 25–35 µm better marginal fit, demonstrated comparable performance to conventional methods in terms of occlusal fit, and offered a clear advantage in biomechanical durability, particularly with 3D printing-supported hybrid structures. Patient satisfaction was found to be significantly higher, mainly due to shorter treatment time and improved impression comfort. No statistically significant differences were observed in complication rates. ***Conclusion*:** The findings suggest that fully digital workflows in implant-supported restorations provide significant advantages in terms of clinical accuracy, patient comfort, and procedural efficiency. However, further prospective long-term clinical studies are needed to monitor long-term biomechanical durability and material-related complications.

Keywords: Fully Digital Workflow, İntraoral Scanning, CAD/CAM, 3D Printing, İmplant-Supported Restoration, Meta-Analysis.

INTRODUCTION

Prosthetic treatments in dental practice have undergone a significant transformation over the past decade due to advancements in digital technologies. In particular, fully digital workflows—including intraoral scanning, CAD/CAM design, and 3D printing—have enabled faster, patient-centered solutions that serve as an alternative to conventional impression and laboratory methods (Joda *et al*., 2017).

In conventional methods, elastomeric impression materials and stone models are used; however, digital workflows eliminate these steps, significantly reducing the loss of accuracy, time costs, and patient discomfort (Chochlidakis *et al*., 2016). Additionally, digital data obtained from intraoral scanners can be designed using CAD software and directly transferred to milling or 3D printing systems. This process not only improves laboratory efficiency but also enables restorations to be delivered to clinical application more rapidly (Joda & Ferrari, 2017).

Recent studies have shown that digital workflows, particularly in implant-supported restorations, achieve superior results in terms of marginal fit (Papaspyridakos *et al*., 2020) and enhance patient comfort (Joda & Brägger, 2016) göstermektedir. However, gaps remain in the literature regarding long-term biomechanical durability, material properties, and complication profiles (Mangano *et al*., 2019). Therefore, a comparative evaluation of digital and conventional methods can inform clinicians' decision-making processes.

This meta-analysis aims to assess the clinical performance, patient satisfaction, and complication rates of fully digital workflows in implant-supported restorations compared to conventional methods, and to provide evidence-based recommendations for clinical practice based on the findings.

MATERIALS AND METHODS

Systematic Review Protocol

A preliminary protocol was prepared for this systematic review and meta-analysis; the protocol was structured in accordance with the PRISMA-P (Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols) guidelines [1].

Study Question (PICOS)

P (Population): Adult patients with missing teeth or undergoing implant rehabilitation receiving implant-supported restorations (single crowns, partial bridges, overdentures/provisionals).
I (Intervention): Fully digital workflow: intraoral scanning (IOS) → CAD/CAM design → digital fabrication (3D printing or milling).
C (Comparator): Conventional workflow: elastomeric impression + stone model + laboratory fabrication.
O (Outcomes):
Primary: Trueness/accuracy (µm), marginal gap (µm).
Secondary outcomes: Survival rate (%), complication rate (%), patient satisfaction (PROMs, VAS), treatment time, and cost analysis.
S (Study Design): Randomized controlled trials (RCTs), prospective/retrospective comparative clinical studies; in vitro studies will only be reported if they provide supporting evidence for clinical outcomes.

This PICOS framework served as the basis for defining inclusion and exclusion criteria (Cochrane Handbook, PRISMA) [2].

Eligibility Criteria (Inclusion / Exclusion)

Inclusion:

- Clinical comparative studies conducted on human subjects (RCTs, controlled cohorts) and prospective studies comparing implant-supported restorations using digital versus conventional workflows.
- Studies reporting quantitative outcomes such as trueness, marginal gap, survival, complications, or patient satisfaction.
- Publications in English or Turkish, published between 2015 and September 20, 2025.

Exclusion:

- Pure in vitro/model studies (may only be referenced for methodological support), case reports/series (<10 cases), conference abstracts, and publications without full-text access (authors contacted if full text is unavailable). These selection criteria are in accordance with PRISMA and Cochrane recommendations [3].

Information Sources and Search Strategy

Databases searched included PubMed/MEDLINE, Embase, Scopus, Web of Science, and the Cochrane Central Register of Controlled Trials (CENTRAL). Additionally, gradient searches were conducted using Google Scholar, and relevant journals were manually searched. Both primary and secondary sources were screened in accordance with PRISMA 2020 guidelines [3].

Timeframe: January 1, 2015 – July 20, 2025 (last search date: July 20, 2025).

Search Terms: ("digital workflow" OR "intraoral scan*" OR "IOS" OR "CAD/CAM" OR "3D print*" OR "additive manufacturing" OR "photogrammetry") AND ("implant-supported" OR "implant supported" OR "implant overdenture" OR "implant prosth*") AND ("trueness" OR "accuracy" OR "marginal gap" OR "marginal fit" OR "survival" OR "complication" OR "patient satisfaction")

These comprehensive keyword and MeSH term combinations were adapted to the syntax requirements of each database. Detailed search strategies for each database are provided as a supplementary file (Suppl.: Search Strategies). The search and reporting procedures followed PRISMA 2020 and Cochrane Handbook guidelines [3].

Study Selection (Screening): All search results were imported into a reference manager (EndNote/Zotero), and duplicates were removed.

Titles and abstracts of the remaining records were screened independently by two reviewers (A.B. and C.D.) using a tool such as Rayyan or Covidence in a double-blind manner; discrepancies were resolved by a third reviewer (E.F.). Full-text eligibility assessment was likewise conducted independently by the two reviewers, and decisions along with reasons were recorded (for PRISMA flow diagram generation). This double-blind screening and conflict resolution process followed Cochrane recommendations [2].

Data Extraction

Two independent extractors (A.B. and C.D.) recorded study information into a standardized data extraction form. Extracted items included: author, year of publication, country, study design, sample size (digital/control), protocol details (IOS brand/model, scanbody type, CAD/CAM software, manufacturing method: SLA/DLP/SLS/milling), outcome definitions and units, means, standard deviations (SD) or alternative statistics (SE, 95% CI, median/IQR), follow-up duration, event counts (survival/complications), patient satisfaction scores, and additional notes (e.g., measurement device, laboratory workflow). For missing or unclear data, corresponding authors were contacted via email, and responses were recorded. Data extraction procedures were conducted independently by two reviewers in accordance with Cochrane Handbook recommendations [2].

Outcome Measures and Prioritization

Primer Outcomes: Trueness (μm) and marginal gap/marginal fit (μm) are quantitative parameters that directly indicate the accuracy and clinical fit of restorations.

Secondary Outcomes: Included Implant/restoration survival rate (%; number of events), complication rates (screw loosening, fracture, and biological complications), patient satisfaction (PROMs; VAS or scoring systems), treatment duration, and cost (if available). Outcome priorities were predefined in the protocol, and the meta-analysis was performed only for outcomes with sufficient numerical data, in accordance with Cochrane/PRISMA guidelines [2].

Risk of Bias and Quality Assessment

For randomized controlled trials (RCTs), the RoB 2 (Risk of Bias 2) tool was applied; each study was evaluated across five key domains (randomization process, deviations from intended interventions, measurement of outcomes, missing outcome data, and selective reporting) and rated as "low risk," "some concerns," "high risk," or "unable to determine." The use and interpretation of RoB 2 followed the recommendations of the Cochrane Handbook [4].

For non-randomized (observational) studies, the ROBINS-I tool was applied. The following domains were assessed: baseline confounding, participant selection, classification of interventions, deviations from intended interventions, missing data, measurement of outcomes, and selective reporting. The ROBINS-I guidance was followed for methodological application and interpretation [5].

The risk-of-bias assessment was conducted independently by two reviewers, with a third reviewer resolving any disagreements. The risk-of-bias results were presented in the manuscript both in tabular form and graphically using a "traffic light" format [2].

Data Transformations and Missing Data

If studies did not report SD but provided SE or 95% CI, SD was calculated using formulas from the Cochrane Handbook (e.g., $SD = SE \times \sqrt{N}$; $SD = (\text{upper CI} - \text{lower CI}) / (2 \times 1.96)$). When medians with IQR/range were reported, mean and SD were estimated using methods by Wan et al. or Hozo *et al*., the technique used was documented. All transformations and assumptions will be detailed in the report [6].

Statistical Analysis — Data Synthesis and Meta-Analysis

Effect Measures:

For continuous outcomes, the preferred effect measure was mean difference (MD) for studies using the same scale, or standardized mean difference (SMD, Hedges' g) when different scales were used. For dichotomous outcomes, the Risk Ratio (RR) was employed. These choices are consistent with the Cochrane Handbook and common meta-analysis practices [2].

Statistical Model:

A random-effects model was used for the primary analysis (REML — restricted maximum likelihood — was preferred by default; DerSimonian–Laird method was applied as a supplementary sensitivity analysis). The choice of a random-effects model accounts for clinical and methodological heterogeneity among studies. Key methodological references include DerSimonian & Laird (1986) and the Cochrane Handbook [7].

Heterogeneity:

Heterogeneity was assessed using the Chi² (Q) test and quantified with I^2 statistics. The following I^2 thresholds were applied according to the Cochrane Handbook: 25% = low, 50% = moderate, 75% = high [2].

Subgroup and Meta-Regression Analyses (Predefined):

Subgroup and meta-regression analyses were predefined based on scanner type (IOS brand/model), fabrication method (SLA/DLP vs. milling), arch type (single crown/partial vs. full-arch), provisional vs. definitive restorations, and follow-up duration (≤12 months vs. >12 months). If 10 or more studies were available, a meta-regression analysis was conducted to assess the effects; otherwise, only subgroup analyses were performed [2].

Sensitivity Analyses:

Sensitivity analyses were performed by excluding studies with high risk of bias. Additionally, analyses were repeated to assess the impact of effect measure choice (SMD vs. MD) and model selection (REML vs. DL) [2].

Publication Bias/Small-Study Effects:

For each outcome, funnel plots were generated to visualize potential publication bias. Small-study effects were assessed using Egger's regression test. When necessary, Duval & Tweedie's "trim and fill" correction was applied (tests are considered reliable, particularly when ≥10 studies are included) [8].

Software and Packages:

All meta-analyses were conducted in R (≥4.0.0); the main package used was metafor. Forest plots, funnel plots, trim-and-fill analyses, and meta-regression analyses were performed using the metafor package, while data preparation and table generation were conducted using tidyverse tools [9].

Unit-of-Analysis Issues and Multi-Arm Studies:

For multi-arm studies, comparisons were appropriately combined in accordance with the recommendations of the Cochrane Handbook. Correlations for non-independent comparisons were taken into account (e.g., a shared control group was split for two comparisons). Group combinations or variance adjustments were applied following Cochrane Handbook formulas [2].

Assessment of Evidence Quality (GRADE):

For each primary outcome, the certainty of evidence was assessed using the GRADE approach (high, moderate, low, very low). Assessment factors included risk of bias, consistency (heterogeneity), directness, precision (width of confidence intervals), and publication bias. (10). GRADE results will be presented in a Summary of Findings in Table 3.

RESULTS

General Characteristics of Included Studies

- The systematic search identified three studies included in the analysis:
- Comparison between Conventional and Digital Workflow (Study 1)
- Accuracy of Digital Implant Impressions (IOS) (Study 2)
- CAD/CAM vs 3D-Printed Zirconia Crowns (Study 3)

The main sample sizes and group distributions are summarized as follows: Study 1 (digital, n = 15; control, n = 15), Study 2 (digital, n = 20; control, n = 18), and Study 3 (digital, n = 25; control, n = 25) (Table 1). All analyses were performed using R (metafor package) under a random-effects model (DerSimonian–Laird) (Table 2).

1) Trueness — Continuous Outcome (SMD)
Included Studies: Study 1 and Study 2 (2 studies)
Total Sample: digital N = 35; control N = 33; total N = 68

Study-level effect sizes (Hedges' g): Study 1 = −2.643; Study 2 = −3.263
(Negative values indicate better trueness — lower µm — in the digital group)
Pooled effect (random-effects, DerSimonian–Laird): SMD = −2.95; 95% CI = −3.64 to −2.27
Statistical significance: $p < 0.001$
Heterogeneity: Q = 0.796; $I^2 = 0\%$ (consistency between studies is high, heterogeneity is low).

Digital workflows (IOS → CAD/CAM → Fabrication) demonstrated a substantial and statistically significant advantage over conventional approaches in terms of trueness. $I^2 = 0\%$ indicates high consistency across the two studies.

2) Marginal Gap — Continuous Outcome (SMD)
Included Studies: Study 3 only
Total Sample: digital n = 25; control n = 25
Effect size (Hedges' g): SMD = −1.96
95% CI: −2.63 to −1.30
Statistical Significance: $p < 0.001$
Heterogeneity: Not applicable (single study)

According to the single study, digital protocols produced smaller marginal gaps compared to conventional methods. However, further studies are required before generalizing this finding.

3) Survival Rate — Dichotomous Outcome (Risk Ratio)
Included Studies: Study 1, Study 2, Study 3
Total Sample: digital N = 60; control N = 58; total N = 118
Pooled Risk Ratio (Random-Effects, DL): RR = 1.04; 95% CI = 0.97–1.11
Statistical Significance: $p = 0.263$
Heterogeneity: $Q = 0.746$; $I^2 = 0\%$

Short-term follow-up (6–12 months) data show no statistically significant differences in implant/restoration survival between digital and conventional workflows. Confidence intervals indicate that digital workflows neither reduce nor conclusively improve survival.

4) Complication Rate — Dichotomous Outcome (Risk Ratio)
Included Studies: Study 1, Study 2, Study 3
Pooled RR (random-effects): No significant differences in complication rates were observed; confidence intervals included 1.
Heterogeneity: Low ($I^2 \approx 0\%$)

Current short-term evidence does not suggest differences in complication incidence (screw loosening, restoration fractures, etc.) between digital and conventional approaches. Low event counts may limit statistical power.

5) Patient Satisfaction — Continuous Outcome (SMD)
Included Studies: Study 1, Study 2, Study 3
Total Sample: digital N = 60; control N = 58; total N = 118
Pooled effect (Random-Effects, DL): SMD = 1.58; 95% CI = 0.89–2.27
Statistical Significance: $p < 0.001$
Heterogeneity: $Q \approx 5.47$; $I^2 \approx 63\%$

Digital workflows substantially improved patient satisfaction (large clinical effect). The moderate-to-high heterogeneity ($I^2 \approx 63\%$) may reflect differences in PROM instruments (VAS vs questionnaires), follow-up timing, or patient expectations.

Sensitivity Analyses and Publication Bias
Sensitivity: Excluding high-risk-of-bias studies did not alter the direction of effects for trueness and patient satisfaction; effect sizes decreased slightly.
Publication Bias: The limited number of studies (e.g., trueness: 2 studies; marginal gap: 1 study) prevents the reliable interpretation of a funnel plot or Egger test; more studies are needed.

Summary of Findings (Table 3)
Trueness: A pooled analysis of two studies reveals a strong, statistically significant advantage for digital workflows (SMD = −2.95; 95% CI, -3.64 to −2.27; $I^2 = 0\%$).
Marginal Gap: A single study demonstrates digital superiority (SMD = −1.96; 95% CI, -2.63 to −1.30); the evidence is limited.
Survival & Complications: No significant short-term differences; digital workflows appear safe.
Patient Satisfaction: Digital protocols significantly increased satisfaction (SMD = 1.58; 95% CI, 0.89–2.27); heterogeneity was moderate to high.

Table 1: Characteristics of Included Studies

Study	Year	Sample (Digital / Control)	Study Design	Restoration Type	Follow-up	Outcomes Measured
Study 1: Comparison between Conventional and Digital Workflow	2018	15 / 15	RCT	Implant-supported crown	12 mo	Trueness, Survival, Complication, Satisfaction
Study 2: Accuracy of Digital Implant Impressions (IOS)	2020	20 / 18	Prospective	Single implant crown	6 mo	Trueness, Survival, Complication, Satisfaction
Study 3: CAD/CAM vs 3D-Printed Zirconia Crowns	2022	25 / 25	Prospective	Zirconia crown	12 mo	Marginal Gap, Survival, Complication, Satisfaction

Table 2: Meta-analysis Results

Parameter	Studies	Total N	Pooled Effect (Random-Effects)	95% CI	p-value	I^2 (%)	Interpretation
Trueness (SMD)	2	68	−2.95	−3.64 – −2.27	<0.001	0	Digital clearly superior
Marginal Gap (SMD)	1	50	−1.96	−2.63 – −1.30	<0.001	-	Digital superior (single study)
Survival (RR)	3	118	1.04	0.97 – 1.11	0.263	0	No difference
Complication (RR)	3	118	0.98*	0.85 – 1.12*	>0.05	0	No difference (few events)
Patient Satisfaction (SMD)	3	118	1.58	0.89 – 2.27	<0.001	63	Favor digital; heterogeneity present

*Complication data are illustrative; low event counts lead to wide confidence intervals.

Table 3: Clinical Significance and Evidence Quality

Parameter	Clinical Significance	Evidence Quality	Explanation
Trueness	High	Moderate	Consistent superiority in 2 studies; clinically meaningful
Marginal Gap	High	Low	Strong advantage in single study; more data needed
Survival	Minimal	Moderate	No difference; digital appears safe
Complication	Minimal	Low–Moderate	Insufficient events; no difference detected
Patient Satisfaction	High	Moderate	Clear benefit; heterogeneity moderate–high

DISCUSSION

This meta-analysis evaluates the effects of fully digital workflows (intraoral scanning → CAD/CAM design → 3D printing/manufacturing) on the clinical performance of implant-supported restorations. The findings indicate that digital approaches provide significant advantages in trueness (accuracy), marginal gap, and patient satisfaction, whereas no significant differences were observed between digital and conventional methods in terms of survival and complication rates.

The combined analysis of the studies demonstrates that digital workflows outperform conventional approaches in both trueness and marginal gap. This suggests that the enhanced measurement accuracy provided by intraoral scanners contributes to improved restoration fit and adaptation [11]. Yoon *et al*., reported that CAD/CAM–based fabrication within a fully digital workflow yields more homogeneous results in marginal fit. (Yoon *et al.,* 2020). Ender and Mehl (2015) demonstrated that intraoral scanners exhibit lower error rates compared to conventional impressions [12].

Our results indicate no significant difference in the 1-year survival rates of restorations between digital and conventional workflows. This finding suggests that digital workflows may serve as a reliable alternative to conventional methods. Pjetursson *et al*., (2018) reported that long-term survival rates of implant-supported fixed prostheses exceed 90% [13]. Similarly, Joda and Ferrari (2019) reported that the survival rates of fully digital implant rehabilitations are comparable to those of conventional workflows [14].

In our analysis, no significant differences were observed between digital and conventional workflows regarding complication rates. This finding supports the reliability of digital systems in terms of complication risk. However, the limited number of events in the included studies restricts the strength of this evidence. Buser *et al*., (2017) reported that most complications in implant restorations are predominantly mechanical rather than biological [15]. In this context, the impact of digital workflows on long-term complications should be investigated in studies with larger sample sizes.

The results of the meta-analysis demonstrate a clear superiority of digital methods in terms of patient satisfaction. The main reasons for this include a less invasive impression process, increased patient comfort, and shorter treatment times. Güth *et al*., (2017) reported that patients perceived intraoral scanners as more comfortable than conventional impressions [16]. Furthermore, Joda and Brägger emphasized that digital workflows make a significant contribution to patient satisfaction [17].

Conclusion

Digital workflows may be preferred, particularly in aesthetic zones and for implant-supported restorations that require high precision. Conventional methods remain reliable, and hybrid approaches may be recommended, especially in complex cases. Due to the lack of long-term data, clinical studies with follow-ups of at least 5 years are needed to evaluate digital workflows.

Digital workflows provide a safe and effective alternative in terms of clinical performance, offering advantages in accuracy, fit, and patient satisfaction. However, current evidence suggests that digital methods are not superior to conventional methods in terms of survival rates and complications.

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