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Review article

Accuracy of static and dynamic computer-aided implant surgery for immediate implant placement: A systematic review and meta-analysis

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Abstract

Purpose: To investigate the accuracy of static and dynamic computer-aided implant surgery (s/d-CAIS) for immediate implant placement for single-tooth replacement in healthy individuals with partially edentulous zones.

Study selection: A systematic search of six electronic databases for clinical studies reporting on Type 1 implant placement identified 15 eligible articles (seven RCTs, two prospective studies, and six retrospective studies) involving 383 patients. The focus question addressed population, intervention, comparison, and outcome criteria. A meta-analysis was performed using a random-effects model to obtain pooled estimates, presented as forest plots with weighted mean differences and 95% confidence intervals. Quality assessment was conducted using the Robin-I and RoB2 tools.

Results: The meta-analysis revealed that s/d-CAIS demonstrated significantly lower global platform and apex deviation compared to freehand placement, with mean differences of -0.70 mm (95% CI -0.74, -0.66; $P < 0.001$) and -0.86 mm (95% CI -1.00, -0.73; $P < 0.001$) respectively. The mean difference in platform depth deviation was statistically significant in favor of CAIS, with a mean difference of -0.73 mm (95% CI -1.04, -0.43; $P < 0.001$). High heterogeneity was observed across studies. The average global coronal, global apex, and angulation deviation for d-CAIS and s-CAIS were 0.72 mm, 0.81 mm, and 2.04 degrees, and 0.80 mm, 1.10 mm, and 2.12 degrees, respectively.

Conclusions: Data on Type 1 implant placement suggest that s/d-CAIS may enhance implant placement accuracy in several dimensions compared with freehand placement, with d-CAIS demonstrating marginally better control over angulation. However, the high heterogeneity across studies with a moderate-to-high risk of bias limits the generalizability of these findings.

Keywords: Dental implant, Computer-aided implant surgery, Immediate implant placement, Accuracy, Systematic review

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1. Introduction

Dental implants are an effective and clinically proven solution for the rehabilitation of partially dentate and edentulous patients. Initially designed for placement in patients with a healed alveolar ridge[1], the indications for dental implants have extended to include support for single crowns, fixed partial prostheses, long-span cross-arch prostheses, and retentive devices for removable prostheses, under different post-extraction placement and loading protocols[2–6].

With advancements in dental implant design, tissue engineering technologies, and surgical techniques, immediate implant placement in both the anterior and posterior regions of the jaw has gained acceptance as a successful treatment modality with clinical documentation and validation[7]. When appropriately applied in carefully selected clinical scenarios, the survival rate is comparable

WHAT IS ALREADY KNOWN ABOUT THE TOPIC?

» *Contemporary implant positioning during surgical placement can be facilitated by computer-aided implant surgery. The previous literature demonstrated promising results with CAIS in edentulous ridges. Meta-analyses of multiple clinical trials have demonstrated comparable results of implant placement accuracy between dynamic CAIS and static CAIS.*

WHAT THIS STUDY ADDS?

» *Several clinical challenges are associated with Type I implant placement. An up-to-date search was conducted between 2008 and 2025. Meta-analysis of the included studies indicates that CAIS may enhance implant placement accuracy in several dimensions when compared to freehand placement. This may overcome challenges with Type I placement.*

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to that of implants placed using other protocols, achieving a survival rate of over 95% in a 5-year observation period[8,9].

Immediate implant placement enhances the clinical experience of patients by reducing the number of surgical visits, shortening the total treatment time, and lowering treatment costs. However, for long-term clinical success in function, aesthetic, and peri-implant health, advanced surgical skills are required to place implants at the optimal presurgically planned three-dimensional position into the unique morphology of a fresh extraction socket with optimal primary stability[10], coupled with soft and hard tissue management. One particular concern is the potential spatial discrepancy between the implant and the bony walls of the extraction socket. This may negatively affect the initial primary stability unless an adequate portion of the implant, minimally 4 to 5mm at its apex, can engage with the surrounding pristine bone[11,12]. In addition, simultaneous ridge augmentation is often necessary in most cases to compensate for post-extraction resorption of the socket wall, posing additional challenges in achieving primary closure of the surgical wound. These factors collectively contribute to increased surgical complexity and a higher risk of complications associated with immediate implant placement surgery[13].

Ensuring proper positioning within the three-dimensional safety zone is challenging under these circumstances. This is of particular concern when implants are placed at sites with aesthetic priority, as a facially malpositioned implant results in a significant risk of midfacial mucosal recession[14,15]. These concerns are further compounded by the synergistic effects of other identified risk factors, including (i) smoking, (ii) a buccal plate thickness of less than 1 mm, and (iii) soft tissue biotype[14,15].

Computer-aided implant surgeries can facilitate contemporary implant positioning during surgical placement. With the use of cone-beam computed tomography (CBCT), intraoral scanning technology, and appropriate software to register both datasets, it is possible to recreate a virtual jaw for implant site assessment and planning according to the diagnostic prosthetic setup of the expected outcome. The virtual implant planning process enables accurate prosthetic-driven planning, which also provides possibilities for transferring the planned implant position into clinical reality. This can be achieved using either a static surgical guide with standard-length osteotomy drills and drill sleeves or a dynamic navigation system, which provides instant osteotomy feedback and unobscured visibility of the surgical sites to operators during implant surgery[16–19]. Both methods have unique advantages and disadvantages.

One of the primary considerations in guided surgery is the accuracy of implant placement with reference to the presurgical plan. A recent systematic review and meta-analysis reported that computerized technology improved the accuracy of implant placement, with a mean deviation of 1.11mm at the entry point and 1.40mm at the apex and an angulation of 3.51°. Among the computerized modalities, the robotic system exhibited the least coronal, apical, and angular deviation[20].

Meta-analyses of multiple clinical trials demonstrated comparable implant placement accuracies between dynamic and static CAIS. Guided surgery, when properly executed, has also shown promising accuracy results for implant placement on healed ridges[21–26]. However, the efficacy of guided implant surgery in immediate implant placement cases, where osteotomy is performed in a fresh extraction socket with an irregular shape, has yet to be systematically analyzed. The preparation of such irregular sockets may negatively affect the stability of the surgical guide in s-CAIS and manual control of the osteotomy drills in d-CAIS, thus leading to a deviation from the intended final implant position. It remains unclear whether both types of CAIS can effectively assist clinicians in achieving the ideal planned three-dimensional (3D) position, particularly with the challenging type 1 placement approach.

This systematic review aimed to assess-the accuracy of the s-CAIS and d-CAIS in immediate implant placement (Type 1 protocol) for single-tooth replacement in healthy adult patients with partially edentulous zones.

2. Methodology

2.1. Registration and study protocol

The review protocol was registered in the International Prospective Register of Systematic Review (PROSPERO) of the National Institute of Health Research (Registration Number: CRD42022313095). The reporting format adhered to the guidelines and recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA). The PRISM checklist is provided in the Supplementary Materials.

2.2. Objectives

This review aimed to address the following question: "What is the clinical accuracy of s-CAIS and d-CAIS in Type 1 implant placement?"

2.3. PICO question

The following population, intervention, comparison, and outcome (PICO) criteria were established to investigate the designed focus question: Population (P): Healthy adult patients (age > 18 years at the time of intervention) with a non-salvageable single tooth requiring immediate implant placement, regardless of tooth position, were included. Both smokers and non-smokers were considered eligible. Studies involving full-arch replacement (removable or fixed restoration) were excluded because this review focused on partially dentated individuals.

Intervention (I): The intervention involved the use of a computer-aided design/computer-aided manufacturing (CAD/CAM) surgical guide designed using implant planning software via CBCT registration and surface scan data from an intraoral scanner or model scanning using a desktop scanner. Only implants placed with full-guide surgical execution were considered. Both milled and 3D-printed static guides were accepted during the selection of the studies.

Dynamic guided surgery can be planned using the aforementioned technique and conducted under the guidance of a 3D surgical navigational system, which provides real-time feedback of the 3D orientation to the surgeon. Orthodontic, pterygoid, and zygomatic implants as well as specialized techniques, including but not limited to simultaneous sinus lifting or the socket shield technique, were excluded.

Comparison (C): Freehand implant placement with presurgical implant planning.

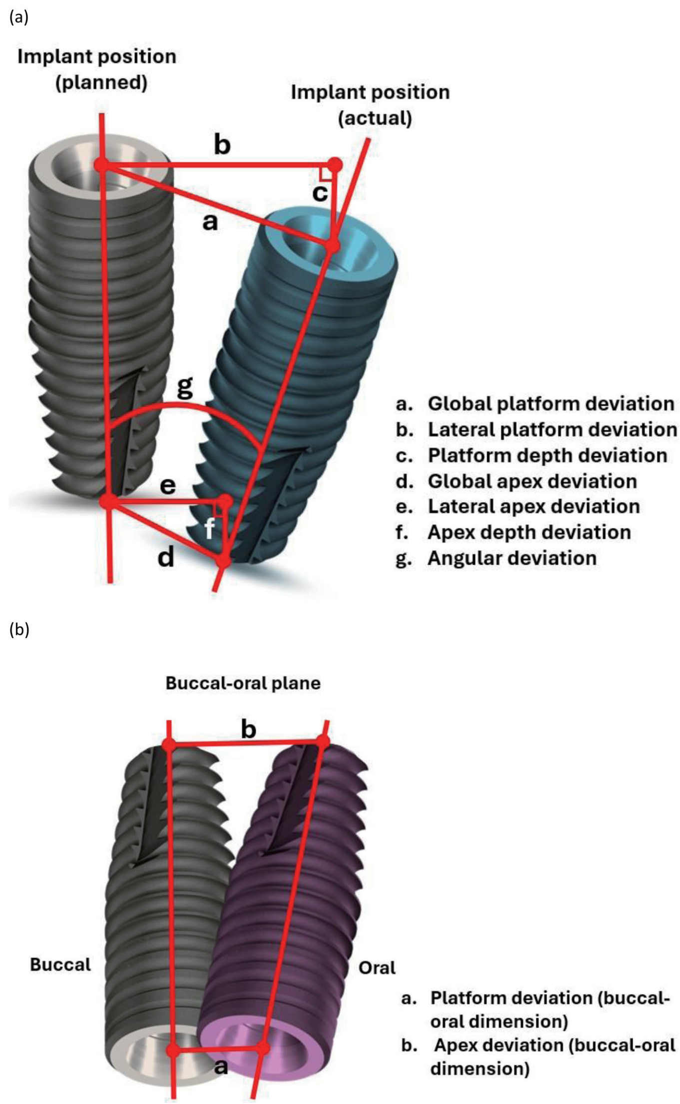

Fig. 1. Three-dimensional difference of final implant position in relation to presurgically planned implant position. (a) Global error at entry point. (b) Global error at the apical point. (c) Depth error. (d) Angle deviation.

Outcome (O): The primary outcomes included the classical parameters measuring the difference in the 3D final implant position in relation to the presurgically planned implant position, as shown in **Figure S1a,** which includes the following:

- Global platform deviation, at the entry point, in millimeters
- Global apex deviation, at apical point, in millimeters
- Angular deviation, in degree

Secondary outcomes included other parameters measuring the difference in the 3D final position and insertion torque recorded during implant placement (**Figs. 1a and b**).

- Lateral platform deviation, in millimeters
- Depth error, platform depth deviation, in millimeters
- Depth error, apex depth deviation, in millimeters
- Lateral apex deviation, in millimeters
- Platform deviation in buccal-oral dimension, in millimeters
- Apex deviation in buccal-oral dimension, in millimeters

Information pertaining to insertion torque was collected and presented narratively to explore the feasibility of achieving good primary stability. Relevant data from selected studies were extracted by K.L. and verified by M.F. The results, as stated above, were collected from qualified research articles and analyzed across the mode of guidance using either d-CAIS or s-CAIS.

2.4. Information sources and search strategy

Six electronic databases were systematically searched for relevant literature: PubMed, Web of Science, MEDLINE, Scopus, Embase, and the Cochrane Central Register of Controlled Trials. Only studies published in English were included in this meta-analysis. The publication time was restricted from January 2008 to January 2025. Previous research has suggested that data generated before 2008 exhibited greater variation in accuracy, which is likely attributable to technological limitations in that era[27]. The search was performed on 15 June 2023, and updated on 23 January 2025, using a combination of free keywords and MeSH terms (**Tables S2 and S3**). The reference lists of the included articles and relevant systematic reviews were reviewed for additional reports. A manual search of the following 10 journals within the same timeframe was also performed to identify relevant materials:

- Clinical Implant Dentistry-Related Research
- Clinical Oral Implants Research
- Implant Dentistry
- Journal of Esthetic and Restorative Dentistry
- International Journal of Oral and Maxillofacial Implants
- International Journal of Oral and Maxillofacial Surgery
- International Journal of Periodontics and Restorative Dentistry
- Journal of Clinical Periodontology
- Journal of Periodontology
- Journal of Prosthetic Dentistry

2.5. Eligibility criteria

2.5.1. Inclusion criteria

This systematic review aimed to encompass relevant findings from clinical studies. Only prospective human randomized or non-randomized controlled trials, cluster trials, prospective and retrospective cohort studies, case-control studies, and case series with a minimum of 10 human participants aged 18 years or older using a tooth-supported static guide with fully guided surgical execution or d-CAIS were included.

Both s-CAIS and d-CAIS were included in this review. Two common drilling protocols have been identified among the static guide systems: the pilot drill guide and the full guide approach. A recent systematic review found a higher degree of accuracy in all measured dimensions when implants were placed using a fully guided approach[27]. To ensure clarity and meaningful comparisons, only tooth-supported static guides with fully guided surgical execution were included in this review.

2.5.2. Exclusion criteria

Case reports, abstracts only, protocols, book chapters and proceedings, reviews, expert opinions, and model, animal, or cadaver studies were excluded from this review.

2.6. Study selection

Title and abstract screening for potential inclusion in this review was conducted independently by K. L. and M.Z. using the Covidence platform (Covidence systematic review software, Veritas Health Innovation, Melbourne, Australia. Available at www.covidence.org.). Full text was obtained if the title or abstract did not report sufficient information regarding the eligibility criteria. Duplicates were manually removed using the automated detection function of the platform. Subsequently, the full texts of the articles that met the initial screening criteria were obtained and thoroughly evaluated. In cases of disagreement during the process, a final decision was made by M.F.; reasons for exclusion following full-text screening were meticulously documented and recorded (**Table S4**). Agreement between the examiners was computed and reported using kappa statistics.

2.7. Data extraction

Data from the selected studies fulfilling the inclusion criteria were extracted and tabulated in an Excel spreadsheet (Microsoft Corp., Redmond, WA, USA) initially by one reviewer (K.L.), and the second reviewer (M.Z.) double-checked all the proceedings. Information regarding the author, year of publication, study design, number of patients, number of implants, presurgical examination, implant planning software, implant brand and size, funding information, and postsurgical examination were gathered as background information.

Data addressing the outcome measures stated in the PICO were extracted for further analysis.

2.8. Quality assessment and risk of bias

Risk of bias analysis of the selected studies was conducted independently by two assessors (K. L. and M. F.). Randomized trials were evaluated using the Cochrane Collaboration's Tool for Assessing Risk of Bias in Randomized Trials (RoB 2)[28], while nonrandomized studies were assessed using the Risk of Bias in Nonrandomized Studies of Interventions (ROBINS-I)[29]. Any disputes were resolved through open discussion until a consensus was reached.

For randomized clinical trials, the risk of bias was assessed using the following domains:
1. Randomization
2. Deviations from the intended interventions (effect of assignment)
3. Missing outcome data
4. Measurement of the outcome
5. Selection of the reported outcome

The overall risk of biased judgment was categorized as follows:
1. Low risk: when all domains presented low risk
2. Some concerns: when some concerns were identified in at least one domain
3. High risk: when a high risk was found in at least one domain or when concerns for multiple domains were identified.

For nonrandomized studies, the risk of bias was assessed in the following domains:
1. Confounding factors
2. Selection of participants for the study
3. Classification of interventions
4. Deviations from the intended interventions (effect of assignment)
5. Missing outcome data
6. Measurement of the outcome
7. Selection of the reported outcome

The overall risk of biased judgment was categorized as follows:
1. Low risk: when all domains presented low risk
2. Moderate risk: when all domains presented low to moderate risk
3. Serious risk: whenever serious risk was identified in at least one of the domains
4. Critical risk: whenever critical risk was identified in at least one of the domains
5. No information: lack of information in at least one domain

2.9. Summary of findings and statistical analysis

The data were tabulated, and a descriptive summary was prepared. The primary studies were evaluated for homogeneity in terms of subject and site selection, intervention type, outcome type, and measurement.

A meta-analysis was performed only when the study design, selection criteria, and surgical protocol were comparable, ensuring a reliable summary of outcome variables.

A narrative summary is presented to provide a comprehensive overview of the findings and characteristics of the included studies. The results of the analyses are presented in a tabulated format.

Summaries of the intervention effects for each study are presented as deviations in positional accuracy (global platform error, global apex error, depth error, and angular deviation). Owing to the expected inter-study heterogeneity, the frequentist (classical) random effect (DerSimonian and Laird (DL) approach) meta-analysis was used to combine the results from the studies with 95% confidence intervals. Two-sided *P* values for each outcome are also presented in a forest plot.

Meta-analysis was performed using Stata version 16 (StataCorp, College Station, TX, USA).

Meta-analyses were performed using random effects models by grouping studies with CAIS as the experimental arm and freehand as the control arm. For these meta-analyses, only studies that used the CAIS (experimental) or freehand placement (control) were included. Forest plots were used to illustrate the meta-analysis outcomes.

The Chi-square-based Q-statistic method and I-squared measurements were used to assess statistical heterogeneity. An I-squared value greater than 40% or *P*-value for the Chi-squared tests less than 0.10 were considered indicative of substantial heterogeneity among studies[30,31].

3. Results

3.1. Summary of the literature review process [SEARCH]

An initial search of the existing literature from six databases (PubMed, Web of Science, Embase, MEDLINE, Scopus, and Cochrane Central Register of Controlled Trials revealed 7189 studies eligible for assessment. After deleting 2392 duplications, 4797 articles were identified. Title and abstract screening led to the exclusion of 4695

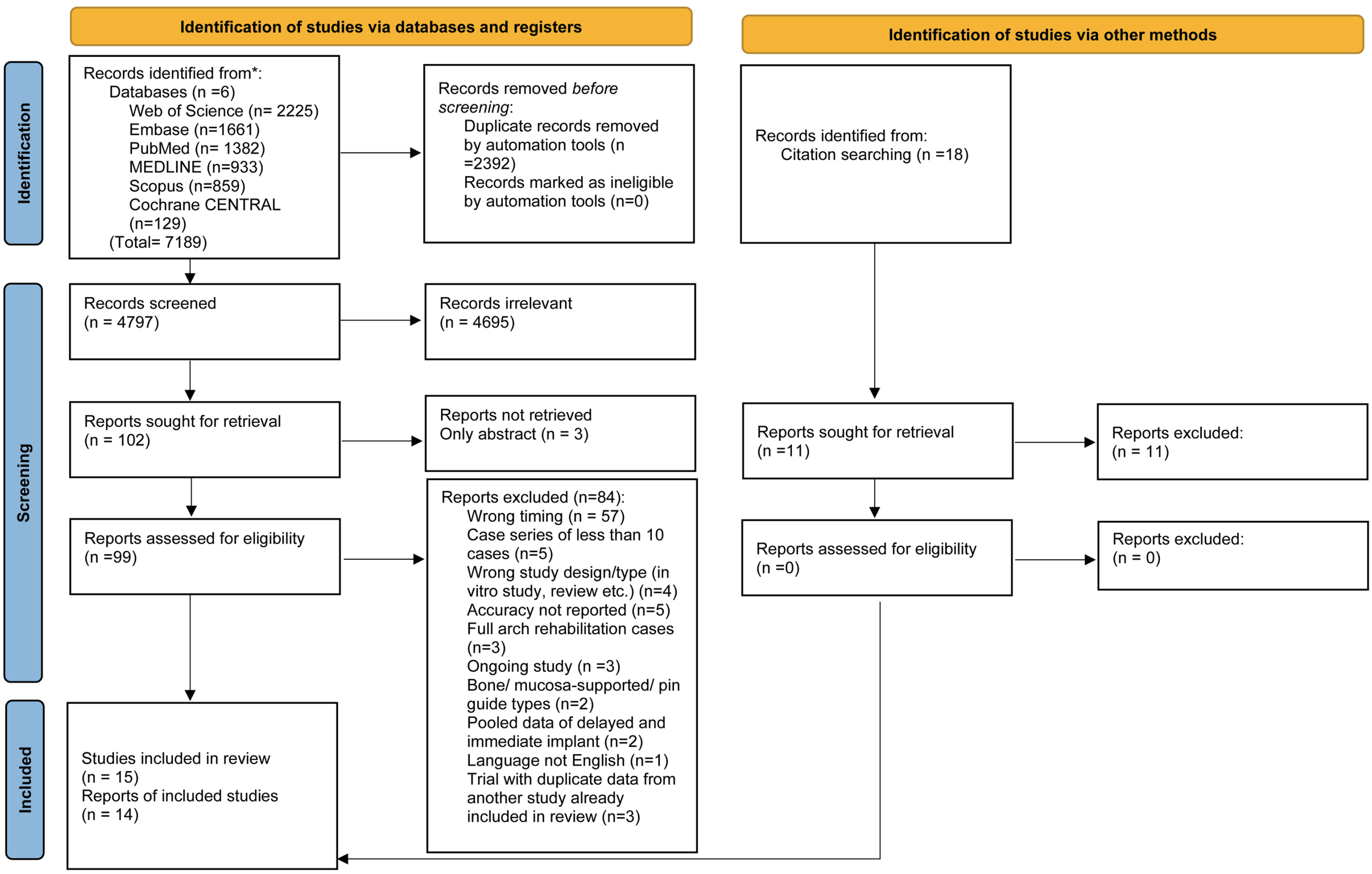

Fig. 2. PRISMA Flow diagram of the search strategy and selection process

articles. The full texts of the remaining 102 studies were retrieved, of which three were not retrievable (Carini *et al.* 2021, Sharma *et al.* 2017, Herklotz *et al.* 2023), and the rest underwent full-text reading. Finally, 15 studies fulfilled the inclusion criteria and were included for this review[32–46]. (**Fig. 2**)

A manual search was conducted within the same timeframe and 18 additional relevant studies were identified. Systematic search of databases revealed eight studies to be duplicate. The full texts of the remaining 11 studies were examined, and no further studies satisfied the inclusion criteria. For title and abstract screening, Cohen's Kappa value was 0.37 between the two assessors. For the full-text review, excellent agreement was demonstrated between the two assessors (K. L. and M. Z.) with a Cohen's Kappa value of 0.80.

3.2.1. Description of included studies

This study included seven randomized controlled clinical trials[33,37–41,46], two prospective studies[42,45], and six retrospective studies[32,34–36,43,44]. Ten studies used the static guidance system[32,33,35–39,42,44,45]. Six studies examined the dynamic navigation system[34,37,40,41,43,46].

The background characteristics of the included studies are presented in **Table 1**. All the included studies were conducted between 2016 and 2025. Altogether, 383 patients were included in the 15 selected studies, with an age range from 18 to 69 years old. Of the included studies, nine originated from China, two from the Middle East, two from Italy, one from Brazil, and one from India. Of the total patients, 241 received immediate implant placement with a full static guide, dynamic guide, or freehand, fitting the criteria for further analysis. A total of 186 and 74 implants were placed with s-CAIS and d-CAIS, respectively.

Table 1 summarizes the background and characteristics of the included studies. All included studies recruited partially edentulous cases with bounded edentulous spans, mostly in the anterior upper and lower aesthetic zones, from the incisor to the premolar region. Four studies included immediate placement in the posterior region[32,43,45,46]. CBCT was utilized to capture presurgical 3D radiographic images of the study participants, while intraoral scanning was performed to obtain virtual surface data. Subsequently, both datasets were transferred to the implant-planning software for positional planning and surgical execution. Most studies mentioned that immediate implants were placed using a flapless approach after careful minimally traumatic extraction of non-salvageable teeth. Implant length and diameter were reported in only five studies[34,35,40,41,46]. Grafting procedures, mainly with xenografts, were reported in five studies[37–41]. One study used connective tissue grafts (CTG) in addition to the xenograft[39]. All studies used CBCT for postoperative evaluation of the implant position, and one study included scanning of the master cast to assess the implant position in the control group[32].

Table 1. Study and patient characteristics of the reviewed studies

		Alzoubi *et al.*, 2016[32]	Chen *et al.*, 2020[36]	Zhang *et al.*, 2021[42]	Battista *et al.*, 2022[34]	Caggiano *et al.*, 2022[35]	Geng *et al.*, 2024[43]	Li *et al.*, 2024[44]	Mittal *et al.*, 2024[45]
Background									
Study design		Retrospective Observational	Retrospective Observational	Prospective NRT	Retrospective Case-series	Retrospective Observational	Retrospective Observational	Retrospective Observational	Prospective Clinical trial
Region and setting		Kuwait (university)	Sichuan, China (university)	Sichuan, China (university)	Naples, Italy (university)	Salerno, Italy NR	Guangzhou, China (University)	Guizhou, China (university)	Jaipur, India (Dental College and Hospital)
Age (years)	Mean (SD) Control Experimental 1 Experimental 2	NR NR	40.69 (13.16) 40.74 (14.14)	41.0 (15.9) 39.6 (14.7)	N/A 45.5 (6.15)	NR NR	48.75 (15.63) 50.32 (19.24) 45.8 (16.48)	41.33 (16.28) 36.22 (12.11)	57
Number assessed (participants/ sites)	Control Experimental 1 Experimental 2	Delayed 9/15 Immediate 20/25	Full guided 13/17 Half guided 19/23	Delayed 14/16 Immediate 11/14	N/A 12/22	Delayed: 58/58 Immediate 37/37	Freehand: 30/46 s-CAIS: 26/44 d- CAIS: 28/40	freehand: 40 s-CAIS: 33	Delayed 12/12 Immediate 12/12
Types of guided surgery (fabrication)		Full static guide	Full/ Half static guided (CAD/CAM)	Full static guided	Dynamic navigation	Static guide (3D printing)	Static guide (3D printing) Dynamic navigation	Static guide (3D printing)	Static guide
Teeth		immediate group: 8 were placed in the anterior region and 17 were placed in the posterior region	Upper and lower anteriors	Anterior aesthetic zone	Maxillary aesthetic zone	Maxillary incisor	Posterior mandibular region	Upper and lower jaw anteriors	Posterior region
Method of assessment		CBCT Cast	CBCT	CBCT	CBCT	CBCT	CBCT	CBCT	CBCT
Accuracy measurement									
Global platform/ coronal/ entry/ neck deviation (mm)	Mean (SD) Control Experimental 1 Experimental 2	N/A N/A	* 0.66 (0.26) 1.10 (0.76)	0.5 (0.3) 0.7 (0.3)	N/A 0.77(0.25)	N/A N/A	* 1.28 (0.12) 0.73 (0.10) 0.55 (0.08)	1.29 (0.52) 1.01 (0.41)	0.15 (0.18) 0.26 (0.30)
Global Apex deviation (mm)	Mean (SD) Control Experimental 1 Experimental 2	N/A N/A	* 0.96 (0.41) 1.43 (0.70)	1.0 (0.5) 1.0 (0.4)	N/A 1.2 (0.61)	N/A N/A	* 2.22 (0.30) 1.33 (0.42) 0.52 (0.13)	* 1.78 (0.59) 1.24 (0.52)	0.25 (0.33) 0.23 (0.24)
Depth deviation at entry level / Platform depth deviation/ vertical coronal deviation (mm)	Mean (SD) Control Experimental	Delay: 0.88 (0.43) Imme: 0.85 (0.65)	* Full: 0.46 (0.24) Half: 0.93 (0.79)	N/A N/A	N/A N/A	N/A N/A	N/A N/A	0.88 (0.51) 0.67 (0.4)	N/A N/A
Apex depth deviation/ vertical apical deviation (mm)	Mean (SD) Control Experimental	* Delay: 1.59 (1.01) Imme: 1.10 (0.65)*	N/A N/A	0.4 (0.3) 0.5 (0.3)	N/A N/A	N/A N/A	N/A N/A	0.89 (0.51) 0.60 (0.42)	* 0.17 (0.10) 0.39 (0.34)
Angulation (degree)	Mean (SD) Control Experimental 1 Experimental 2	4.29 (2.46) 3.49 (2.83)	* 1.69 (0.94) 2.57 (1.57)	* 2.0 (1.1) 1.7 (1.0)	N/A 2.5 (0.41)	* 1.18 (0.54) 1.04 (0.56)	* 3.52 (1.03) 1.77 (0.30) 0.88 (0.45)	* 6.46 (2.21) 2.94 (1.71)	* 0.53 (060) 1.03 (0.70)

3.2.2. *Quality assessment*

Eight nonrandomized controlled studies, including six retrospective studies[32,34–36,43,44] and two prospective studies[45,47] were assessed using the ROBINS-I tool. Most patients presented a serious risk of bias, while three presented a moderate risk (**Fig. 3a**).

Eight RCTs were assessed using the RoB2 tool. One study presented with a low risk, five of them were presented with a moderate risk, and two of them were presented with a high risk of bias. One of the studies with a high risk of bias[48] was excluded from the meta-analysis because the guided surgery did not meet the inclusion criteria of the current review (**Fig. 3b**).

The study by KR *et al.* (2023)[48] fit most of the inclusion criteria. However, only patients with distal edentulous spans were included

Table 1. Continued

		Kraft *et al.*, 2020[39]	**Han *et al.*, 2021[38]**	**Ayman *et al.*, 2022[33]**	**Feng *et al.*, 2022[37]**	**Wei *et al.*, 2022[41]**	**Wei *et al.*, 2022 [40]**	**Chandran *et al.*, 2023[49]**	**Yang *et al.*, 2024[46]**
Background									
Study design		RCT Parallel	RCT Parallel	RCT Parallel	RCT Parallel	RCT Parallel	RCT Parallel	RCT Parallel	RCT Parallel
Region		Brazil (University)	Inner Mongolia, China (University)	Cairo, Egypt (University)	Sichuan, China (University)	Shanghai, China (University)	Shanghai, China (University)	India (University)	Guangzhou, (University, Hospital)
Age (years)	Mean (SD) Control Experimental	NR NR	32.94 (6.76) 31.08 (5.81)	NR NR	42.60 (12.83) 36.40 (13.11)	31.00 (5.71) 32.88 (7.30)	40 (17) 35 (15)	36.03 38.2	48.26 (20.15) 43.7 (17.59)
Number of subjects/ number of implants	Control Experimental	Partly static guided 12/12 Full static guide 12/12	Conventional static guide 30/52 Whole process digitalisation static guide 30/50	Freehand 11/11 Static guided 11/11	Static 20/20 Dynamic 20/20	Dynamic-guided Tapered implant 10/10 Dynamic-guided Straight implant 10/10	Freehand 12/12 Dynamic 12/12	Freehand 32/40 Guided 29/40	Freehand 28/46 Dynamic 32/50
Types of guided surgery	Control Experimental	Partially static guided Fully static guided	2mm plastic film for simple surgical guide Digital design guide plate	Freehand Static guided	Static guided Dynamic navigation	Dynamic navigation for both arms	Freehand Dynamic navigation	Freehand Static guided	Freehand Dynamic navigation
Teeth		Maxillary incisor	Maxillary aesthetic zone	Maxillary aesthetic zone	Maxillary aesthetic zone	Maxillary anterior teeth	Maxillary anterior teeth	Maxilla/ mandible Single/ multiple gaps	Posterior maxillary region
Method of assessment		CBCT	CBCT	CBCT	CBCT	CBCT	CBCT	CBCT	CBCT
Accuracy measurement									
Global platform/ coronal/ entry/ neck deviation (mm)	Mean (SD) Control Experimental Combined	1.34 (0.99) 1.26 (0.57)	0.87 (0.39) 0.74 (0.21)	1.43 (1.14) 0.69 (0.36)	0.99 (0.63) 1.06 (0.55)	0.86 (0.26) 0.89 (0.44) 0.87 (0.35)	* 1.51 (0.67) 1.01 (0.41)	* 1.13 (0.89) 0.34 (0.26)	* 1.26 (0.13) 0.56 (0.07)
Global Apex/ root deviation (mm)	Mean (SD) Control Experimental Combined	* 1.97 (1.04) 2.50 (1.67)	0.93 (0.25) 0.81 (0.16)	* 2.35 (1.05) 1.26 (0.42)	1.50 (0.75) 1.18 (0.53)	0.76 (0.33) 0.88 (0.36) 0.81 (0.34)	* 1.94 (0.86) 0.88 (0.43)	* 4.04 (1.90) 0.97 (0.55)	* 1.33 (0.42) 0.49 (0.26)
Depth deviation at entry level / Platform depth deviation (mm)	Mean (SD) Control Experimental	1.04 (1.05) 0.90 (0.63)	0.48 (0.20) 0.39 (0.12)	* 1.27 (0.16) 0.43 (0.41)	0.44 (0.81) 0.59 (0.78)	N/A N/A	* 0.95 (0.68) 0.44 (0.46)	N/A N/A	N/A N/A
Apex depth deviation (mm)	Mean (SD) Control Experimental	1.04 (1.05) 1.01 (0.64)	N/A N/A	* 2.08 (1.32) 0.61 (0.33)	0.50 (0.81) 0.63 (0.75)	N/A N/A	0.83 (0.69) 0.45 (0.57)	N/A N/A	N/A N/A
Angulation	Mean (SD) Control Experimental Combined	3.60 (2.84) 5.36 (4.53)	* 2.98 (1.93) 2.17 (0.92)	3.18 (0.96) 3.14 (1.37)	3.07 (2.18) 3.23 (1.67)	2.49 (1.54) 2.31 (1.01) 2.40 (1.31)	5.97 (5.37) 2.51 (1.50)	* 6.09 (3.23) 0.83 (0.53)	* 3.35 (1.12) 1.03 (0.55)

N/A: not applicable; NR: not reported; *Statistically significant difference between control and experimental group; †Depth deviation in coronal or apical dimension not specified

in the study. Given the aforementioned considerations, non-tooth-bounded saddles with static guides that did not rest on the adjacent teeth were excluded from the current review. The study details are included in **Table S1**. A Risk of Bias (RoB) analysis was performed. Moreover, this selection renders a more appropriate comparison with the dynamic guided system, which consistently follows fully guided implant insertion. Nonetheless, a sensitivity analysis was performed to evaluate the impact of including this study in the meta-analysis results.

3.3. Main findings

3.3.1. Pooled accuracy of s-CAIS, d-CAIS, and freehand implant surgery for Type I implant placement

The pooled mean deviations of the accuracies of different CAIS and freehand implant surgeries from studies reporting the same primary outcome were assessed. The common parameters used for accurate measurements, including angular deviation, global platform deviation, and global apex deviation, are reported in this section. Other parameters found in the literature, including platform

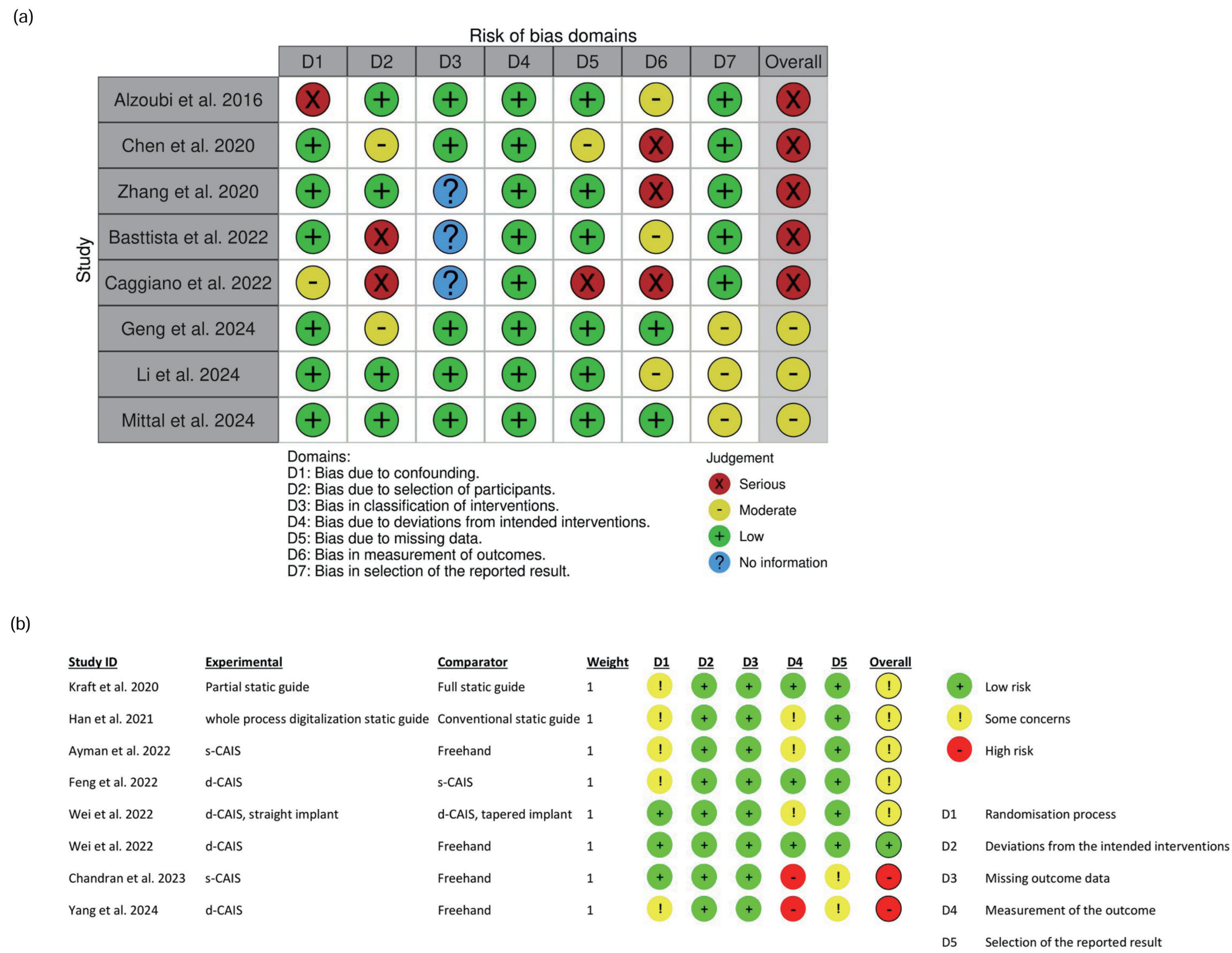

Fig. 3. Risk of bias assessment. (a) Quality assessment for non-randomized controlled studies. (Robins-I). (b) Quality assessment for randomized controlled studies. (Rob 2.0). s-CAIS: static computer-aided implant surgery, d-CAIS: dynamic computer-aided implant surgery.

depth deviations, lateral platform deviations, apex depth deviations, general depth deviation, platform deviations, and apex deviations in the buccaloral dimension are reported in the Supplementary section (**Figs. S1-S7**).

3.3.1.1. Angulation deviation

The mean angular deviations of the implants placed with d-CAIS, s-CAIS, and freehand were 2.04 degrees (95% CI 1.31-2.77), 2.12 degrees (95% CI 1.74-2.50), and 4.27 degrees (95% CI 3.30-5.24), respectively, as reported in the random effects model. Substantial heterogeneity was detected for the studies utilizing all three modalities, d-CAIS (I^2=98.2%, $P < 0.001$), s-CAIS (I^2=92.7%, $P < 0.001$), and freehand placement (I^2=94.3%, $P < 0.001$) (**Fig. 4**).

3.3.1.2. Global platform deviation

For global platform deviation, the mean deviations of implants placed with d-CAIS, s-CAIS, and freehand were 0.72mm (95% CI 0.63-0.80), 0.80mm (95% CI 0.72-0.88), and 1.27mm (95% CI 1.25-1.30), respectively. Freehand placement reported across studies demonstrated the lowest heterogeneity (I^2=0%, P = 0.668), whereas moderate and substantial heterogeneity was observed in studies reporting implants placed using s-CAIS (I^2=75.0%, $P < 0.001$) and d-CAIS (I^2=91.9%, $P < 0.001$), respectively (**Fig. 5a**).

3.3.1.3. Global apex deviation

For global apex deviation, the mean deviations of implants placed with d-CAIS, s-CAIS, and freehand were 0.81 mm (95% CI 0.63-0.99), 1.10 mm (95% CI 0.84-1.36), and 1.90 mm (95% CI 1.43-2.37), respectively. High heterogeneity was observed in studies reporting d-CAIS (I^2=93.5%, $P < 0.001$), s-CAIS (I^2=96.0%, $P < 0.001$), and freehand placement (I^2=97.2%, $P < 0.001$) (**Fig. 5b**).

3.3.2. Accuracy of freehand implant surgery versus d/s-CAIS

Three of the RCTs included in this review were comparable in terms of the control and intervention arms: parallel-group RCTs conducted by Ayman *et al.* (freehand vs. s-CAIS)[33], Wei *et al.* (free-

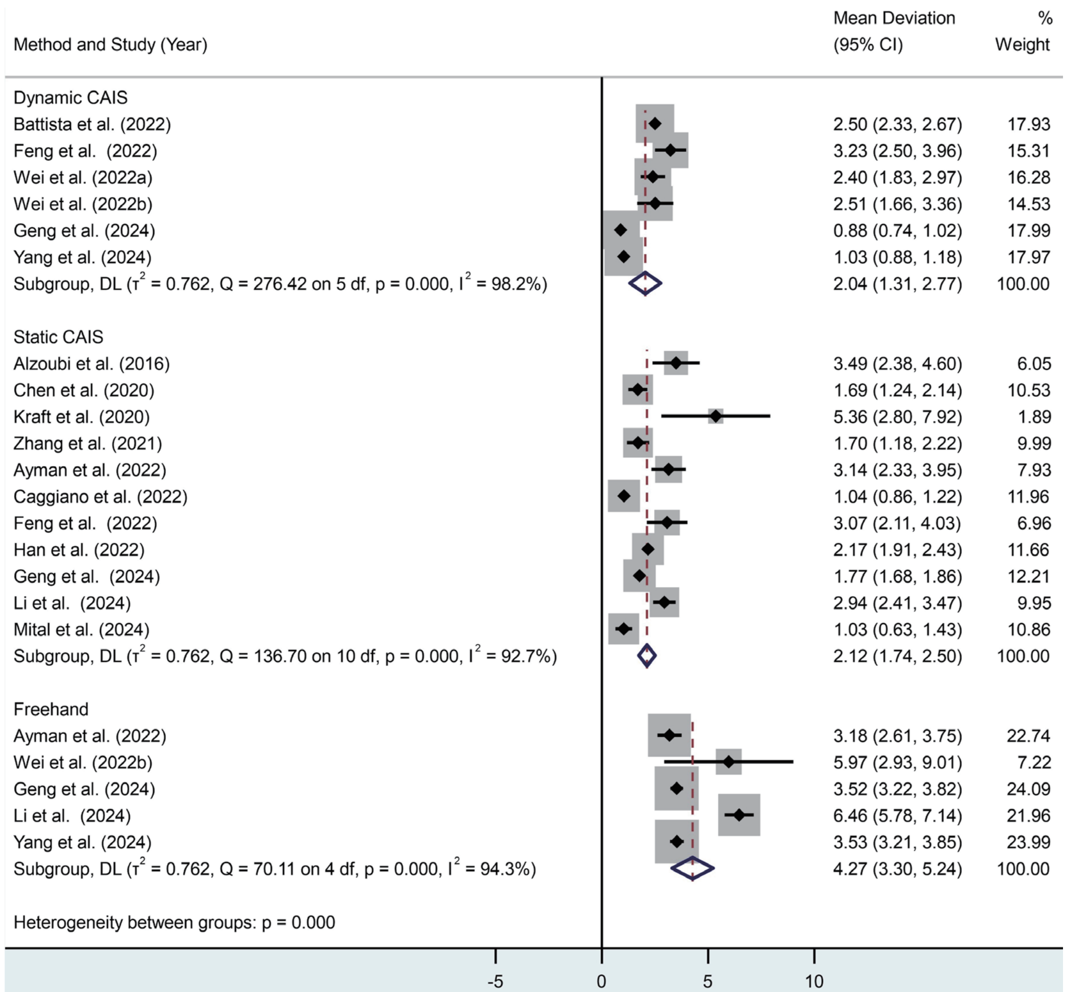

Fig. 4. Mean angulation deviations of implants placed with dynamic computer-aided implant surgery (d-CAIS), static computer-aided implant surgery (s-CAIS), and freehand.

hand vs. d-CAIS)[40], and Yang *et al.* (freehand vs. d-CAIS)[46]. These studies reported angulation, global platform, global apex, platform and apex depth, and lateral platform and apex deviations. Data from both static and dynamic guided implant surgeries were pooled for the meta-analysis. Subgroup analyses were performed for three main parameters: angular, global platform, and global apex deviations. A random-effects model was used for analysis.

3.3.2.1. Angulation deviation

The meta-analysis of angular deviation from the planned implant position yielded a weighted mean difference of -1.67 degrees (95% CI -3.57-0.23). No statistically significant difference in implant angulation was observed between immediate placement with CAIS and freehand placement (P = 0.085). However, substantial heterogeneity was detected in the analysis (I^2=89.4%, $P < 0.001$) (**Fig. 6**). On comparing d-CAIS with freehand placement, the meta-analysis yielded a weighted mean difference of -2.33 degree (95% CI -2.69, -1.96). A statistically significant difference was observed between d-CAIS and freehand placement in terms of angulation from the planned position ($P < 0.001$), with low heterogeneity observed between studies (I^2=0%, P = 0.482) (**Fig. 6**).

3.3.2.2. Global platform deviation

The mean difference in global platform deviation between CAIS and freehand placement was 0.70 mm (95% CI -0.74, -0.66). A statistically significant difference favoring immediate placement with both the d-CAIS and s-CAIS for freehand placement was observed ($P <$ 0.001). Heterogeneity, as expressed by the I^2 test, was 0% (P = 0.676) (**Fig. 7a**).

3.3.2.3. Global apex deviation

The mean difference in global apex deviation between CAIS and freehand placement was -0.86 mm (95% CI -1.00, -0.73; $P < 0.001$). A statistically significant difference was observed between immediate d-CAIS and s-CAIS placements and freehand placement. The heterogeneity, as expressed by the I^2 test, was 0% (P = 0.592) (**Fig. 7b**).

3.3.2.4. Platform and apex depth deviations

Depth deviation was described in some of the included studies in the platform and apical regions. One study[46] did not specify the region of the depth deviation measurement and was therefore excluded from the meta-analysis.

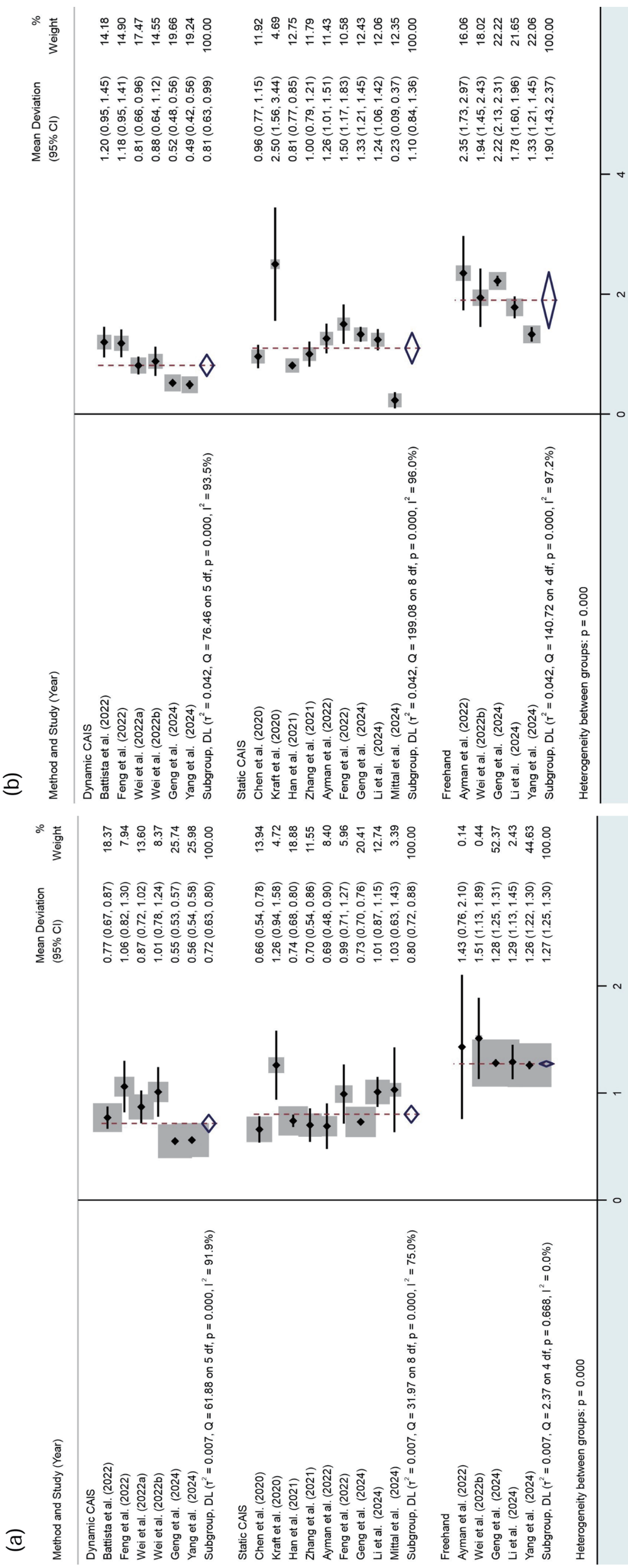

Fig. 5. (a) Mean global platform deviations. (b) Mean global apex deviations of implants placed with dynamic computer-aided implant surgery (d-CAIS), static computer-aided implant surgery (s-CAIS), and freehand.

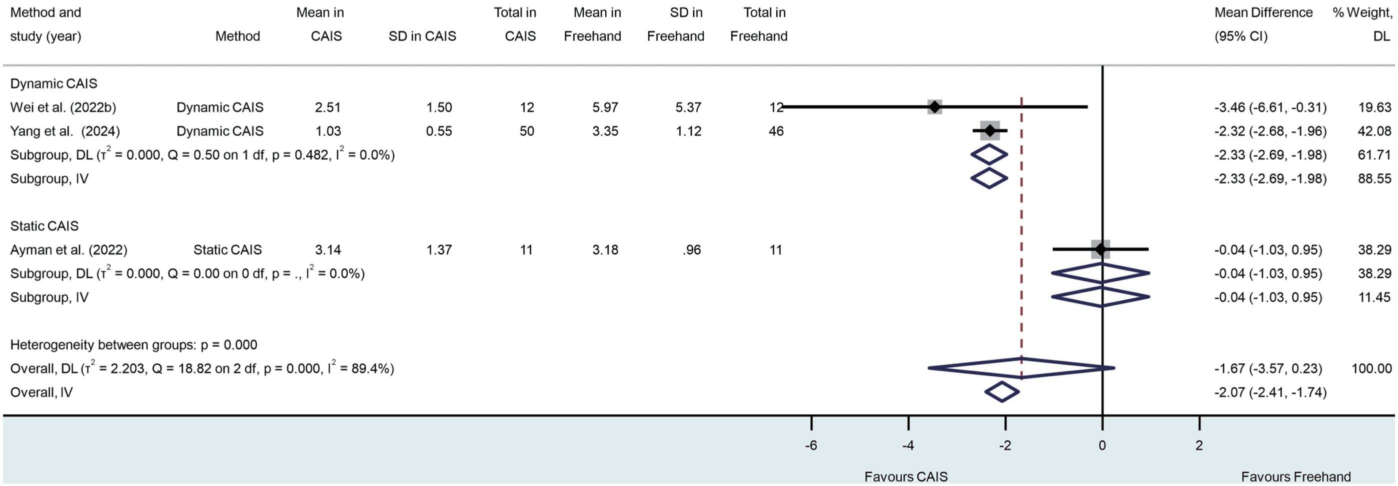

Fig. 6. Angulation deviation of computer-aided implant surgery (CAIS) versus freehand placement

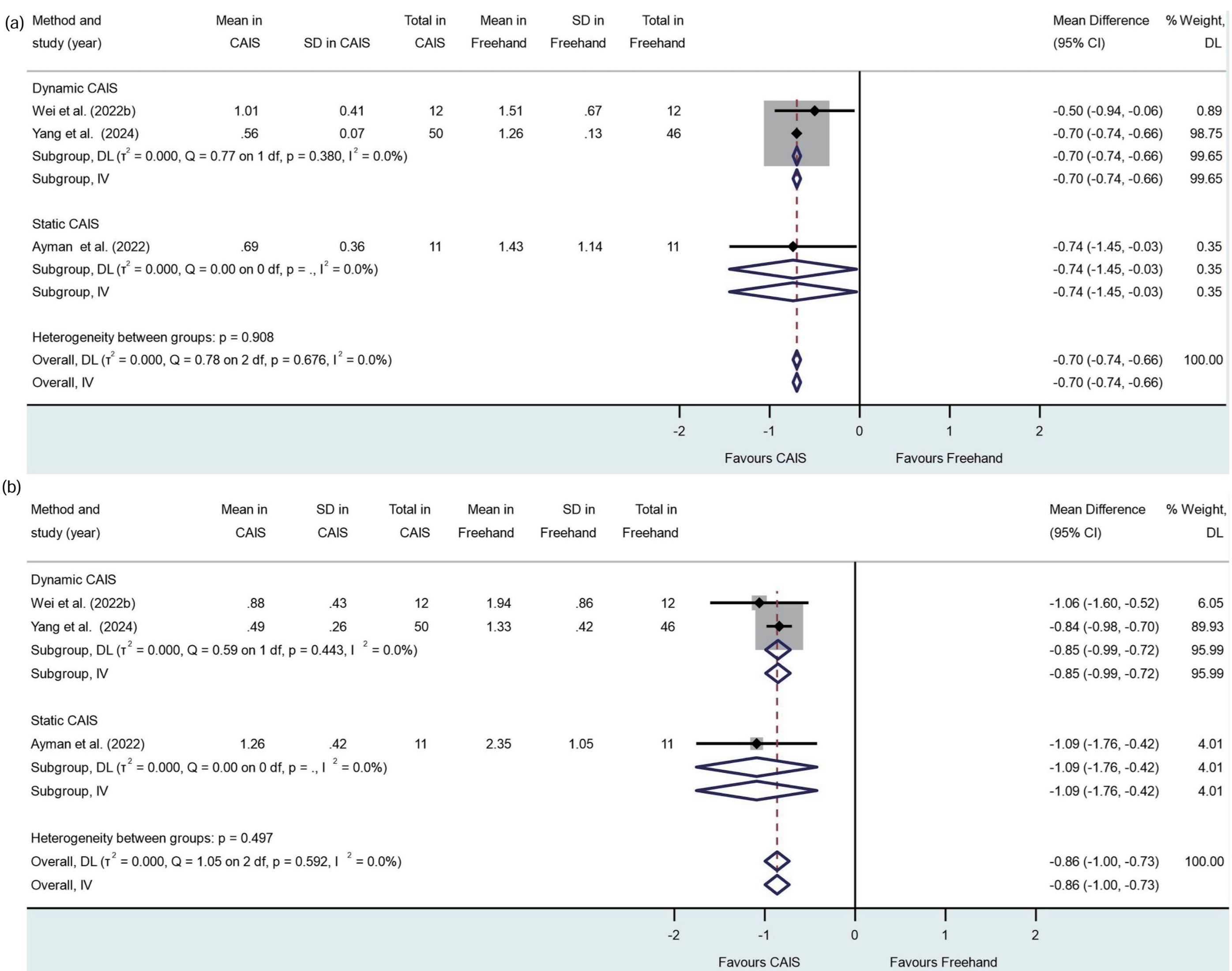

Fig. 7. (a) Global platform deviation. (b) Global apex deviation of computer-aided implant surgery (CAIS) versus freehand placement.

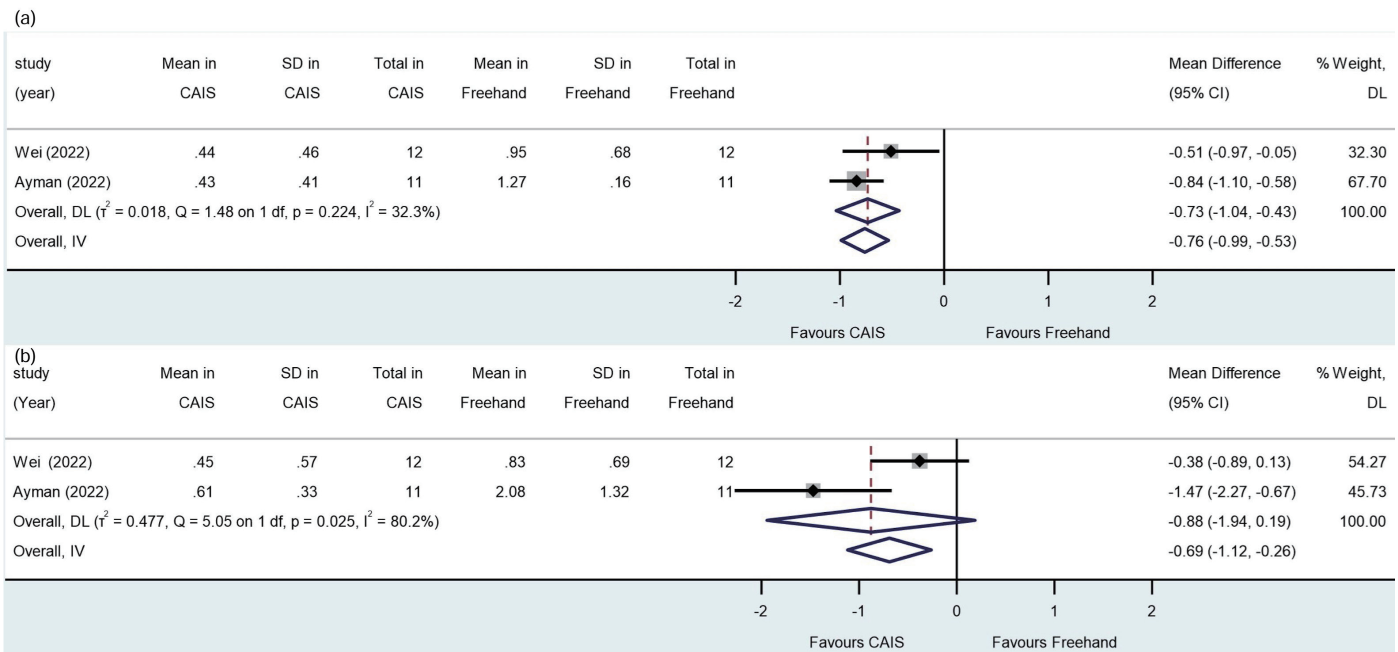

Fig. 8. (a) Platform deviation. (b) apex depth deviation of computer-aided implant surgery (CAIS) versus freehand placement.

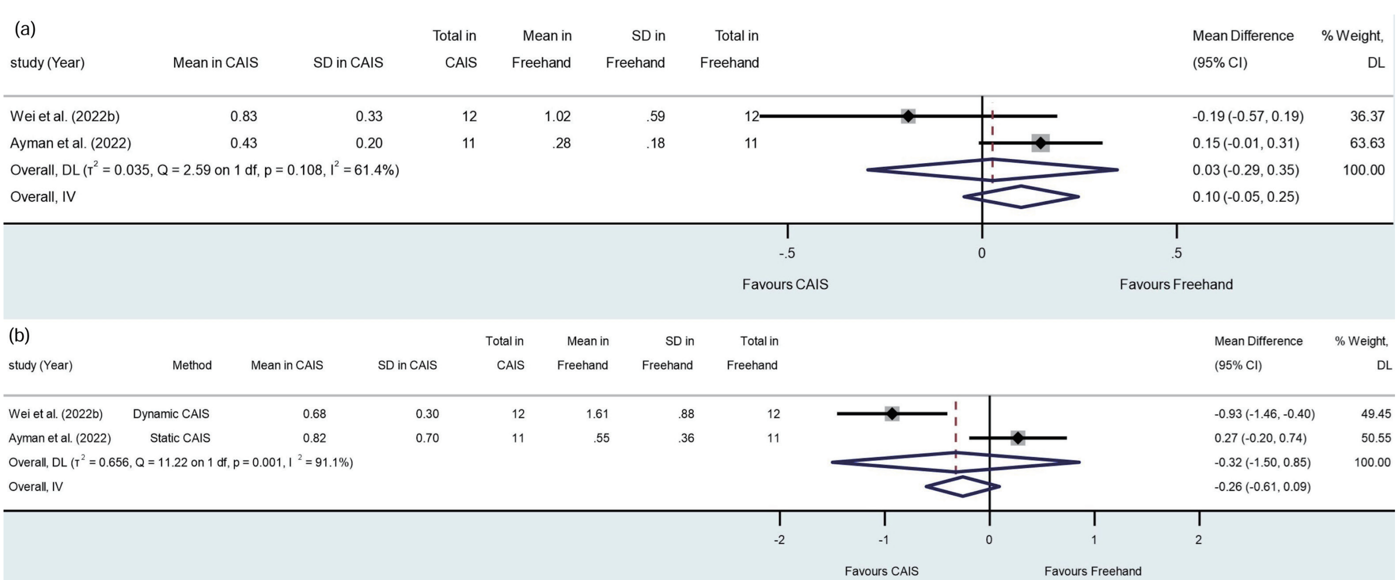

Fig. 9. (a) Lateral platform deviation. (b) Apex lateral deviation of computer-aided implant surgery (CAIS) versus freehand placement.

The mean difference in platform depth deviation of implants placed with CAIS and freehand was -0.73 mm (95% CI -1.04, -0.43; $P < 0.001$). A statistically significant difference was observed in the platform depth deviation. Heterogeneity, as expressed by the I^2 test, was 32.3% ($P = 0.224$) (**Fig. 8a**).

The mean difference in the apex depth deviation of implants placed with CAIS and freehand was 0.88 mm (95% CI -1.94, 0.19; $P = 0.106$). No statistically significant difference in apex depth deviation was observed between the two modalities. Heterogeneity, as expressed by the I^2 test, was 80.2% ($P = 0.025$) (**Fig. 8b**).

3.3.2.5. Lateral platform and apex deviation

The mean difference in the lateral platform deviation of implants placed with CAIS and freehand was 0.03 mm (95% CI -0.29, 0.35; $P = 0.872$). No statistically significant difference in lateral platform deviation was observed between immediate placement with CAIS and freehand placement. Heterogeneity, as expressed by the I^2 test, was 61.4% ($P = 0.108$) (**Fig. 9a**).

The mean difference in the lateral apex deviation of implants placed with CAIS and freehand was 0.32 mm (95% CI -1.50, 0.85; $P = 0.590$). No statistically significant difference was found between CAIS and freehand placement in terms of lateral apex deviation. Heterogeneity, as expressed by the I^2 test, was 91.1% ($P = 0.001$) (**Fig. 9b**).

3.3.2.6. Sensitivity analysis

A sensitivity analysis was performed to evaluate the impact of including the results of the study by KR *et al.* (2023) in the meta-analysis[48]. The inclusion of this study did not significantly affect the heterogeneity of studies assessing angular deviation in s-CAIS (I^2=95.2%; $P < 0.001$) (**Fig. S8a**). However, the meta-analysis of angular deviation with the inclusion changed the results to favor CAIS in terms of angular deviation. The mean difference in the angular deviation of implants placed with CAIS and freehand was -2.69 mm (95% CI -4.71, -0.67; $P = 0.009$). This contrasts with the main analysis, where no significant difference was observed between CAIS and freehand (**Fig. S8b**).

Furthermore, the sensitivity analysis indicated a reduction in heterogeneity from over 90% to 75% in the assessment of global platform deviation in the s-CAIS group when the study was included ($P < 0.001$) (**Fig. S9a**). However, the meta-analysis of CAIS versus freehand showed similar results to those of the analysis without the addition of the study, where a statistically significant difference in the above accuracy parameter favoring immediate placement with both the d-CAIS and s-CAIS compared to freehand placement was still observed (95% CI, -0.74, -0.66; $P < 0.001$). The heterogeneity of the s-CAIS studies included in this analysis was low (I^2=0%, $P = 0.592$) (**Fig. S9b**).

For global apex deviation, the heterogeneity of the s-CAIS studies for the pooled accuracy assessment remained high, with or without the addition of this study (I^2=95.5%, $P < 0.001$) (**Fig. S10a**). The meta-analysis of CAIS versus freehand continued to demonstrate results comparable to those of previous analyses. A statistically significant result favoring CAIS in terms of global apex deviation was observed, with the mean difference of -1.50 mm (95% CI -2.41, -0.59; $P = 0.001$) (**Fig. S10b**).

3.3.3. Insertion torque

Ten studies reported insertion torque values[32,37–43,45,46]. Not all studies reported actual mean torque values. In general, the reported insertion torque ranges from less than or equal to 15 Ncm to larger than 50 Ncm in one study (**Table S1**). It is important to note that torque values may vary depending on the implant system and the clinical situation.

4. Discussion

Based on our findings, for d-CAIS, the average global coronal deviation, global apex deviation, and angulation deviation were 0.72 mm, 0.81 mm, and 2.04 degrees respectively; and that for s-CAIS were 0.80 mm, 1.10 mm, and 2.12 degrees respectively. These findings were based on seven RCTs and eight nonrandomized controlled trials (NCTs) that focused on Type I implant placement in bounded partially edentulous cases.

Multiple systematic reviews have reported the accuracy of surgery using the s-CAIS or d-CAIS, owing to the rising popularity of computer-guided or aided surgery. A meta-analysis by Tahmaseb *et al.* investigated the accuracy of s-CAIS[21]. Their study revealed a pooled mean deviation of 1.2 mm (95% CI 1.04 - 1.44) at the platform level and 1.4 mm (95% CI 1.28 - 1.58) at the apex level, along with a deviation of 3.5 degrees (95% CI 3.00 - 3.96). This analysis was based on 20 clinical studies, 18 of which focused on completely edentulous cases and utilized mucosa-supported surgical guides with or without pins, or bone-supported guides with stabilization screws. In their study, partially edentulous patients achieved a more accurate implant positioning than fully edentulous patients. Putra and coworkers conducted a review of 18 clinical studies on static guided surgery, suggesting that a bounded edentulous saddle, CAD/CAM-manufactured surgical guide, and the use of a fully guided protocol enhanced the accuracy of implant placement in s-CAIS[27]. In contrast, dynamic guided surgery exhibited a higher degree of similarity to freehand surgery, with the system providing augmented surgical experience through continuous real-time feedback to the surgeon. This feedback informs the surgeon regarding the magnitude of deviation of the drilling position and angulation from the planned position. The surgeon also maintains full autonomy of the surgery because no physical restriction is implemented in the drilling process The study by Wei *et al.*[49] investigated accuracy of d-CAIS. In their meta-analysis of five clinical trials and five *in vitro* studies, the pooled average global platform, apex, and angular deviations were 1.02 mm (95% CI 0.83 - 1.21); 1.33 mm (95% CI 0.98 - 1.67), and 3.59 degrees (95% CI 2.09 - 5.09), respectively.

The current systematic review found that the accuracy of both s-CAIS and d-CAIS was on par with previously reported values. On the further research, a statistically significant difference in implant placement accuracy was detected among s-CAIS, d-CAIS, and non-guided surgery in the dimensions of global platform, global apex, and platform depth deviations, but not angular deviation. The present systematic review suggests that both guided systems have the potential to achieve implant placement with clinical accuracy comparable to that reported in previous systematic reviews, particularly in more anatomically challenging situations, such as the immediate placement approach.

Osteotomy preparation and implant placement in areas of asymmetric bone density may result in a shift in the drill position towards the direction of least resistance. Some examples have been discussed, including immediate implant placement in both anterior (single-rooted tooth) and posterior (multi-rooted tooth) sites or in areas with thick and uneven cortical bone[50,51]. In these situations, a sideways shift may be experienced at two time points: during osteotomy preparation, when the twist drill starts cutting into the bone at the side, and during implant insertion, when the implant body first contacts the bony wall within the usually downsized osteotomy[52,53]. Experienced operators routinely apply counteracting forces to maintain the osteotomy and implant placement in the planned 3D position. It was speculated that the assumed accuracy of guided surgery may hinder the detection of the intrinsic error[54,55] and the possible chance of intrasurgical adjustment.

The phenomenon and magnitude of implant deflection during immediate placement under a surgical guide system were investigated both *in vitro* and *ex vivo*. Wang and coworkers examined the difference in accuracy between static and dynamic guided systems in healed and fresh extraction sockets in 3D-printed maxillary models[56]. Within the well-controlled *in vitro* environment with all implants placed by a single experienced operator, d-CAIS was found to present with more accurate results than s-CAIS in terms of coronal (0.60 +/– 0.29 mm vs 1.24 +/– 0.26 mm, $P < 0.001$), apical (0.78 +/– 0.33 mm vs 1.69 +/– 0.34 mm, $P < 0.001$), and angular deviation (2.47 +/− 1.09 degrees vs 3.44 +/− 1.06 degrees, $P = 0.01$) in anterior fresh extraction sockets. It was concluded that an uneven bone morphology influenced the accuracy of implant placement using d-CAIS. A cadaver study by Chen *et al.*[57] reported that s-CAIS was more accurate than freehanded surgery for immediate implant placement in terms of global platform, apex, and angular deviations. However, the deviation in depth was not significant. In addition to the classical parameters used to measure deviation in this type of study, they also presented data on bucco-oral and mesiodistal deviations. Buccal displacement at platform level and apical level was noticed in implants placed by both techniques, but the extent was less in the s-CAIS group (buccal platform deviation 0.32 +/− 0.32 vs 046 +/− 0.86, $P = 0.640$).

Preclinical studies have suggested that d-CAIS is the most accurate technique, followed by s-CAIS and freehanded surgery. The results from the clinical studies analyzed in our systematic review, however, did not detect any significant difference between s-CAIS and d-CAIS or non-guided surgery in most clinical parameters, except for global platform, global apex, and platform depth deviations. Possible explanations for the similar clinical performance between s-CAIS and d-CAIS may be because clinical studies address the influence of patients' movement, mouth opening, soft tissues, saliva, and blood on visibility, and other unavoidable environmental factors. Another factor to be considered is that CBCT image acquisition, processing, and measurement of implant position may encounter more errors in clinical settings than in laboratory settings. Error accumulation may mask true but small differences. The small number of included studies warrants a cautious interpretation of the results.

However, the relatively large heterogeneity of the included studies reporting the d-CAIS, s-CAIS, and freehand placement require attention. The heterogeneity observed in the d-CAIS group may be attributed to several factors. One of the potential reasons could be the learning curve associated with dynamic guided surgery, where real-time adjustments may be carried out during the procedures, and experienced operators in implant dentistry might perform better in terms of accuracy and time management[58]. The large heterogeneity within the static guided surgery group also prompted closer examination. One factor to consider is the method used to fabricate static surgical guides, including 3D printing and milling techniques. Previous studies have highlighted that 3D printing may result in a suboptimal fit compared with milling methods, which is plausibly caused by polymerization shrinkage[59]. Differences in the accuracy of implant placement have been reported for various manufacturing methods, which affect the precision and consistency of static guided surgeries.

The range of measurement deviation observed in freehanded surgery also necessitates a thorough examination. Wei *et al.*[40] presented results from a single experienced operator that had a wide 95% confidence interval for all measured parameters compared with the study by Han *et al.* that also provided data from freehanded surgery[38]. In the measurement of angular deviation, the large range of angulation deviation from 1.67 degrees to 12.51 degrees provoked concerns regarding non-guided placement (**Fig. 3**). A plausible reason for this could be that during the freehand implant placement approach, clinicians may always attempt maximum implant-osteotomy site engagement to achieve maximum primary stability based on their chairside judgment. Therefore, the final implant position may deviate from the originally planned position. In the context of freehand surgery, operator experience plays a crucial role in achieving optimal outcomes. This was illustrated in an *in vitro* study, where a skilled surgeon achieved an angular deviation of 6.69 degree, and inexperienced operators demonstrated a significantly higher angular deviation. This study also highlighted that even the use of a pilot guide did not fully compensate for the level of operator experience[60]. In contrast, the s-CAIS and d-CAIS reduced the effect of subjective chairside judgment, and implants could be placed in planned positions most of the time. Therefore, the results from guided surgery provide a higher degree of precision, represented by the narrower range of the 95% confidence interval, when compared with freehand implant placement. In fact, a deviation of 3 degrees in angulation from the planned implant position may render a straight screw channel being shown through at the prosthesis's incisal edge rather than at the cingulum. This degree of angular deviation may impose a concern regarding the screw hole position for screw-retained restorations, although this can be overcome using a new screw design with multiple engagement angles.

Additionally, the clinical definition of immediate implant placement may include a variety of anatomical variations. Perhaps a more analogous representation of a standardized experimental setup was presented in the model study by Thangwarawut and coworkers[61], in which 3D printed blocks of 0 degrees, 45 degrees, and 60 degrees inclinations were used for guided model surgery to examine the degree of inaccuracy of implant placement at different interfaces, although similar standardization may not be reproduced clinically. Sagittal root position (SRP), as described by Kan[62], provides some insight into this aspect, as it classifies socket morphology, which may influence the mechanism and magnitude of implant contact with the bone. The properly planned axis of anterior implants in the aesthetic zone usually allows the screw hole to exit at the cingulum position for the connection of the screw-retained implant crown. However, the implant apex may be placed at the palatal socket wall, buccal socket wall, or directly at the apical end of the socket, depending upon different socket morphologies. Posterior immediate implantation also depends on the root divergence of the pre-extraction tooth. A wide septum between the roots of a hopeless tooth may allow easier centering, whereas a narrow septum or unevenly distributed roots may result in a higher tendency of bur slipping. When different conditions are pooled into the same category of fresh extraction sockets in which the implant is placed immediately, the deviation in the results may be diluted.

Further analysis was performed to address the principal question of this study, which was to explore the impact of implant placement accuracy on Type I procedures performed through computer-guided surgery. The results of different studies were categorized according to s-CAIS, d-CAIS, or freehanded placement and pooled into subgroups for comparison among studies. Both randomized and non-randomized studies were combined. With the intention of generalization and presenting heterogeneity, a random-effects model was utilized in the meta-regression to allow all effect sizes to be represented by the different included studies. Additionally, a fixed-effects model was applied for sensitivity analysis.

Despite the limited number of included studies, meta-analyses comparing the d-CAIS, s-CAIS, and freehand surgeries were conducted using selected accuracy parameters, suggesting that guided surgery may achieve better accuracy in various dimensions. Subgroup analysis further revealed that dynamic and static guided surgeries exhibited comparable levels of accuracy, with dynamic surgery showing slight superiority in some aspects. Although systematic reviews often lead to statistical inferences about broader populations, such extrapolations may be justified in the present study. This can be illustrated by a sensitivity analysis. Although the analyses seem comparable, the inclusion of specific studies may influence certain accuracy parameters, underscoring the impact of individual studies on outcomes, especially in case of small number of included studies. Given that our study exclusively incorporated clinical trials to derive more relevant conclusions for actual clinical scenarios, the limited number of studies, heterogeneity, and predominance of high-risk bias studies have rendered the results less generalizable. Therefore, the results of this meta-analysis should be interpreted with caution.

Further systematic reviews and meta-analyses of rigorously designed and executed randomized controlled clinical trials may offer more robust and conclusive answers to this clinical question. To conduct similar studies in the future, several aspects should be considered. It may be advantageous to adopt a standardized approach to measure the vector of error, including mesial, distal, labial, and palatal/lingual (oral), for both angular and linear measurements in addition to classical measurements. This will enhance clinical relevance and may facilitate comparisons of reported errors across studies. Of particular importance in the context of aesthetic risk is the measurement of buccal angular and linear deviations. However, other measurements, which may provide hints of potential risks to neighboring anatomical structures and inform us of the safe distance for surgery using this surgical approach, should be considered.

Furthermore, it is essential to report the deviations in depth at both implant ends. Deviation in depth at the platform level has a direct impact on the emergence profile of future prostheses, which is critical for achieving optimal aesthetic outcomes and facilitating proper peri-implant hygiene for patients. Similarly, a deviation in depth at the apex level is crucial to ensure a safe distance from the surrounding vital structures when the implant is placed in close proximity. However, these parameters have not been frequently reported in literature, despite their importance.

Reporting on whether the operator who performed the surgery was responsible for preoperative implant planning was infrequent among the studies reviewed. Given that the final implant position is driven by the operator's clinical decision, particularly in cases of freehanded or dynamic guided surgery, it is recommended that the operator responsible for performing the surgery be responsible for case planning to minimize the impact of operator preference.

Furthermore, it would be of great value to investigate the actual clinical outcome in terms of aesthetics by CAIS in immediate implant placement, particularly regarding short- and long-term soft tissue responses, such as mucosal recession. This is an area of great interest and importance for both patients and clinicians, given the pivotal role of implant position in achieving optimal aesthetic outcomes in the maxillary aesthetic zone.

The studies included in this systematic review exhibited high heterogeneity in terms of study design, sample size, and methodology. This heterogeneity may have influenced the analysis results and limited the generalizability of the findings. By exploring the aforementioned key aspects in future research, with the standardization of error vector measurements, guided implant surgery can be further studied with more refined decision-making by clinicians, thus further improving patient outcomes.

5. Conclusions

The use of guided surgery resulted in higher accuracy, resulting in less global platform, global apex, and platform depth deviations when compared with freehand placement in Type I implant placement. While other measurements did not show statistical significance, the data suggest that guided surgery may be preferred over freehand placement. d-CAIS demonstrated marginally superior precision in terms of angulation compared with s-CAIS. Nonetheless, the discrepancies between s-CAIS and d-CAIS are minuscule, falling within an order of magnitude of 0.1 mm and 0.1 degrees. These minor differences are within the acceptable range for clinical tolerance. Within the heterogeneity of this study, it can be concluded that guided implant surgery for Type I placement of implants is an effective and promising technique that could, to some extent, increase implant placement accuracy in several dimensions. Future studies with larger sample sizes and more standardized measurements are required.

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Author contributions

Conceptualization, D.H., M.F.; methodology, M.F., K.L., T.F.; formal analysis and writing—original draft preparation, K.L, M.F.; writing—review and editing, M.F., G.P.; supervision, M.F., G.P.; K.L. & M.F. contributed equally to this work.

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Conflict of interest

The authors have no conflicts of interest to declare.

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