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SYSTEMATIC REVIEW

Impact of operator experience on intraoral digital scanning: A systematic review, meta-analysis, and meta-regression. *Report of the Committee on Research in Fixed Prosthodontics of the American Academy of Fixed Prosthodontics*

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ABSTRACT

Statement of problem. How much operator experience influences intraoral digital scanning outcomes is unclear, as previous studies have shown inconsistent results.

Purpose. The purpose of this systematic review, meta-analysis, and meta-regression was to answer the following 2 complementary research questions based on the population, intervention, comparison, outcomes, and study design (PICOS) framework: in intraoral scanning of dentate, partially edentulous, or completely edentulous patients, with or without dental implants, can differences be found between inexperienced and experienced operators, and can differences be found before and after receiving training sessions when assessing accuracy in in vitro studies, as well as in scanning time and patient satisfaction in randomized and nonrandomized controlled clinical trials (CCTs)?

Material and methods. Three databases (Embase, Medline, and The Cochrane Library) were systematically searched from their inception to March 2025 to identify studies addressing the PICOS questions. Risk of bias (RoB) was assessed using the ROB 2.0, ROBINS-I, and QUIN tools. The primary outcome measure was scanning trueness. Secondary outcomes included precision, scanning time, and patient satisfaction. Data were pooled and analyzed using mean differences (MDs) and prediction intervals (PIs) when significant heterogeneity was observed ($P<.05$). Subgroup analyses were conducted, when possible, based on clinical situation (dentate, partial edentulous, edentulous, single implant, 2 implants, and complete arch implant-supported prostheses), scan extension (sextant, half or complete arch impression), outcome measurement (root mean square, linear and angular deviation), and operator experience. A meta-regression was performed on the year of the scanner's market release, intraoral scanner (IOS), clinical situation, arch (maxilla and mandible), and outcome measurement to explore sources of heterogeneity. The certainty of the evidence (CE) was assessed using the GRADE system.

Results. Inexperienced operators showed lower trueness (MD 2.51 µm [95% CI:.16 to 4.86]; P=.04; 8 in vitro studies; 720 scans on casts; CE: low), no difference in precision (MD −1.23 µm [95% CI: −4.97 to 2.50]; P=.52; 3 in vitro studies; 280 scans on casts; CE: low), longer scanning time (MD 40.95 seconds [95% CI: 17.10 to 64.80]; P<.001; 3 controlled clinical trials; 180 scans on patients; CE: low), and provided less patient satisfaction (visual analog scale: MD −12.69% [95% CI: −20.96 to −4.42]; P<.001; 1 controlled clinical trial; 40 scans on patients; CE: very low) compared with experienced operator. After training, operators showed better trueness (MD −19.22 µm [95% CI: −26.29 to −12.15]; P<.001; 2 in vitro studies; 120 scans on casts; CE: low), no change in precision (MD 0.34 µm [95% CI: −1.26 to 1.93]; P=.68; 1 in vitro study; 40 scans on casts; CE: very low), and faster scanning times (MD −76.46 seconds [95% CI: −122.16 to −30.76]; P<.001; 2 controlled clinical trials; 298 scans on patients; CE: low). The improvement in scanning time after training was greater in inexperienced operators compared with experienced ones (P<.05).

Conclusions. Operator inexperience may minimally compromise scan accuracy, potentially increase scanning time and reducing patient satisfaction. Training sessions were associated with improved accuracy and efficiency in intraoral scanning. (J Prosthet Dent 2026;135:297.e1-e13)

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Clinical Implications

Training in intraoral scanning, combining theoretical knowledge and hands-on practice, might enhance scan accuracy and reduce scanning time. Clinical experience additionally reinforces these improvements and supports greater patient satisfaction.

Impression-making is an essential step to ensuring prosthodontic treatment success.[1] Over the past decade, there has been a progressive adoption of intraoral scanners (IOS) in clinical settings,[2] accompanied by an increasing diversity of scanners available on the market. Focal distance, scanning speed, scanner head size, and handle ergonomics differ significantly across manufacturers and devices, presenting a learning curve even for experienced operators to adapt to the features of each device.[3] The accuracy of IOS varies depending on operator- and patient-related factors.[4]

A recent review has identified the operator's prior experience with IOSs as a factor that may influence scanning accuracy, with inconsistent results.[4] While some studies have reported no significant differences,[5–8] others have suggested that greater operator experience correlated with higher scanning accuracy across different clinical situations.[9–13] Furthermore, it remains unclear whether this relationship is less pronounced when using recently introduced IOSs.

Becoming proficient with IOSs is typically a result of repeated clinical use. In addition, completing theoretical and hands-on training sessions may deepen the clinician's understanding of the factors affecting scanning accuracy, the integrated software tools, and the maneuvers that improve patient comfort, ultimately elevating the quality of the clinical care delivered.[14–18] Nonetheless, the extent to which training improves scanning outcomes in both novice and experienced users remains uncertain.

Therefore, the present study aimed to systematically review the literature to answer the following 2 aligned and complementary research questions based on the population, intervention, comparison, outcomes, and study design (PICOS) framework. PICOS #1: in intraoral scanning of dentate, partially edentulous, or completely edentulous patients, with or without dental implants, can differences be found between inexperienced and experienced operators when assessing accuracy in the in vitro studies, as well as in scanning time and patient satisfaction in randomized and nonrandomized controlled clinical trials (CCTs)? PICOS #2: in intraoral scanning of dentate, partially edentulous, or completely edentulous patients, with or without dental implants, can differences be found before and after receiving training sessions when assessing accuracy in the in vitro studies, as well as in scanning time and patient satisfaction in randomized and nonrandomized controlled clinical trials (CCTs)?

MATERIAL AND METHODS

This systematic review was conducted by following the 2020 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) reporting guidelines[13] and was based on a protocol registered before its initiation on the PROSPERO international registry platform (CRD42025649866). The impact of operator experience on intraoral scanning (PICO #1) was evaluated by comparing inexperienced and experienced operators across 3 outcome domains: accuracy (assessed through trueness and precision), efficiency (assessed through scanning time), and patient-reported outcomes (assessed through patient satisfaction). Operators were classified as experienced if they had a minimum of 1 year of intraoral scanning experience, whereas those with less than 1 month of experience were classified as inexperienced. The effect of training sessions on intraoral scanning (PICO #2) was assessed by comparing outcomes before and after training across 2 domains: accuracy (assessed through trueness and precision) and efficiency (assessed through scanning time).

This systematic review prioritized the inclusion of clinical studies (randomized and nonrandomized controlled) to assess scanning-related outcomes such as scanning time and patient satisfaction. However, for accuracy-related outcomes (trueness and precision), the inclusion of in vitro studies was considered more appropriate, as they enable the use of valid reference scans obtained through coordinate measuring machines (CMMs), industrial scanners, or high-accuracy desktop scanners. Clinical studies, by contrast, often used conventional impressions as reference scans, which offered insufficient accuracy for this purpose, increasing the risk of biased measurements and compromising their validity for accuracy assessment. Studies with alternative designs or those of the same design that did not report the specific outcomes outlined in the PICOS framework were excluded.

Three databases (Embase, PubMed/Medline, and Cochrane) were systematically searched from their inception to March 2025 without language restrictions. The search was complemented by a manual search of the reference lists of included publications and related review articles and the inclusion of nonpeer-reviewed literature through ongoing trial databases, including the International Clinical Trials Registry Platform (ICTRP) and ClinicalTrials.gov. Search strategies for all databases are detailed in Supplemental Table 1 (available online).

Two investigators (A.L., A.S.) independently screened all titles and abstracts, retrieving the full text of any potentially eligible reference. The same investigators evaluated the full-text articles against the eligibility criteria. Any disagreements were resolved through consultation with a third reviewer (D.M.). Reasons for exclusion during full-text screening are reported in Supplemental Table 2, available online. The inter-reviewer reliability (percentage of agreement and kappa correlation coefficient) of the full-text analysis was calculated. The same 2 investigators independently extracted the data and assessed the risk of bias (RoB) in the included studies using the ROB 2.0,[14] ROBINS-I v2,[15] and QUIN[16] tools employing predesigned sheets that were subsequently cross-checked for consistency.

Statistical analysis was performed using a software program (Stata, v.18; StataCorp LP). Homogeneous studies reporting the same outcome measures were combined in meta-analyses. All outcome measures were treated as continuous variables and analyzed using mean differences (MDs) and standard deviation (SD). When a study investigated multiple modifiers, each was treated as an independent study in the analysis and was assigned a letter (a–f) by following the publication year. The data necessary for inclusion in the analysis were calculated to obtain the mean and SD for the overall estimate. In cases of missing data, the corresponding authors were contacted. The generic inverse-variance method was used for continuous outcomes to calculate MDs. A random-effects model (DerSimonian and Laird) was selected based on the *P* value of the Cochran Q test and the I^2 statistic, with prediction intervals (PIs) applied when significant heterogeneity was detected ($I^2>50\%$).[17] Subgroup analyses were conducted based on the clinical scenario, the scan extension, and the outcome measurements when possible. A random-effects meta-regression analysis was conducted for 5 covariates: year of the scanner's market release, intraoral scanner (IOS), clinical scenario (dentate, partial edentulous, edentulous, single implant-supported, partial implant-supported, and complete arch implant-supported prosthesis), arch (maxilla and mandible), and outcome measurement (RMS, linear, and angular deviation) to study interstudy variability (sources of heterogeneity and confounding). The percentage of heterogeneity explained by each confounder was calculated using the adjusted R^2 of the model. Results of the meta-regression were illustrated using bubble plots. Publication bias was assessed graphically (using funnel plots) and statistically (via the Egger test).[18] Sensitivity analyses were conducted using the leave-one-out method to evaluate the impact of individual studies on the pooled outcomes.[19] The certainty of the evidence was assessed using the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) system based on its 8 domains.[20] The results were presented in a Summary of Findings (SoF) table by following the format proposed by Carrasco Labra et al.[21]

RESULTS

After the title and abstract screening, a total of 17 studies (13 addressing PICO #1 and 4 addressing PICO #2) were included in this systematic review (agreement=96.58%; κ=0.70) and full-text assessment (agreement=93.02%; κ=0.86).[5–12,22–31] Figure 1 depicts the inclusion and exclusion study flow chart. Reasons for full-text exclusions are available in Supplemental Table 2, available online.

The characteristics of the included studies are presented in Table 1. PICOS #1 included 8 in vitro studies and 3 clinical trials conducted in dentate,[7,25,26] partially edentulous,[5,8,10,12,24,26] and edentulous situations.[5,6,8,9,11,12,22,23] Seven studies involved single, partial, or complete arch implant-supported prostheses.[5,6,9,11,12,22,23] Six studies considered 2 or more years of intraoral scanning experience as the threshold for classifying an operator as experienced,[5,6,10–12,26] while 4 studies considered 3 or more years of experience were needed.[9,22–24] Two studies did not report the number of years of experience with an IOS.[7,8] All studies reported that the inexperienced group had less than 1 month of experience using an IOS.

PICOS #2 included 2 in vitro studies and 2 clinical trials in the meta-analysis. All of them were conducted in dentate or partially edentulous situations.[27–31] All included studies indicated that the training in intraoral scanning combined theoretical knowledge and hands-on practice.[27–31] Two studies involved only inexperienced operators,[27,28] 1 study included only experienced operators,[29] and 1 study involved both experienced and inexperienced operators.[30,31]

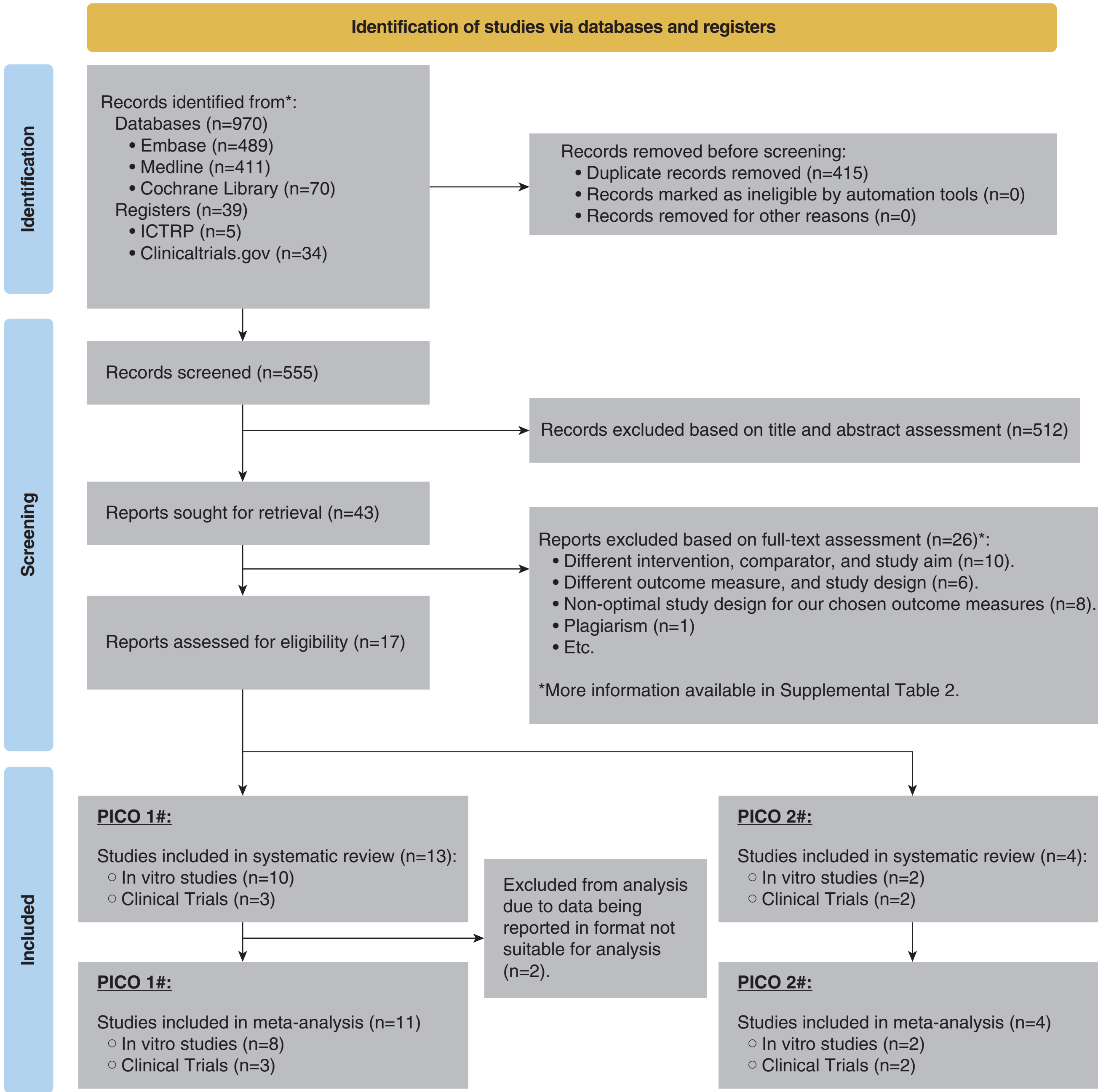

Figure 1. Diagram flowchart.

No included studies reported conflicts of interest, and all were primarily funded by public and academic institutions. Each study design was assessed using the described risk of bias tools without detecting any critical potential bias (Supplemental Tables 3, 4, available online). The summary of findings table for PICOS #1 is presented in Table 2, and the forest plots of the meta-analysis are in Figure 2.

Overall accuracy analysis showed that inexperienced operators had slightly lower trueness (MD 2.51 μm [95% CI:.16 to 4.86]; *P*=.04; 8 in vitro studies; 720 scans on casts; CE: low) (Fig. 2A), with no difference in precision

Table 1. Characteristics of included studies

	Author (s), Year	Study Design	Funding / Support	Operator Experience [in Years of Experience] Intervention (I) Comparator (C)	Outcome Measures Assessed	Included Outcome Measurements	Intraoral Scanner	Clinical Scenario	Impression Extension
PICOS #1	Canullo et al, 2020[1]	In vitro	NR	I: Inexperienced: 0 years C: Experienced: ≥ 2 years	Accuracy	RMS error	CS 3600; Carestream TRIOS 3; 3Shape A/S	Single implant Two implants Complete arch implants	Complete arch
	Ciocca et al, 2018[2]	In vitro	NR	I: Inexperienced: NR C: Experienced: 4 years	Accuracy	Linear inter-implant deviations Linear intra-implant deviations	True Definition; 3M ESPE	Complete arch implants	Complete arch
	Dias Resende et al, 2021[3]	In vitro	NR	I: Inexperienced: 0 years C: Experienced: ≥ 2 years	Accuracy	RMS error	CEREC Omnicam; Dentsply Sirona TRIOS 3; 3Shape	Prepare teeth Partial edentulism	Complete arch
	Giménez et al, 2014[4]	In vitro	Createch Medical Ltd	I: Inexperienced: 0 years C: Experienced: ≥ 2 years	Accuracy	Linear inter-implant deviations	Cadent Itero, Align Technology	Complete arch implants	Complete arch
	Giménez et al, 2015[5]	In vitro	Createch Medical Ltd	I: Inexperienced: 0 years C: Experienced: ≥ 2 years	Accuracy	Linear inter-implant deviations	Lava Chairside; 3M ESPE	Complete arch implants	Complete arch
	Giménez et al, 2017[6]	In vitro	NR	I: Inexperienced: 0 years C: Experienced: ≥ 4 years	Accuracy	Linear and angular inter-implant deviations	True Definition; 3M ESPE	Complete arch implants	Complete arch
	Giuliodori et al, 2023[7]	In vitro	No external funding	I: Inexperienced: 0 years C: Experienced: NR	Accuracy	RMS error	Dexis IS 3700; DITC iTero 5D; Align Technology Medit i700; Medit Corp CEREC Omnicam; Dentsply Sirona Primescan; Dentsply Sirona TRIOS 4; 3Shape	Dentate	Complete arch
	Pesce et al, 2021[8]	In vitro	No external funding	I: Inexperienced: 0 years C: Experienced: ≥ 2 years	Accuracy	RMS error	Opera MC, Opera System Itero, Align Technology	Single implant Two implants Complete arch implants	Complete arch
	Revell et al, 2022[9]	In vitro (ex vivo)	Government funding	I: Inexperienced: 0 years C: Experienced: ≥ 4 years	Accuracy	Linear and angular intra-implant deviations	iTero Element 2; Align Technology Medit i500; Medit Corp Primescan; Dentsply Sirona TRIOS 3; 3Shape TRIOS 4; 3Shape	Complete arch implants	Complete arch
	Schimmel et al, 2021[10]	In vitro	University of Bern	I: Inexperienced: 0 years C: Experienced: NR	Accuracy	RMS error	Primescan; Dentsply Sirona	Partially edentulous Edentulous	Complete arch
	Cheng et al, 2021[11]	RCT (Crosso-ver)	Government funding	I: Inexperienced: ≤ 1 year C: Experienced: ≥ 3 years	Efficiency	Scanning Time	CS 3500; Carestream	Partially edentulous	Sextant
	Thomas et al, 2022[12]	CCT	No external funding	I: Inexperienced: 1 months I: Inexperienced: 3–6 months C: Experienced: ≥ 1 years	Efficiency	Scanning Time	Medit i500; Medit Corp TRIOS 3; 3Shape	Dentate	Complete arch
	Yilmaz et al, 2021[13]	CCT	NR	I: Inexperienced: 0 year C: Experienced: ≥ 2 years	Efficiency PROMs	Scanning Time Patient Satisfaction	TRIOS 3; 3Shape	Dentate Partially edentulous	Complete arch
	Author(s), year	**Study design**	**Funding / Support**	**Training sessions (C: before / I: after) and Level of Experience**	**Outcome measures**	**Outcome measurements**	**Intraoral Scanner**	**Clinical Scenario**	**Impression extension**
PICOS #2	Gao et al, 2023[14]	In vitro	No external funding	Theory and hands-on training sessions for inexperienced operators, delivered over 3 days and 10 scans.	Accuracy	RMS error	TRIOS 3; 3Shape	Dentate	Complete arch
	Waldecker et al, 2021 (Part II)[15]	In vitro	University of Heidelberg	Theory and hands-on training sessions for inexperienced operators, delivered over 3 days and 10 scans.	Accuracy	Linear deviation	CEREC Omnicam; Dentsply Sirona	Partially edentulous	Complete arch
	Kim et al, 2016[16]	CCT	Government funding	Theory and hands-on training session for experienced operators, delivered over 4 days and 10 scans.	Efficiency	Scanning Time	TRIOS 3; 3Shape Cadent Itero, Align Technology	Dentate	Complete arch
	Zarauz et al, 2021 and 2023[17,18]	CCT	Complutense University of Madrid	Theory and hands-on training sessions for experienced and inexperience operators, delivered over 4 days and 20 scans.	Efficiency	Scanning Time	TRIOS 3; 3Shape True Definition; 3M-ESPE	Dentate	Half arch

C, comparator; CCT, controlled clinical trial; I, intervention; NR, not reported; RCT, Randomized controlled trial.

Table 2. Summary of Finding (SoF) table for PICO #1

Population: Digital scans in dentate, partially edentulous, or completely edentulous scenarios.
Intervention: Operators without experience using intraoral scanners.
Control: Operators with verified prior experience using intraoral scanners.
Outcome domains and measures: Accuracy: trueness (primary outcome) and precision; Efficiency: scanning time; and PROMs: patient satisfaction (secondary outcomes).
Study design: In vitro studies to assess accuracy-related outcomes; and randomized or nonrandomized CCTs to evaluate efficiency and PROMs.

Outcome Domain	Outcome Measures Outcome Measurements	№ digital scans (Study design)	Illustrative comparative risks* (95% CI)		Difference (IC 95%) [PI if $I^2 > 50\%$] Rounded Values	Certainty of the evidence (GRADE)	Comments (Interpretation)
			Assumed risk* (With prior experience - Comparator)	Corresponding risk* (Without prior experience - Intervention]			
Accuracy	Trueness [µm]: o RMS error [µm]; o Linear inter-implant deviations [µm]; o Linear intra-implant (Platform) deviations [µm]	720 digital scans in casts (8 in vitro studies)	Mean 43 µm	Mean 46 µm	MD 3 µm (0 a 5) [PI: −9 to 14]	⊕⊕◯◯ LOW[a,b] Because of indirectness, and inconsistency.	Inexperienced operators showed lower trueness compared to experienced operators.
	Precision [µm]: o RMS error [µm]; o Linear inter-implant deviations [µm]; o Linear intra-implant (Platform) deviations [µm]	280 digital scans in casts (3 in vitro studies)	Mean 48 µm	Mean 53 µm	MD −1 µm (−5 a 3) [PI: −11 to 9]	⊕⊕◯◯ LOW[a,b] Because of indirectness, and inconsistency.	Inexperienced operators showed no difference in precision compared to experienced operators.
Efficiency	Scanning time [s]	180 digital scans in patients (3 clinical trials)	Mean 2 min 9 s	Mean 3 min	MD 41 s (17 a 65) [PI: −42 to 241]	⊕⊕◯◯ LOW[b,c] Because of imprecision, and inconsistency.	Inexperienced operators showed longer scanning times compared to experienced operators.
Patient Reported Outcomes (PROMs)	Patient Satisfaction [mm]: [VAS: 1 - 100 mm]	40 digital scans in patients (1 clinical trial)	Mean 86%	Mean 73%	MD −13% (−21 to −4)	⊕◯◯◯ VERY LOW[c] Because of imprecision.	Inexperienced operators provide less comfort to patients compared to experienced operators.

CI, confidence interval; MD, mean difference; PI, prediction interval; PROMSs, patient reported outcome measures; RMS, root mean square; VAS, visual analog scale.
[a] **Indirectness:** Data obtained from in vitro settings rather than clinical settings, where obtaining reference model for comparisons not possible, thus compromising external validity and requiring reduction in certainty of evidence.
[b] **Inconsistency:** Presence of unexplained heterogeneity.
[c] **Imprecision:** Reduced sample size.

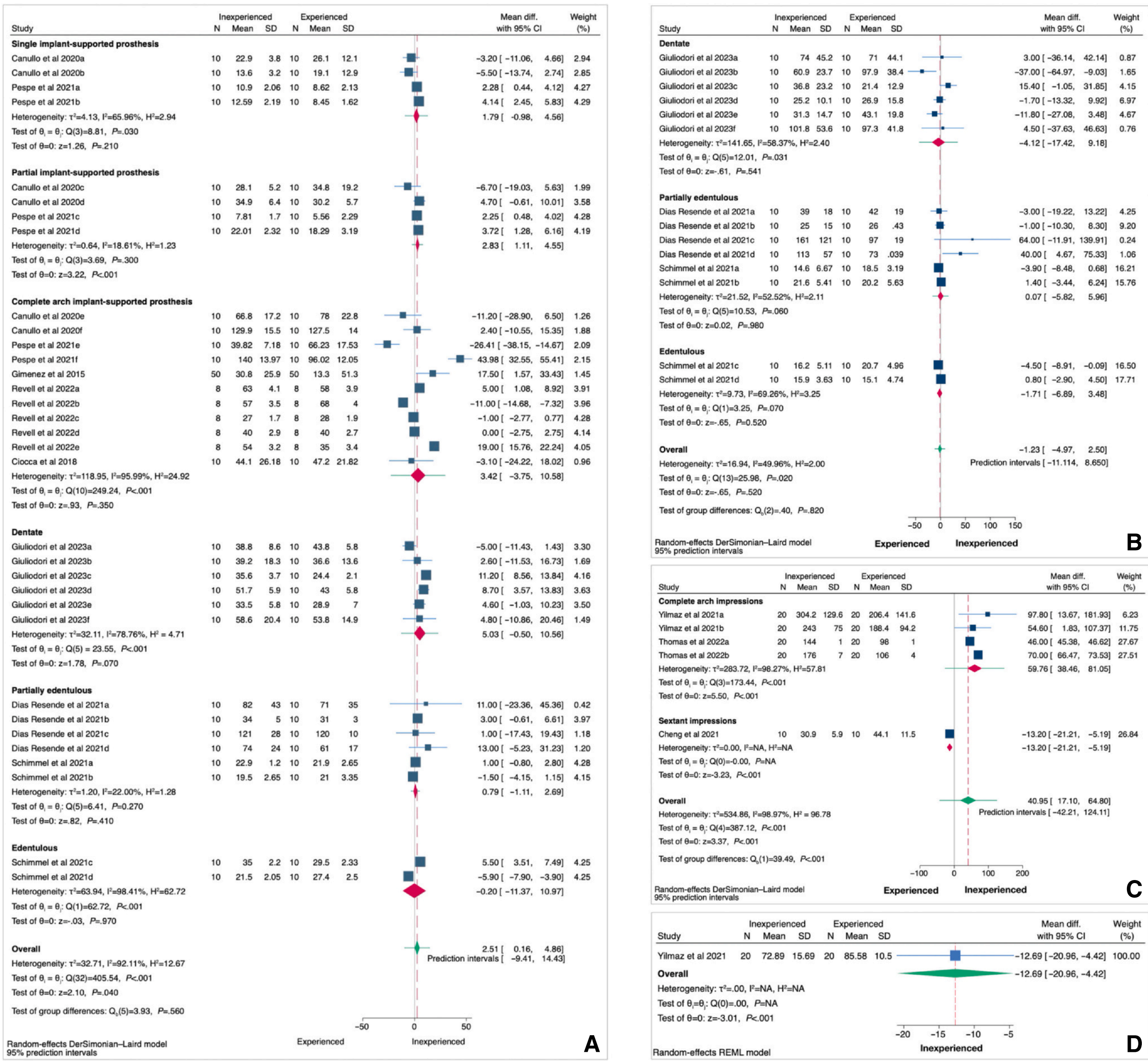

Figure 2. Forest plots of PICOS #1 evaluating impact of operator experience. A, Trueness [µm]: subgroup analysis by clinical scenario. B, Precision [µm]: subgroup analysis by clinical scenario. C, Scanning time [s]: subgroup analysis by impression extension.; D, Patient satisfaction [VAS scale: mm].

(MD −1.23 µm [95% CI: −4.97 to 2.50]; P=.52; 3 in vitro studies; 280 scans on casts; CE: low) (Fig. 2B). Subgroup analyses by clinical scenario consistently showed no statistically significant differences in trueness and precision respectively for dentate (P=.07; P=.54), partial edentulous (P=.41; P=.98), edentulous (P=.97; P=.52), single implant-supported (P=.21; no data), and complete arch implant-supported prosthesis (P=.35; no data), except for the partial implant-supported prosthesis, where inexperienced operators demonstrated lower trueness (MD 2.83 µm [95% CI: 1.11 to 4.55]; P<.001) (Fig. 2A, B). Intersubgroup analysis by clinical scenario was also not significant (P=.56; P=.82) (Fig. 2A, B). Intersubgroup analysis by outcome measurements was also not significant (P=.18; no data) (Supplemental Fig. 1, available online).

The efficiency analysis showed that inexperienced operators required higher scanning time (MD

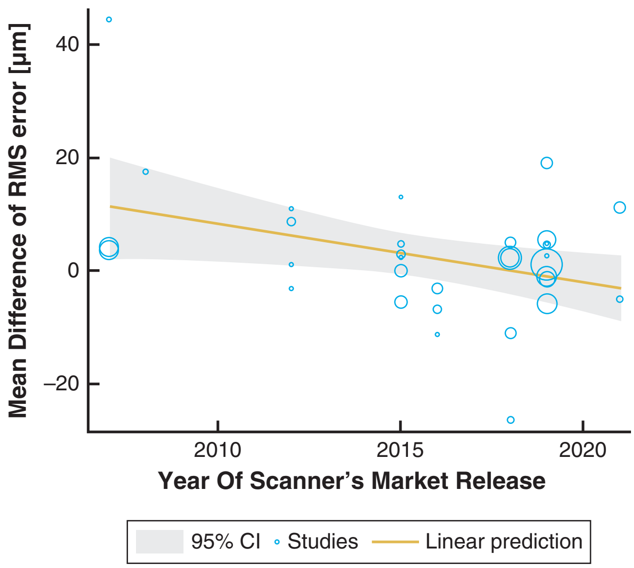

Figure 3. Bubble plot from meta-regression analysis illustrating impact of scanner's market release year on operator experience-related trueness.

40.95 seconds [95% CI: 17.10 to 64.80]; *P*<.001; 3 controlled clinical trials; 180 patient scans; CE: low) compared with experienced operators (Fig. 2C). The PROMs analysis showed that inexperienced operators provided less patient satisfaction (visual analog scale [VAS]: MD −12.69% [95% CI: −20.96 to −4.42]; *P*=.68; 1 controlled clinical trial; 40 scans on patients; CE: very low) compared with experienced operators (Fig. 2D).

Because of the limited number of included studies, meta-regression, heterogeneity analysis, publication bias assessment, and sensitivity analysis were conducted only for the primary outcome (trueness) of PICOS #1. The meta-regression analysis assessed sources of heterogeneity and the potential influence of several confounding factors on the comparison between inexperienced and experienced operators (Table 4), such as the year of scanner's market release, IOS, clinical scenario, arch, and outcome measurement. None of these variables demonstrated a statistically significant effect, except for arch type (maxillary versus mandibular; *P*=.045) and the scanner's market release year (*P*=.026). The scanner's market release showed a statistically significant negative association (coefficient β=−1.01), indicating that more recent IOSs were associated with a smaller difference between inexperienced and experienced operators in trueness, potentially explaining part of the observed heterogeneity in this analysis (Fig. 3).

Heterogeneity was further evaluated visually using a Galbraith plot (Supplemental Fig. 2, available online) to identify specific sources of variability. These studies differed methodologically by specifically focusing on complete arch implant scans, as opposed to the dentate or partially edentulous situations typically examined in other studies. Furthermore, Revell et al[23] used an ex vivo design with a fresh cadaver head. These methodological differences are likely additional factors contributing to the observed heterogeneity.

No publication bias was detected, as assessed statistically (via Egger test: *P*=.836) and visually through funnel plot symmetry (Supplemental Fig. 3, available online). The sensitivity analysis using the leave-one-out method demonstrated that no single study disproportionately influenced the overall results (Supplemental Fig. 4, available online).

The summary of findings for PICOS #2 is presented in Table 3, and the forest plots of the meta-analysis are in Figure 4. Training also significantly improved trueness (MD −19.22 µm [95% CI: −26.29 to −12.15]; 2 in vitro studies; 120 scans on casts; CE: low) (Fig. 4A), did not affect precision (MD.34 µm [95% CI: −1.26 to 1.93]; 1 in vitro study; 40 scans on casts; CE: very low) (Fig. 4B), and reduced scanning time (MD −76.46 seconds [95% CI: −122.16 to −30.76]; *P*<.001; 2 controlled clinical trials; 298 patient scans; CE: low) (Fig. 4C). Intersubgroup analysis by operator experience showed the improvement was more pronounced in inexperienced operators compared with experienced ones (*P*=.05) (Fig. 4C), suggesting a stronger learning effect among those with limited prior experience. Because of the limited number of included studies, heterogeneity analysis, publication bias assessment, sensitivity analysis, and meta-regression could not be performed, as the available data lacked sufficient statistical power to support meaningful conclusions in this regard.

Overall, the certainty of the evidence was rated as low to very low, primarily because of high imprecision, inconsistency, and indirectness in both PICOS questions. Imprecision was driven by small sample sizes and wide prediction intervals that overlapped multiple effect thresholds, including no effect (as determined by the minimally important difference), small, and moderate effects. Inconsistency arose from substantial heterogeneity across studies, which could be minimally explained through subgroup analyses or meta-regression. Finally, indirectness was present when data were derived from in vitro studies, limiting their applicability to real clinical settings.

Table 3. Summary of Finding (SoF) table for PICO #2

Population: Digital scans in dentate, partially edentulous, or completely edentulous scenarios.
Intervention: Operators without experience using intraoral scanners.
Control: Operators with verified prior experience using intraoral scanners.
Outcome domains and measures: Accuracy: trueness (primary outcome) and precision; Efficiency: scanning time; and PROMs: patient satisfaction (secondary outcomes).
Study design: In vitro studies to assess accuracy-related outcomes; and randomized or nonrandomized CCTs to evaluate efficiency and PROMs.

Outcome Domain	Outcome Measures Outcome Measurements	№ digital scans (Study design)	Illustrative comparative risks* (95% CI)		Difference (IC 95%) [PI if I^2>50%] Rounded Values	Certainty of the evidence (GRADE)	Comments (Interpretation)
			Assumed risk* (With prior experience - Comparator)	Corresponding risk* (Without prior experience - Intervention]			
Accuracy	Trueness [µm]: o RMS error [µm]; o Linear deviations [µm]	120 digital scans in casts (2 in vitro studies)	Mean 80 µm	Mean 63 µm	MD −19 µm (−26 to −12)	⊕⊕◯◯ LOW[a,b] Due to indirectness, inconsistency.	Receiving training sessions improve trueness of digital scanning.
	Precision [µm]: o RMS error [µm]; o Linear deviations [µm]	40 digital scans in casts (1 in vitro studies)	Mean 47 µm	Mean 53 µm	MD 0 µm (−1 to 2) [PI: −5 to 6]	⊕◯◯◯ VERY LOW[a,b] Due to indirectness, inconsistency, and imprecision.	Receiving training sessions does not improve precision of intraoral scanning.
Efficiency	Scanning time [s]	298 digital scans in patients (2 clinical trials)	Mean 9 min 93 s	Mean 7 min 3 s	MD −77 s (−122 to −31) [PI: −221 to 68]	⊕⊕◯◯ LOW[b,c] Due to imprecision, and inconsistency.	Receiving training sessions improves efficiency of digital scanning.

CI, confidence interval; MD, mean difference; PI, prediction interval; PROMSs, patient reported outcome measures; RMS, root mean square; VAS, visual analog scale

GRADE Working Group grades of evidence High certainty: Very confident that true effect lies close to that of estimate of effect. Moderate certainty: Moderately confident in effect estimate: true effect likely to be close to estimate of effect, but possibility that it is substantially different. Low certainty: Confidence in effect estimate limited: true effect may be substantially different from estimate of effect. Very low certainty: Very little confidence in effect estimate: true effect likely to be substantially different from estimate of effect.

[a] **Indirectness:** Data obtained from in vitro settings rather than clinical settings, where obtaining reference model for comparisons not possible, thus compromising external validity and requiring reduction in certainty of evidence.

[b] **Inconsistency:** Presence of unexplained heterogeneity.

[c] **Imprecision:** Reduced sample size.

Table 4. Meta-regression results

Moderators	Coefficient (β)	95% CI	Adjusted R2 (%)	*P*
Market release	**−1.014**	**−1.908, −0.119**	**9.63%**	**.026***
IOS	0.635	−0.206, 1.475	4.44%	.190
Clinical scenario	1.119	−0.807, 3.044	0.00%	.829
Arch	**−9.731**	**- 19.223, - 0.239**	**12.75%***	**.045***
Outcome measurement	−0.642	- 4.404, 3.121	0.00%	.738

**P*<.05

DISCUSSION

This systematic review provided evidence of the influence of operator experience on intraoral digital scanning. The findings suggested that operator experience may minimally reduce scanning trueness, without affecting precision, increase scanning time, and decrease patient satisfaction. However, the certainty of evidence was rated as low to very low, primarily associated with unexplained heterogeneity that could not be fully explained by subgroup analyses or meta-regression, reduced sample sizes (imprecision), and the in vitro nature of the accuracy assessments, limiting clinical representativeness (indirectness).

Among the evaluated confounding factors on the primary outcome, market release year, IOS, clinical scenario, arch, and outcome measurement, only arch (maxilla versus mandible) and the market release year of the scanner showed significant effects. More recent intraoral scanners were associated with smaller differences between inexperienced and experienced operators.

The increased scanning time and decreased patient satisfaction may be associated with multiple interruptions, inefficient scanner handling, or repeated scans, all of which extend chair time and contribute to patient discomfort. Capturing anatomically challenging regions, such as the retromolar pad or maxillary tuberosity, with the scanner can be difficult and require specific maneuvers, for example, instructing the patient to shift the mandible toward the same side to create adequate space at the maxillary tuberosity for scanning. Without such maneuvers, the operator may apply pressure to the soft tissues with the scanner, producing pain or discomfort. These and other techniques are typically acquired during training sessions to improve clinical scanning skills.

The secondary research question aimed to assess the real impact of training sessions on the accuracy and efficiency of intraoral scanning and to show that participation in such sessions was associated with clinically relevant improvements in both outcomes among inexperienced and experienced operators. Subgroup analysis indicated that the benefits of training were evident across all levels of clinical experience, particularly in enhancing efficiency, as reflected by reduced scanning time. Regarding accuracy, training sessions may also provide added value by helping clinicians understand and manage evidence-based modifying factors that influence scanning accuracy. The greater the understanding of these factors, the more accurate the digital scans will be, and fewer deviations will be introduced. This is illustrated in Figure 5, which presents an overview of how operator experience minimally, and training sessions slightly decrease deviations, based on the 2 PICO questions of this review.

Most training sessions have consisted of a hybrid format combining theoretical and practical components and are conducted in a preclinical or clinical setting. Typically, the training includes a slide presentation delivered by an experienced operator, along with educational videos and hands-on practice involving more than 10 training scans, distributed across 1 to 4 sessions. They are designed to cover scanning patterns, software tools that assist during the scanning process, clinical workflows, key modifying factors that can influence accuracy, and scanning tips.

Despite these findings, an expert consensus is still needed to establish consistency in selecting and reporting core outcome measurements for evaluating scanning accuracy to prevent the waste of resources in the field. One potential limitation of this meta-analysis is the variability in outcome measurements used across the included studies to assess accuracy, including RMS error as well as linear inter- and intra-implant deviations. However, the meta-regression did not reveal any significant impact of this variability in outcome measurements on the overall result for the primary outcome. Additionally, a subgroup analysis was conducted to evaluate the direction of findings for each outcome measurement individually (Supplemental Fig. 1, available online), again revealing no relevant differences; also, no differences were revealed in the sensitivity analysis. The most significant limitation in this systematic review was the presence of statistical heterogeneity in the results without a clearly identifiable cause, suggesting the influence of other confounding factors that were not consistently reported or controlled for across the included studies.

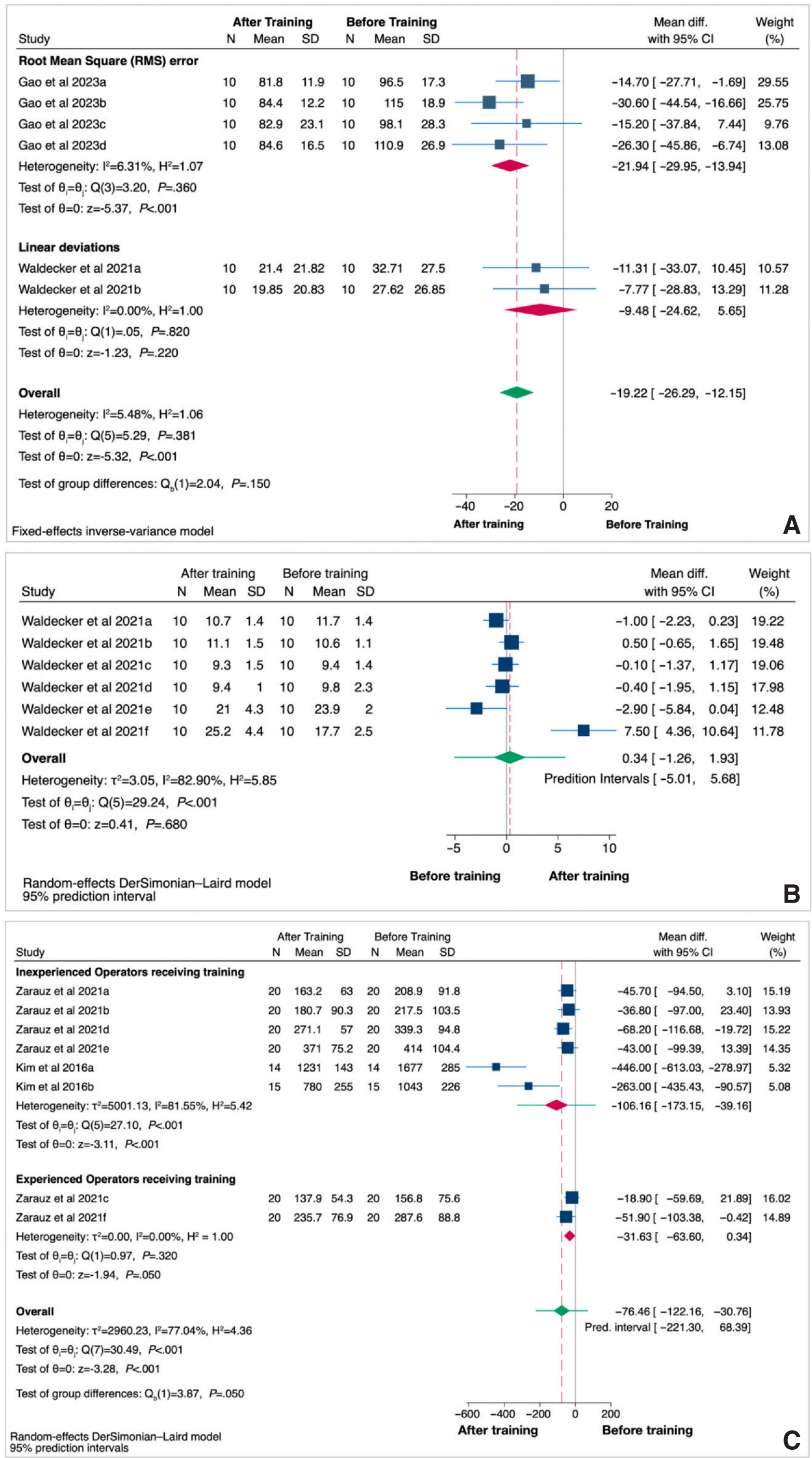

Figure 4. Forest plots of PICOS #2 evaluating impact of receiving training lessons on: A, Trueness [μm]: subgroup analysis by outcome measurement. B, Precision [μm]. C, Scanning time [s]: subgroup analysis by prior clinical experience.

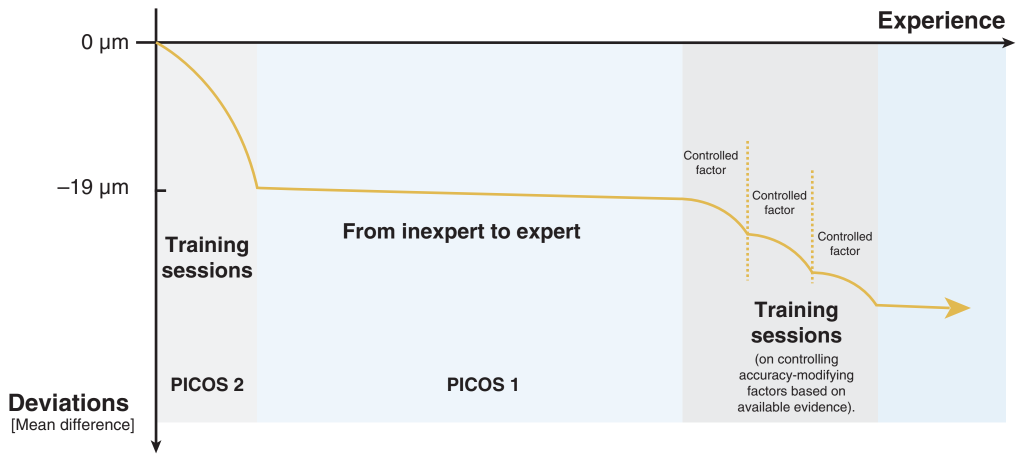

Figure 5. Impact of training and experience on minimizing scanning deviations.

CONCLUSIONS

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

1. Operator inexperience may minimally compromise scan accuracy, prolong scanning times, and reduce patient satisfaction.
2. Participation in training sessions equips clinicians with the theoretical knowledge and practical skills that are associated with clinically relevant improvements in both the accuracy and efficiency of intraoral digital scanning.

APPENDIX A. SUPPORTING INFORMATION

Supplemental data associated with this article can be found in the online version at doi:10.1016/j.prosdent.2025.09.008.

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