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Effect of scanning strategies on the accuracy of digital intraoral scanners: a meta-analysis of *in vitro* studies

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PURPOSE. This study aimed to investigate whether the accuracy of intraoral scanners is influenced by different scanning strategies in an *in vitro* setting, through a systematic review and meta-analysis. **MATERIALS AND METHODS.** This review was conducted in accordance with the PRISMA 2020 standard. The following PICOS approach was used: population, tooth impressions; intervention, the use of intraoral scanners with scanning strategies different from the manufacturer's instructions; control, the use of intraoral scanners following the manufacturers' requirements; outcome, accuracy of intraoral scanners; type of studies, *in vitro.* A comprehensive literature search was conducted across various databases including Embase, SciELO, PubMed, Scopus, and Web of Science. The inclusion criteria were based on *in vitro* studies that reported the accuracy of digital impressions using intraoral scanners. Analysis was performed using Review Manager software (version 5.3.5; Cochrane Collaboration, Copenhagen, Denmark). Global comparisons were made using a standardized mean difference based on random-effect models, with a significance level of $\alpha = 0.05$. **RESULTS.** The meta-analysis included 15 articles. Digital impression accuracy significantly improved under dry conditions ($P < 0.001$). Moreover, trueness and precision were enhanced when artificial landmarks were used ($P \leq 0.02$) and when an S-shaped pattern was followed ($P \leq 0.01$). However, the type of light used did not have a significant impact on the accuracy of the digital intraoral scanners ($P \geq 0.16$). **CONCLUSION.** The accuracy of digital intraoral scanners can be enhanced by employing scanning processes using artificial landmarks and digital impressions under dry conditions. [J Adv Prosthodont 2023;15:315-32]

KEYWORDS
Accuracy; Computer-Aided Design; Digital impression; Intraoral scanner; Precision; Dental impression technique; Computer-assisted diagnosis

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INTRODUCTION

Conventional impression procedures have traditionally been used to capture the three-dimensional (3D) geometry of dental tissues. However, these methods have limitations due to the potential for errors in analogue impression material volume and the subsequent expansion of dental stone, often necessitating additional dental laboratory services.[1-3] In response to these challenges, intraoral scanners (IOS) have been developed for dental clinicians.[4,5]

Critical to any lifelong dental restoration is the accuracy of the impression, which determines the marginal fit and overall quality of the final restoration.[5,6] It's important to note that the accuracy of a measurement method should adhere to the International Organization for Standardization (ISO) guidelines, which encompass both trueness and precision (ISO 5725-1).[7] Trueness relates to the systematic error or measurement bias between the target object and the reference object, indicating the agreement between an accepted reference value and the mean value derived from multiple test outcomes. In contrast, precision accounts for the random errors when a procedure is repeated.[8-10] Prior research has reported precision and trueness values for conventional impressions for full-arch models in the range of 13 - 61 mm and 20 - 55 mm, respectively, while digital impressions using IOSs have shown corresponding values of 31 - 60 mm and 40 - 59 mm.[11,12]

Integrating an IOS into a dental practice can enhance treatment quality and the patient experience while serving as a valuable marketing tool.[13] Therefore, it's imperative for clinicians to understand IOS technology to efficiently integrate it into chairside dentistry.[5] These IOS devices offer various scanning settings, and scanning procedures can be customized to suit operator preferences.[14] All IOS systems generate 3D models by "stitching" together multiple images captured from different angles, with the success of this merging process closely tied to the operator's steadiness during scanning.[15]

However, it's essential to acknowledge that IOSs have limitations, which may restrict their use in certain clinical situations. IOSs typically require a well-defined finish line geometry for accurate scanning. Additionally, deep vertical preparations can impede proper light penetration for precise digital reconstruction, and environmental factors such as humidity and ambient lighting can affect the quality of the scanned surface.[16-19]

As of now, there is not a single IOS device recognized as the gold standard for the accuracy of digital impressions in fabricating dental restorations. Therefore, the aim of this study is to investigate whether *in vitro*, the accuracy of IOSs can be enhanced through alternative techniques through a systematic review and meta-analysis. The null hypothesis for this review posits that no difference in accuracy will be observed when employing alternative techniques in contrast to the manufacturer's guidelines.

MATERIALS AND METHODS

This paper was achieved in agreement with the PRISMA 2020 guidelines.[20] The protocol and important documents regarding to this review were recorded at Open Science Framework (https://osf.io/gf7b4/). The succeeding PICOS approach was executed: population, tooth impression; intervention, the use of digital (IOS) with strategies different to those suggested by the company; control, the use of digital (IOS) concurring to the manufacturers' instructions; outcome, the accuracy (trueness and precision); type of studies, *in vitro* findings. A research question was performed: Does the use of strategies different to those recommended by the manufacturer improve the accuracy of IOS when taking a tooth impression?

1. Literature search

A search of the literature was accompanied until January 12th, 2023. The following databases were investigated: Embase, Scielo, PubMed, Scopus, and Web of Science. The search strategy and the keywords used in PubMed are outlined in Table 1; these were adapted for use in other databases. After completing the search, all identified articles were imported into the Rayyan QCRI mobile application.[21]

2. Study selection

Two experienced researchers (CECS and RB) individually evaluated the titles and abstracts of all the

Table 1. Search strategy used in PubMed

Search number	Keywords
#1	Intraoral scanner OR Intraoral scanning device OR Digital impression scanner
#2	Accuracy OR Precision OR Trueness
#3	# 1 AND #2

articles. Selection was based on the following inclusion criteria: (1) *in vitro* studies reporting the accuracy of digital impressions using IOS, (2) evaluated the accuracy of quadrant or full-arch impressions, (3) inclusion of a control group using IOS following the manufacturer's guidelines, and (4) availability of mean and standard deviation (SD) data. Review papers, case reports, case series, and documents published in languages other than English were excluded. In cases where the necessary information was lacking, the full article was thoroughly reviewed to ascertain eligibility. Additionally, the reference lists of selected articles were manually searched to identify any potentially overlooked manuscripts during the initial search, while adhering to the specified criteria. Any discrepancies in article eligibility were resolved through the judgment of a third researcher (LH).

3. Data Extraction

Relevant data from the selected articles were extracted using Microsoft Office Excel 2019 (Microsoft Corporation, Redmond, WA, USA). This information encompassed the study's publication year, the IOS used, the tested strategies or techniques, and the primary results. In cases of missing or unclear data, the corresponding researchers of the studies were contacted via email to acquire the necessary information. Any unreceived information after a two-week waiting period was omitted from this review.

4. Quality Assessment

The risk of bias (RoB) of the manuscripts included in this review was independently assessed by two participants of the review (LH and RB) according to the evaluation of the following parameters: specimen randomization, single operator, control group, operator blinded, standardized specimens, and sample size calculation. If the authors reported the parameter, the study received a "√" for that parameter. In the case of not reporting the information, such parameter received a "X". The RoB was classified according to the sum of "√" answers received: 1 to 2 denoted a high bias, 3 to 4 medium, and 5 to 6 showed a low RoB.

5. Statistical analysis

The meta-analysis was performed using the Review Manager software (version 5.3.5; The Cochrane Collaboration, Copenhagen, Denmark). A random-effect model was used for the analyses, and pooled-effect estimates were obtained by comparing the standardized mean difference of the trueness and precision of the digital models obtained following the manufacturers' recommendations against the other strategies. A P-value < .05 was considered statistically significant. The heterogeneity and inconsistency were measured using the Cochran Q test and the I^2 test.

RESULTS

A total of 3268 documents were initially retrieved from the various databases. After removing duplicates entries, 2628 articles were assessed by reading the title and abstract. Subsequently, 92 studies persisted for full text examination. Among these, 37 studies were excluded for the following reasons: (23) did not include comparisons between different scanning techniques,[22-44] (7) were clinical studies,[45-51] (5) full-text manuscripts were inaccessible,[52-56] (1) did not assess accuracy on teeth,[57] and (1) did not use any digital IOS.[58] Ultimately, 55 documents were included in the qualitative analysis. From these, 40 articles were further excluded from the meta-analysis due to the following reasons: (15) had dissimilar test conditions compared to other studies,[59-73] (10) lacked available mean and standard deviation data,[6,74-82] (9) did not have other studies available for comparison,[14,15,58,83-88] (3) did not include a control group,[89-91] and (3) the accuracy could not be determined.[16,92,93] Consequently, 15 articles remained for the quantitative analysis.[94-108] A flowchart of the study selection process agreeing to the PRISMA statement is presented in Figure 1.

Table 2 provides an overview of the characteristics of the studies included in the qualitative analysis. These studies evaluated various IOSs, and among

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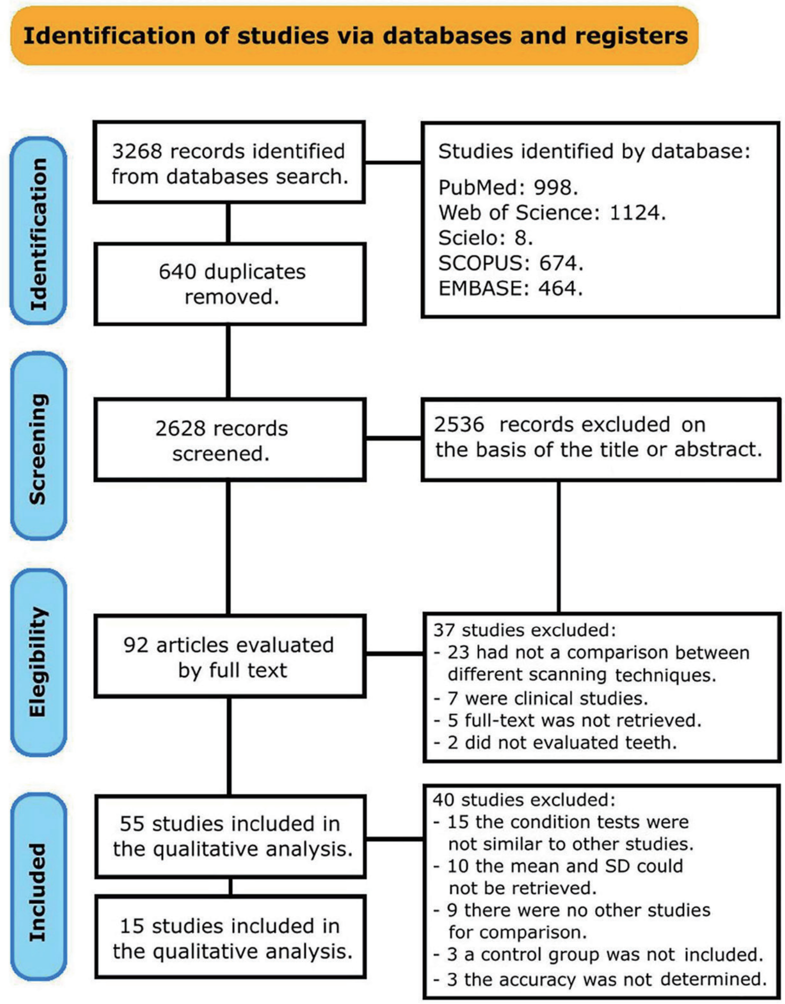

Fig. 1. PRISMA 2020 flow diagram of study identification.

the different techniques tested, the most commonly examined factors included scanning speed, scanning pattern, tip size, illuminance and color temperature of ambient light, position and operator, presence of humidity, scanning resolution, software version used, use of artificial markers, scanning distance, model stitching, and the utilization of scanning-aid materials.

Results from the meta-analysis are described in Figures 2 - 6. Figure 2 illustrates the impact of humidity on the accuracy of digital intraoral scanners. The analysis reveals that the presence of humidity negatively affected the accuracy of digital IOSs ($P < .001$).

Study or Subgroup	Dry Mean	Dry SD	Dry Total	Wet Mean	Wet SD	Wet Total	Weight	Std. Mean Difference IV, Random, 95% CI
Chen 2021	109.29	22.86	60	159.49	27.59	60	14.9%	-1.97 [-2.41, -1.53]
Chen 2021	104.72	10.06	60	142.38	13.08	60	14.7%	-3.21 [-3.75, -2.66]
Gómez-Polo 2022b	95	84	10	97	93	10	14.2%	-0.02 [-0.90, 0.85]
Gómez-Polo 2022b	228	170	10	236	156	10	14.2%	-0.05 [-0.92, 0.83]
Rapone 2020	43.31	31.86	40	298.62	97.6	40	14.5%	-3.48 [-4.19, -2.78]
Rapone 2020	53.65	15.13	40	226.93	74.55	40	14.6%	-3.19 [-3.86, -2.52]
Rapone 2020	87.24	22.5	40	434.27	53.85	40	12.9%	-8.33 [-9.72, -6.93]
Total (95% CI)			**260**			**260**	**100.0%**	**-2.82 [-4.14, -1.51]**

Heterogeneity: Tau² = 2.98; Chi² = 151.50, df = 6 (P < 0.00001); I² = 96%
Test for overall effect: Z = 4.20 (P < 0.0001)

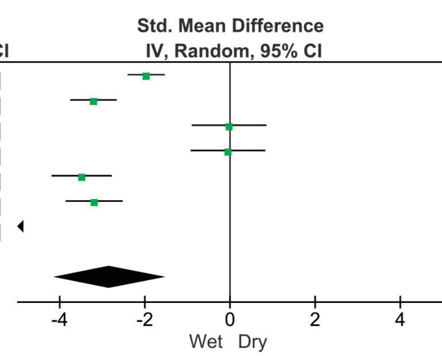

Fig. 2. Forest plot of the accuracy of intraoral scanners when used under wet or dry conditions.

Table 2. Summary of findings

Study and year	Intraoral scanner used	Strategy or technique tested	Main results
Al-ibrahim, 2021[83]	inEos X5 (Dentsply-Sirona) 3Shape D2000 (3Shape)	Scanning speed.	Different scanning speeds did not affect the precision. However, the trueness was affected between slow and standard scanning speed.
An, 2022[95]	Emerald (Planmeca)	Scanning speed. Scanning patterns.	Small scanner tip adversely influenced trueness and precision. Fast scanning speed and S-shaped scan strategy has lower precision.
Alenezi, 2022[92]	ARCTICA AutoScan (KaVo)	Scanning patterns.	Straight and zigzag scan patterns had marginal and internal gaps that were clinically recognized.
Donmez, 2022[97]	TRIOS 3 (3Shape)	Scanning patterns.	After linear scan of complete arch, the rotational scanning of the palate did not develop any supplementary advantage for accuracy.
Ender, 2013[12]	Lava COS (3MESPE) Cerec Bluecam (Sirona Dental Systems) Cadent iTero (Cadent Ltd.)	Scanning patterns.	Full arch dental impressions were feasible with a high accuracy, if satisfactory scan approaches were implemented.
Feng, 2021[86]	TRIOS 3 (3Shape)	Scanning patterns.	The accuracy of IOS differed for full-arch from maxillary to mandibulary archs.
Gavounelis, 2022[98]	i500 (Medit)	Scanning patterns.	The scan strategy affected the accuracy of complete-arch impressions.
Kim, 2022[63]	TRIOS 3 (3Shape)	Scanning patterns.	The scan origin location have an influence on the accuracy of IOS.
Latham, 2019[76]	Planmeca Emerald (Planmeca) TRIOS 3 (3Shape) iTero Element (Align Technology) CEREC Omnicam (Dentsply Sirona)	Scanning patterns.	The trueness and precision for some IOS were affected by scan pattern.
Li, 2022[102]	TRIOS 3 (3Shape) Carestream CS 3600 (Carestream)	Scanning patterns.	For complete-arch implant rehabilitation, the scan display meaningfully affected the speed and the accuracy of a digital impression.
Mai, 2022[93]	i700 (Medit)	Scanning patterns.	The segmental scan by means of two scan parts seems to be efficient for full-arch intraoral scans.
Pattamavilai, 2022[71]	Virtuo Vivo (Dental Wings Inc) TRIOS 3 (3Shape) True Definition (3M ESPE)	Scanning patterns.	Scanning pattern affected the trueness of the IOS.
Kanjanasavitree, 2022[100]	Trios (3Shape)	Scanning patterns.	Scanning patterns and artificial landmarks had influence on the accuracy of the IOS.
Diker, 2021[61]	Trios 3 (3Shape) iTero Element 2 (Align Technology) CEREC Omnicam (Dentsply Sirona) Emerald (Planmeca) Virtuo Vivo (Dental Wings)	Scanning patterns.	The accuracy was influenced by the scanning sequence of the different IOS tested.
Diker, 2021[59]	TRIOS 3 (3Shape) iTero Element 2 (Align Technology Inc) Cerec Omnicam (Dentsply Sirona) Planmeca Emerald (Plan- meca Oy) Cerec Primescan (Dentsply Sirona) Virtuo Vivo (Dental Wings Inc)	Scanning patterns.	The scanning sequence affected the accuracy of the IOS tested.
Diker, 2020[60]	Trios 3 (3Shape) iTero Element (Align Technology Inc) Cerec Omnicam (Dentsply-Sirona) Planmeca Emerald (Planmeca) Cerec Primescan (Dentsply-Sirona) Virtuo Vivo (Dental Wings Inc)	Scanning patterns.	The scanning sequence affected the accuracy of digital impressions of IOS used.

Table 2. (Continued) Summary of findings

Study and year	Intraoral scanner used	Strategy or technique tested	Main results
Zarone, 2020[82]	TRIOS 3 (3Shape)	Scanning patterns.	Buccopalatal technique showed superior trueness and precision than palatobuccal strategy for the wrinkled typodont scans.
Arakida, 2018[94]	True Definition (3M ESPE Dental Products)	Ambient light conditions.	For an appropriate digital impression, the 3900 K and 500 lux conditions were efficient for lighting condition.
Ochoa-López, 2022[69]	TRIOS 3 (3Shape) Primescan (Dentsply Sirona). iTero Element 5D (Align Technology) i500 (Medit), i700 (Medit) CS3600 (Carestream) CS3700 (Carestream)	Ambient light conditions.	Ambient light affected the accuracy of IOSs evaluated.
Wesemann, 2020[81]	TRIOS 3 (3shape) Cerec Omnicam iTero Element (Dentsply Sirona) iTero Element (Align Technology) CS 3600 (Carestream Dental, Triangulation) Planmeca Emerald (Planmeca) Aadva IOS (GC Europe)	Ambient light conditions.	The accuracy and scanning time of IOS was affected by the ambient light.
Revilla-León, 2019[16]	iTero Element (Cadent Ltd) CEREC Omnicam (Dentsply, Sirona) TRIOS 3 (3Shape)	Ambient light conditions.	The conditions of ambient light influenced the accuracy of the IOSs used in this study.
Revilla-León, 2020[80]	iTero Element (Cadent LTD) Omnicam (Cerec-Sirona) TRIOS 3 (3Shape).	Ambient light conditions.	Variations in ambient scanning light condition significantly affect the mesh quality.
Revilla-León, 2021[107]	TRIOS 3 (3Shape)	Ambient light conditions.	1000-lux of illumination light condition was suggested in an attempt to increase the scanning accuracy of the IOS. The chair light must be prevented.
Cakmak, 2022[85]	ATOS 5 (GOM) TRIOS 3 (3Shape)	Software version.	Deviations in implant scan body scans could differ if different software version were used.
Haddadi, 2018[15]	ATOS 5 (GOM) Cerec Omnicam (Dentsply Sirona)	Software version.	The accuracy of an IOS was influenced by the software version.
Peroz, 2021[79]	TRIOS 3 (3shape)	Software version.	The operator, the inspection software, and the mesh density displayed no influence on the trueness of the result.
Chen, 2021[96]	Trios 3 (3Shape) Primescan (Dentsply-Sirona)	Presence of humidity.	The presence of liquid on the tooth surface might influence the accuracy of the IOS.
Goómez-Polo, 2022[99]	TRIOS 3 (3Shape)	Presence of humidity.	By drying of the surface scanned, there is a rise in the IOS accuracy.
Rapone, 2020[106]	CS 3600 (Carestream Dental) TRIOS 3 (3Shape) CEREC Omnicam (Dentsply Sirona)	Presence of humidity.	Humidity affected the accuracy of IOS.
You, 2022[91]	Trios 3 (3Shape)	Presence of humidity and variations in occlusal force during intraoral scanning.	A moist cavity surface without visually evident salivary contamination is acceptable.
Song, 2020[90]	CS3600 (Carestream Dental) i500 (Medit Corp) Trios3 (3Shape) Omnicam (Dentsply Sirona)	Presence of humidity.	The presence of artificial saliva influenced the scanned images.
Mizumoto, 2019[67]	TRIOS 3 (3Shape)	Scanning strategies.	Scanning techniques and scan bodies affected the accuracy of the IOS evaluated in this study.

Table 2. (Continued) Summary of findings

Study and year	Intraoral scanner used	Strategy or technique tested	Main results
Mizumoto, 2019b[77]	Trios3 (3Shape)	Scanning strategies.	The accuracy of digital scans of edentulous maxillary arch was alike regardless of the stitching procedure.
Motel, 2020[78]	TRIOS 3 (3Shape)	Scanning strategies.	Scan strategies affected the quality of digital impressions.
Müller, 2016[68]	TRIOS Pod scanner (3Shape)	Scanning strategies.	The strategy suggested by the company demonstrated the highest precision and trueness of full-arch scans.
Oh, 2020[70]	i500 (Medit) TRIOS 3 (3Shape)	Scanning strategies.	The segmental method for scanning the area improved the accuracy of IOS.
Lopes, 2022[64]	CEREC Primescan (Dentsply Sirona)	Scanning strategies.	Scan strategies affected the accuracy, however, implant angulation did not influence the accuracy of IOS.
Mandelli, 2018[65]	3M True Definition Scanner (3M ESPE)	Scanning strategies.	No stitching strategy showed less precision when compared to the stitching strategy.
Medina-Sotomayor, 2018[66]	Trios (3Shape) iTero (Align Technology Inc) Cerec AC Omnicam (Dentsply Sirona) True Definition (3M ESPE)	Scanning strategies.	The scanning strategy affected the accuracy of the IOS evaluated.
Passos, 2019[105]	Omnicam (Dentsply Sirona) Primescan (Dentsply Sirona)	Scanning strategies.	The linear experimental group showed the greatest scanning time for IOS tested.
Stefanelli, 2021[73]	i500 (Medit)	Scanning strategies.	Newer tips appears to be effective for improving the accuracy of IOS.
Oh, 2020b[104]	Trios 3 (3Shape)	Scanning-aid agents.	The liquid type agent gave more accuracy for an IOS.
Oh, 2021[103]	i500 (Medit) TRIOS (3shape)	Scanning-aid agents.	The use of a scanning-aid material shortened the scanning time.
Oh, 2022[89]	i500 (Medit)	Scanning-aid agents.	To obtain more accurate scanning images, the use of liquid agent was proved to be efficient.
Kim, 2019[62]	TRIOS 3 (3Shape) CS 3500 (Carestream) PlanScan (Planmeca)	Scanning distance.	A difference was found between the accuracy of the scan distance and the accuracy of the IOS.
Rotar, 2022[72]	i700 (Medit)	Scanning distance.	Increased scanning distances might lessen the accuracy of a digital impression.
Kim, 2016[101]	CS3500 (Carestream) Cerec Omnicam (Dentsply Sirona) TRIOS 3 (3Shape)	Artificial landmarks.	The accuracy of IOS was improved by alumina landmarks.
Tao, 2020[108]	TRIOS 3 (3Shape)	Artificial landmarks.	Resin markers placed on the hard palate of edentulous maxillary model might increase the precision of the IOS.
Chiu, 2020[14]	TRIOS 3 (3Shape)	Scan resolution.	A high-resolution mode of the software obtained more data and this could not certainly advantage the scanner accuracy.
Hayama, 2018[6]	Model non specified (Carestream)	Head scanner size.	Larger scanning head may improve the accuracy of removable partially edentulous denture.
Kurz, 2015[87]	CEREC Omnicam (Dentsply Sirona)	Powder-free system.	The powder-free tested system could be used safely to scan different material surfaces.
Revilla-Leoón, 2022[88]	TRIOS 4 (3Shape)	Ambient temperature changes.	Increasing the ambient temperature has a superior effect on the IOS accuracy compared with a decrease ambient temperature.
Arcuri, 2019[74]	Trios3 (3Shape)	Scanbody material, position and operator.	The use of a PEEK scan body achieved higher outcomes. Operator did not demonstrate influence on the accuracy.
Baek, 2022[84]	i500 (Medit)	Superimposing the custom abutment library data.	The accuracy of IOS was improved by means of superimposition of a titanium custom abutment with a prescanned custom abutment collection data.

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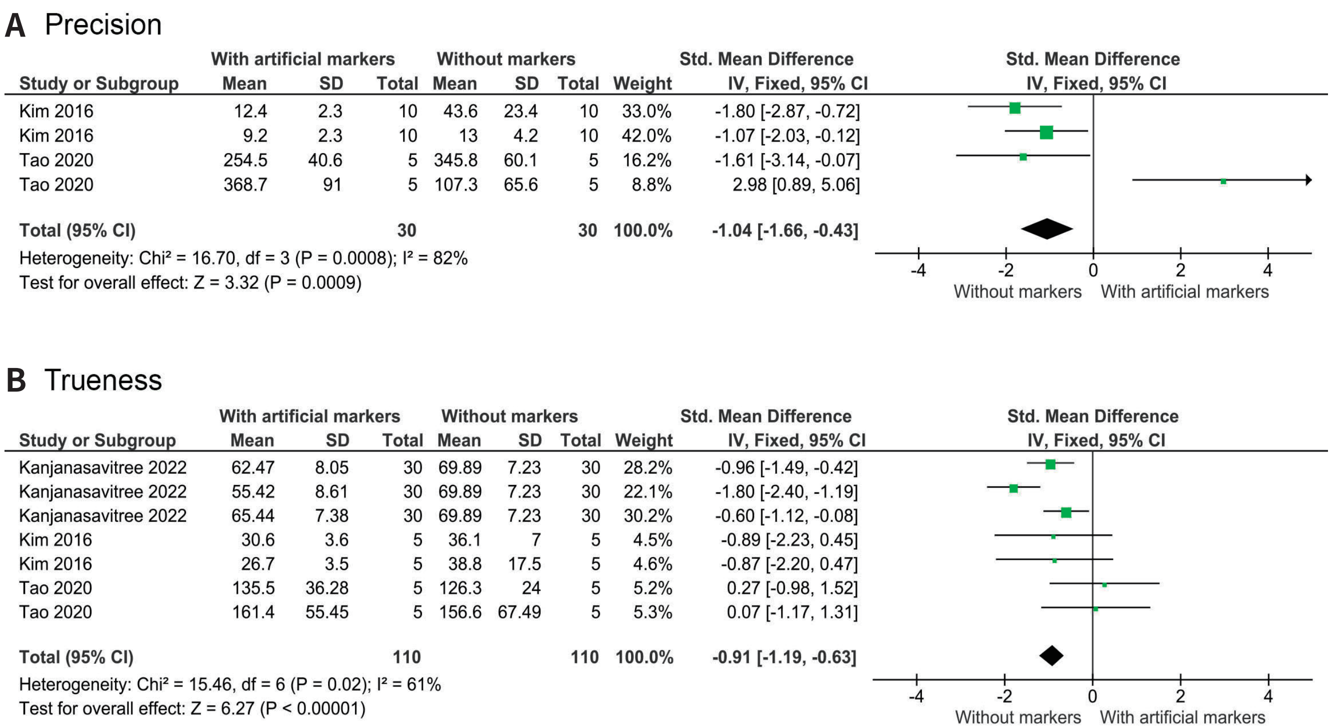

Fig. 3. Forest plot of the precision (A) and trueness (B) of intraoral scanners when used with artificial landmarks.

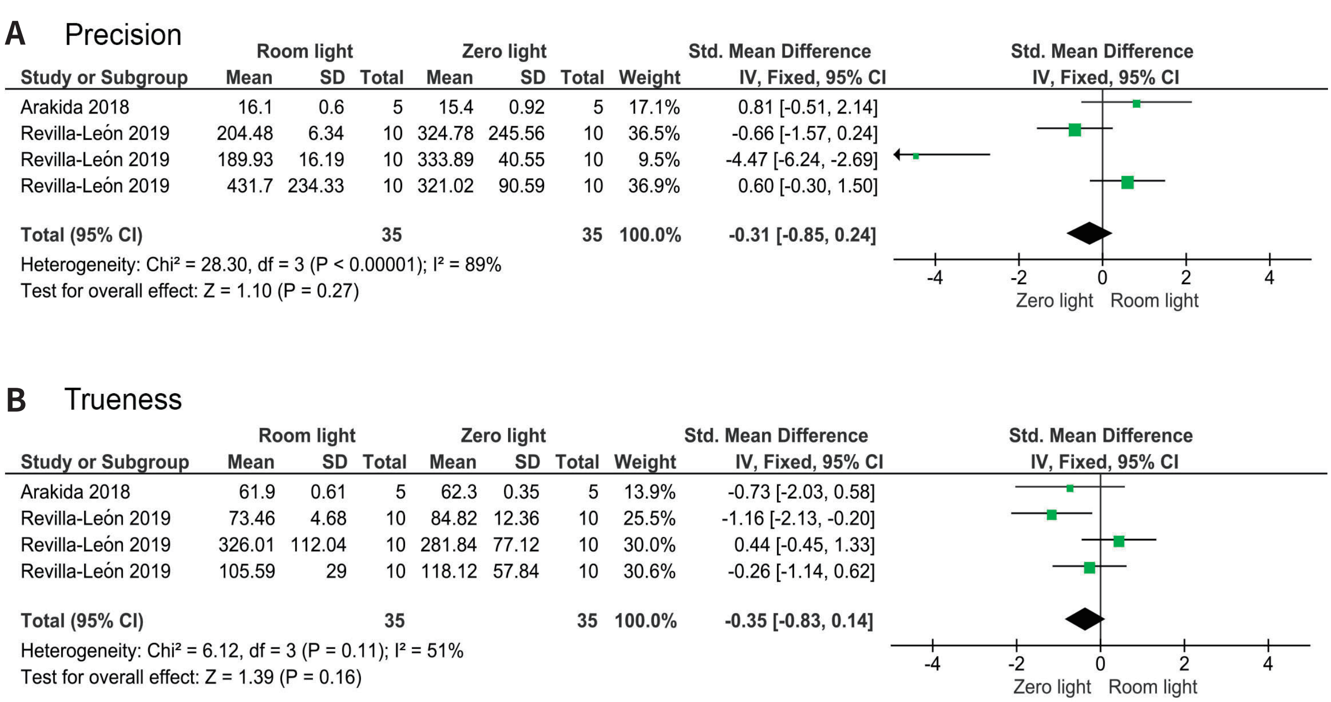

Fig. 4. Forest plot of the precision (A) and trueness (B) of intraoral scanners when used under different illumination conditions.

A Precision

Study or Subgroup	Linear Mean	Linear SD	Linear Total	S-shaped Mean	S-shaped SD	S-shaped Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Ann 2022	78.33	37.62	60	110.83	52.65	60	37.4%	-0.71 [-1.07, -0.34]
Donmez 2022	24.17	19.23	24	23.07	20.19	24	15.9%	0.05 [-0.51, 0.62]
Kanjanasavitree 2022	15.39	5.84	40	15.99	4.89	40	26.5%	-0.11 [-0.55, 0.33]
Li 2022	15.52	3.4	10	37.05	22.83	10	5.3%	-1.26 [-2.24, -0.28]
Li 2022	83.18	30.09	10	87.95	46.22	10	6.6%	-0.12 [-0.99, 0.76]
Passos 2019	13.43	8.26	10	8.26	3.35	10	6.1%	0.79 [-0.13, 1.70]
Passos 2019	16.75	2.4	10	30.01	4.47	10	2.2%	-3.54 [-5.05, -2.03]
Total (95% CI)			**164**			**164**	**100.0%**	**-0.39 [-0.62, -0.17]**

Heterogeneity: Chi² = 33.29, df = 6 (P < 0.00001); I² = 82%
Test for overall effect: Z = 3.40 (P = 0.0007)

B Trueness

Study or Subgroup	Linear Mean	Linear SD	Linear Total	S-shaped Mean	S-shaped SD	S-shaped Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Ann 2022	115.33	34.64	60	102.67	42.32	60	27.2%	0.33 [-0.03, 0.69]
Donmez 2022	94.57	56.02	24	61.77	33.26	24	10.3%	0.70 [0.12, 1.28]
Gavounelis 2022	45	18.98	60	43.85	20.04	60	27.6%	0.06 [-0.30, 0.42]
Kanjanasavitree 2022	66.92	6.45	40	67.66	8.68	40	18.4%	-0.10 [-0.53, 0.34]
Li 2022	167.07	33.04	10	106.3	37.6	10	3.2%	1.64 [0.60, 2.69]
Li 2022	91.95	6.85	10	79.63	29.65	10	4.4%	0.55 [-0.35, 1.45]
Passos 2019	36.26	3	10	36.79	2.83	10	4.6%	-0.17 [-1.05, 0.70]
Passos 2019	8.84	3.38	10	11.3	3.66	10	4.3%	-0.67 [-1.58, 0.24]
Total (95% CI)			**224**			**224**	**100.0%**	**0.20 [0.01, 0.39]**

Heterogeneity: Chi² = 17.77, df = 7 (P = 0.01); I² = 61%
Test for overall effect: Z = 2.09 (P = 0.04)

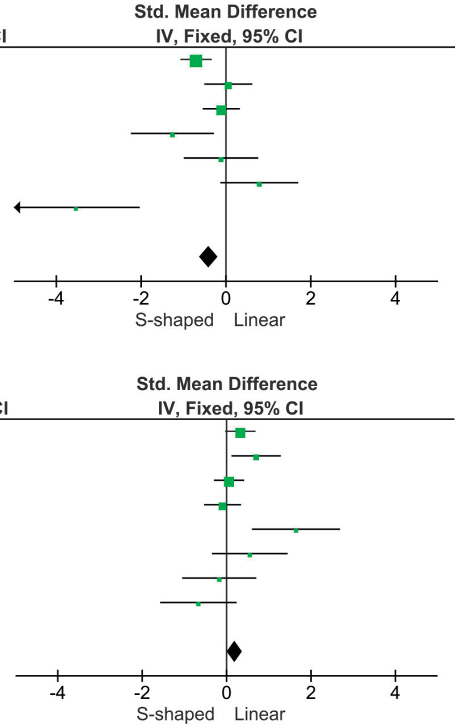

Fig. 5. Forest plot of the precision (A) and trueness (B) of intraoral scanners when used under different scanning patterns.

A Precision

Study or Subgroup	No treatement Mean	No treatement SD	No treatement Total	Scanning-Aid Material Mean	Scanning-Aid Material SD	Scanning-Aid Material Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Oh 2020b	40.24	18.69	10	42.33	35.48	30	17.7%	-0.06 [-0.78, 0.65]
Oh 2020b	40.24	18.69	10	28.52	19.06	30	17.1%	0.61 [-0.12, 1.33]
Oh 2020b	40.24	18.69	10	44.33	28.45	30	17.7%	-0.15 [-0.87, 0.57]
Oh 2021	198	42.5	10	114	40.8	10	7.5%	1.93 [0.83, 3.03]
Oh 2021	198	42.5	10	133	35.7	10	8.5%	1.59 [0.55, 2.62]
Oh 2021	198	42.5	10	74.3	27.9	10	4.4%	3.30 [1.86, 4.73]
Oh 2021	134	34.7	10	92.9	34.2	10	9.8%	1.14 [0.18, 2.10]
Oh 2021	134	34.7	10	91.3	32.5	10	9.6%	1.22 [0.24, 2.19]
Oh 2021	134	34.7	10	76.1	22.4	10	7.6%	1.90 [0.80, 2.99]
Total (95% CI)			**90**			**150**	**100.0%**	**0.86 [0.56, 1.16]**

Heterogeneity: Chi² = 35.37, df = 8 (P < 0.0001); I² = 77%
Test for overall effect: Z = 5.61 (P < 0.00001)

B Trueness

Study or Subgroup	No treatment Mean	No treatment SD	No treatment Total	Scanning-Aid Material Mean	Scanning-Aid Material SD	Scanning-Aid Material Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Oh 2020b	51.09	11.88	5	51.83	16.75	15	14.3%	-0.04 [-1.06, 0.97]
Oh 2020b	51.09	11.88	5	77.99	26.55	15	12.6%	-1.07 [-2.15, 0.01]
Oh 2020b	51.09	11.88	5	78.99	14.23	15	9.9%	-1.94 [-3.16, -0.73]
Oh 2021	141.7	11.89	5	136.18	23.69	5	9.4%	0.27 [-0.98, 1.51]
Oh 2021	141.7	11.89	5	143.48	11.99	5	9.5%	-0.13 [-1.38, 1.11]
Oh 2021	141.7	11.89	5	138.18	36.98	5	9.5%	0.12 [-1.13, 1.36]
Oh 2021	105.02	11.25	5	92.9	34.2	10	12.4%	0.39 [-0.69, 1.48]
Oh 2021	105.02	11.25	5	91.3	32.5	10	12.3%	0.47 [-0.63, 1.56]
Oh 2021	105.02	11.25	5	76.1	22.4	10	9.9%	1.38 [0.17, 2.60]
Total (95% CI)			**45**			**90**	**100.0%**	**-0.07 [-0.45, 0.31]**

Heterogeneity: Chi² = 19.92, df = 8 (P = 0.01); I² = 60%
Test for overall effect: Z = 0.35 (P = 0.73)

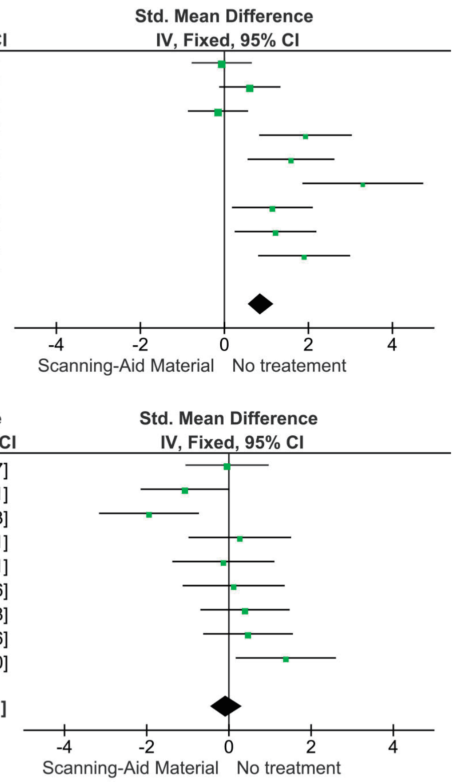

Fig. 6. Forest plot of the precision (A) and trueness (B) of intraoral scanners when used with scanning-aid materials.

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In Figure 3, the meta-analysis results on the precision and trueness of digital IOSs when used in conjunction with artificial landmarks are presented. Both precision (P = .0009) and trueness (P < .001) improved when artificial landmarks were employed.

The impact of ambient light conditions on the precision and trueness of IOSs is shown in Figure 4. The meta-analysis results indicate that these parameters were not significantly affected when the digitalization process was performed under room light or zero-light conditions (P = .27; P = .16).

Figure 5 illustrates the effect of the scanning pattern on the precision and trueness of IOSs. The analysis indicates that differences in measurements were more pronounced when an S-shaped pattern was used (P = .0007). Conversely, discrepancies between a master model and the digital scanner were more substantial when a linear pattern was employed (P = .04).

Finally, the forest plot of the accuracy of IOSs when used in conjunction with scanning-aid materials is presented in Figure 6. The results reveal that only precision is affected by the use of scanning-aid materials (P < .001).

Table 3 provides an analysis of the Risk of Bias (RoB) in the articles included in the qualitative review. Most of the articles were categorized as having a medium RoB. The categories that most manuscripts did not meet included the assessment of a single operator, operator blinding, and sample size calculation.

DISCUSSION

This systematic review and meta-analysis assessed the accuracy of IOSs under various conditions, including humidity, light illuminance, the use of artificial markers, scanning patterns, and scanning-aid materials. The results revealed that certain techniques enhanced the accuracy of IOSs, while others had no significant impact. As a result, the initial hypothesis, which posited that no variation in IOS accuracy would occur when using alternative methods contrary to the manufacturer's instructions, was only partially accepted.

The accuracy of IOSs decreased when used in humid conditions, such as saliva contamination, leading to increased discrepancies compared to dry conditions. It's worth noting that while IOSs offer advantages like improved diagnostic efficacy, reduced patient discomfort, simplified clinical procedures, and time savings when taking optical impressions, they are susceptible to factors like saliva secretion, humidity, and intraoral temperature variations, which can affect accuracy.[71,106,109-112] Initially, saliva negatively affects digital impressions by washing out the contrasting powder applied in some IOS. Specifically, saliva can negatively impact digital impressions, causing the scanner to misinterpret the geometry due to the presence of saliva on the tooth's surface.[87] In addition to this, a previous study demonstrated that the measurement of deviations in 'saliva samples' is much higher than the clinically adequate cut-off value of 120 microns.[113]

When comparing zero-light conditions to room light, the accuracy of IOSs in terms of precision and trueness remained unaffected. Determining the ideal lighting condition for accurate scans remains a subject of debate, as different recommendations exist for dental operatory lighting conditions.[107] Recommendations regarding the optimal operating light in an office of a dental operatory are varied. The European Standard for Illumination (EN 12464) suggest 500 lux as general lighting, 1000 lux in medical or examination rooms, and 10000 lux inside the mouth.[114] Revilla-León *et al*.[107] established that the lighting condition must be selected with reference to the specific IOS system used. Arakida *et al*.[94] studied the effect of illuminance and the color temperature of ambient light on the precision, trueness, and the scanning time of a digital impression and determined that 500 lux with 3900 K was the most suitable lighting condition for digital impressions. Further, another previous study[115] deduced that the total absence of an external light delivers optimum outcomes. Overall, each scanner must have its own specifications.

In a clinical environment, an IOS might not deliver accurate scans mainly because of excess afterimages caused by the presence of movable tissues like the tongue or the frenum.[108] To solve this issue, the use of resin markers on the palate surface was proposed.[116,117] This claim matched the results of this analysis, since the use of artificial markers influenced both the precision and trueness of IOSs. In cases in-

Table 3. Risk of bias analysis

Study	Specimens randomization	Single Operator	Control group	Operator blinded	Standardized specimens	Sample size calculation	Risk of bias
Al-ibrahim, 2021	X	√	√	X	√	X	Medium
Alenezi, 2022	X	√	√	X	√	X	Medium
An, 2022	X	X	√	X	√	X	High
Arakida, 2018	X	X	√	X	√	X	High
Arcuri, 2019	√	X	√	√	√	X	Medium
Baek, 2022	X	√	√	X	√	X	Medium
Çakmak, 2022	X	X	√	X	√	X	High
Chen, 2021	X	√	√	X	√	√	Medium
Chiu, 2020	X	X	√	X	√	X	High
Diker, 2020	X	X	√	X	√	X	High
Diker, 2021	X	√	√	X	√	√	Medium
Diker, 2021b	X	X	√	X	√	√	Medium
Donmez, 2021	X	√	√	X	√	X	Medium
Ender, 2013	X	X	√	X	√	X	High
Feng, 2021	X	X	√	X	√	√	Medium
Gavounelis, 2022	X	X	√	X	√	√	Medium
Gómez-Polo, 2022b	√	√	√	X	√	√	Low
Haddadi, 2018	X	√	√	X	√	X	Medium
Hayama, 2018	X	√	√	X	√	X	Medium
Kanjanasavitree, 2022	√	X	√	X	√	X	Medium
Kim, 2016	X	X	√	X	√	X	High
Kim, 2019	√	√	√	X	√	X	Medium
Kim, 2022	X	X	√	X	√	√	Medium
Kurz, 2015	X	√	√	X	√	X	Medium
Latham, 2019	√	√	√	X	√	√	Low
Li, 2022	X	√	√	X	√	X	Medium
Lopes, 2022	X	√	√	X	√	√	Medium
Yen Mai, 2022	X	√	√	√	√	X	Medium
Mandelli, 2018	X	X	√	X	√	X	High
Medina-Sotomayor, 2018	X	X	√	X	√	√	Medium
Mizumoto, 2019	√	√	√	X	√	X	Medium
Mizumoto, 2019b	X	√	√	X	√	X	Medium
Motel, 2020	X	X	√	X	√	X	High
Müller, 2016	X	X	√	X	√	X	High
Ochoa-López, 2022	X	√	√	√	√	√	Low
Oh, 2020	X	X	√	X	√	X	High
Oh, 2020b	X	X	√	X	√	X	High
Oh, 2021	X	X	√	X	√	X	High
Oh, 2022	X	X	√	X	√	X	High
Passos, 2019	√	√	√	X	√	X	Medium
Pattamavilai, 2022	√	√	√	X	√	X	Medium
Peroz, 2021	X	√	√	X	√	X	Medium
Rapone, 2020	X	√	√	X	√	X	Medium
Revilla-León, 2019	X	X	√	X	√	X	High
Revilla-León, 2020	X	X	√	X	√	√	Medium
Revilla-León, 2021	X	X	√	X	√	X	High
Revilla-León, 2022b	X	X	√	X	√	X	High
Rotar, 2022	X	√	√	X	√	X	Medium
Song, 2020	X	X	√	X	√	X	High
Stefanelli, 2021	X	√	√	X	√	X	Medium
Tao, 2020	X	X	√	X	√	X	High
Wesemann, 2020	X	X	√	X	√	√	Medium
You, 2022	X	X	√	X	√	X	High
Zarone, 2020	√	X	√	X	√	X	Medium

√=YES and X= NO

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volving fully edentulous arches or implant overdenture frameworks, obtaining accurate digital impressions can be challenging due to mobile tissue.[118,119] Additionally, Flügge *et al*.,[120] conveyed that the accuracy of scanned areas decreased when significant distances separated dental implant scanbodies. Furthermore, the presence of stable attached gingiva or palate wasn't enough to eliminate complications in stitching scans obtained from IOSs due to the absence of clear anatomical landmarks.[121] Clinicians recommend the use of artificial markers to overcome these challenges, and this study confirmed that the quality of scan data improved when artificial markers were used.[101]

For the influence of the scanning pattern on the precision and trueness of IOSs, the discrepancies between different measurements of IOSs were higher when a s-shaped pattern was used. On the other hand, the discrepancies between a master model and the digital scanner were higher when a linear pattern was used. The precision of the digital model relies on the starting point of the scan area as demonstrated previously.[122] In contrast, another study stating that the starting position of the area scanned does not influence accuracy and highlighted that the rotational and vertical movements of the IOSs head must be diminished, as an alteration of the direction might disturb an image-stitching procedure. Additionally, a report[70] determined that the vertical rotation of the IOS must be prevented. Previous manuscripts.[66,105] established numerous IOSs and discovered that the scan strategy influences the accuracy differently, depending on the data capturing method of each scanner. The scan strategy is strictly linked to the image merging software; if the scanner movement has severe changes in orientation or too fast, the stitching procedure might be compromised.[5,15] Scanning pattern that include a rotation of the IOS head may be delicate to the examiner. In all clinical scenarios, a careful scanning without a time limit is proposed, and trained operator should follow the recommendation of the manufacturer for better accuracy.

Finally, when the accuracy of IOSs is used in conjunction with scanning-aid materials, the results showed that only the precision is affected. It's worth noting that most IOSs in the dental market are powder-free, eliminating the need for scanning sprays. However, the clinical performance of these systems is limited to short-distance indications.[12,123] Besides, even though it is for a short distance, in some clinical situations, a challenge could occur when the clinician aims to obtain a reliable and a precise data for the required parts in the narrow and deep parts of the prepared teeth and prostheses using metallic materials as there is a light reflection.[124] Actually, the IOSs used in dental field are particularly sensitive to the transparency and glossiness of the scanned zone.[125,126] To address this limitation, researchers have explored the use of powder coatings to enhance opacity and eliminate reflections. Nevertheless, when the dentists use powder-type agents on teeth surface, making a uniform layer of powder by spraying is difficult, as the quantity of applied powder is importantly affected by the presence of saliva, the skills of operators, and the presence of tongue, adding the space between the dental arches.[127] Thus, the powder necessities to be applied as thin as possible, and the spraying time must be as short as possible.[107] Liquid-type scanning-aid materials with brush techniques have also been proposed to create thinner and more uniform layers compared to powder sprays, improving accuracy.[104] The results from this study propose that scanning-aid materials might be used efficiently to attain full-arch scan data.

Several limitations should be considered in this systematic review and meta-analysis. First, clinical studies were not included, limiting the generalizability of these findings to clinical scenarios. Additionally, the exclusion of some articles from the meta-analysis due to non-standardized scanning procedures affected the overall robustness of the analysis. Standardization in research methods is essential to facilitate meaningful comparisons in future meta-analyses. Lastly, it's essential to emphasize the importance of continuous training and education for clinicians and lab technicians to maintain a high clinical standard in the rapidly evolving field of digital dentistry.

CONCLUSION

Within the scope of this study, it can be concluded that several techniques, different from those recommended by the manufacturers of intraoral digital scanners, have been proposed. In order to improve the accuracy of these devices, this systematic review recommends taking digital impressions in dry conditions and using artificial landmarks, especially in cases without intraoral landmarks, such as edentulous patients.

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