

Accuracy of Free-Hand *Versus* Various Computer-Assisted Techniques in Dental Implant Surgery: a Systematic Review

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ABSTRACT

Objectives: The aim of this systematic review was to compare the positional accuracy of dental implant placement using free-hand to different computer-assisted implant surgery techniques.

Material and Methods: The literature search was conducted by using PubMed, ScienceDirect, and Cochrane Library databases. Studies comparing implant placement accuracy among free-hand and three computer-assisted implant surgery (CAIS) techniques - robotic (rCAIS), static (sCAIS), and dynamic (dCAIS) - were analysed. Inclusion and exclusion criteria, as well as PRISMA guidelines, were applied. Data were collected from human published studies in English between January 2016 and April 2026.

Results: Twelve articles were included, with a total of 586 implants placed, from which 296 were done by free-hand, 77 by rCAIS, 117 by sCAIS, and 85 by dCAIS. Across all studies, CAIS consistently yielded lower angular, apical, and platform deviations than free-hand placement, with angular deviation showing the largest statistically significant differences. Among the CAIS techniques, rCAIS demonstrated the lowest deviations, in all three parameters, along with the smallest inter-study variability. Although to a lesser extent, sCAIS and dCAIS also demonstrated deviation reduction, compared to free-hand, but with greater variability. Free-hand placement consistently reported the highest deviation values in all comparisons to CAIS techniques.

Conclusions: Computer-assisted techniques demonstrated higher accuracy when compared to free-hand placement in terms of angular, apical, and platform deviations, with the greatest improvement observed in the angular deviation. The largest deviation reductions were observed in the robotic computer-assisted implant surgery groups.

Keywords: computer-assisted surgery; dental implantation; dental implants; robotic surgical procedures; surgery.

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INTRODUCTION

Dental implant therapy remains a cornerstone of modern reconstructive dentistry, driven by a large number of ongoing research and innovation [1]. The use of dental implants has significantly changed and improved people's lifestyles, oral function, and aesthetics. Concurrently, it has enabled clinicians across multiple specialties, including prosthodontists, orthodontists, and oral and maxillofacial surgeons, to achieve their treatment goals [2,3].

Dental implants were initially created for the replacement of missing teeth. However, today they have become widely used for other reasons, such as orthodontic anchorage, as well as to support maxillofacial prostheses after tumour resection or trauma [4]. It has become an essential and indispensable tool in dentistry, making its placement accuracy very important [5].

A successful implant placement is commonly defined by its accurate position and long-term stability. It mainly relies on angulation, deviation, positioning, and depth [6]. However, other important factors can also influence the success of a dental implant leading to its failure. These factors include patient-related factors (smoking, diabetes, poor bone quality, poor compliance), biological factors (lack of osseointegration, marginal bone resorption, mucositis), surgical complications (aggressive flap elevation, root fractures, bone necrosis due to overheating, nerve damage, sinus perforations), implant design, and surgeon's lack of experience [5,7-9].

These variables can make a free-hand implant placement challenging in some cases. This justifies the major innovations done around that field aimed at improving accuracy and stability of an implant placement. Modern innovations have led to the development of computer-assisted and robotic technologies. Computer-assisted implant surgeries (CAIS) have improved planning and are able to transfer virtual implant position to the surgical procedures, while newer robotic technologies are able to track the implant's position while working, guide the hands of a surgeon and even provide physical resistance when needed [10,11].

Computer-assisted implant surgery workflows are broadly categorized into two modalities: static and dynamic. On the one hand, static computer-assisted implant surgery (sCAIS) involves prefabricated three-dimensional (3D) printed guides that help improve the implant's angulation and depth position [11]. They can be semi or fully guided. A semi-guided sCAIS provides a head start and controls the position of the

implant by setting its initial direction. The rest of the procedure is done by free-hand. Fully-guided sCAIS is completely based on computer planning and cone-beam computed tomography (CBCT) [12]. Guides are made using CAD/CAM and are used to control the depth, position, angulation, and placement of the dental implant. Guides should be supported by either mucosa, bone or teeth [13]. However, they do have some limitations, such as the need of additional time, error possibilities, and the lack of dynamic changes [11]. On the other hand, dynamic computer-assisted implant surgery (dCAIS) consists of a real-life navigation which allows dynamic changes during the surgery [12]. It offers continuous visual feedback and adjustment at any time if needed [11]. It uses virtual imaging tools as well as 3D software to enable dynamic navigation [13]. However, it requires considerable skills and experience to master its use [14].

The literature presents conflicting evidence regarding the accuracy of sCAIS versus dCAIS [15]. Some research has found no significant difference between sCAIS and dCAIS [16,17]. Others have shown that dCAIS can offer better accuracy and precision due to its capacity to navigate during a surgery [6,18]. However, as mentioned previously, dCAIS has a disadvantage: balancing between performing the surgery and navigating which can be complex and requires extensive training [6]. Therefore, robotic-assisted dental implant surgery (rCAIS) is later introduced to improve further precision, autonomy and accuracy [19]. Robotic computer-assisted surgery (rCAIS) utilizes 3D imaging and digital scans. The system comprises a robotic arm, a vision system, surgical accessories, and dedicated software, which stores patient data, plans implant position, sequences surgical steps, and controls the robot's movements. The vision device calculates the robotic arm movements. It then sends a motion command, directing the arm to its precise position [20]. The system offers real-time visual navigation for implant positioning and haptic feedback that physically guides the dentist's hand movements. Thus, rCAIS combines the advantages of static and dynamic techniques [21]. While individual studies have reported favourable accuracy outcomes for CAIS compared to free-hand placement, a comprehensive comparison of all three CAIS modalities (rCAIS, sCAIS, dCAIS) within a single systematic review remains lacking. Furthermore, the long-term safety and clinical reliability of these technologies have not been firmly established. Therefore, the aim of this study is to compare and evaluate the accuracy of implant placement using free-hand and different computer-

assisted techniques.

The objectives of this systematic review were:

- To evaluate and compare angular, apical, and platform deviations of implant placement using free-hand, static, dynamic and robotic computer-assisted techniques.
- To determine whether computer-assisted surgery techniques can provide superior outcomes compared to free-hand implant placement.
- To assess the potential of computer-assisted surgery to become a dominant technique for implant placement in future practice.
- To evaluate whether the available data are consistent enough to support a unified conclusion regarding the superiority of specific computer-assisted implant surgery modalities: robotic, static, or dynamic.

MATERIAL AND METHODS

Protocol and registration

This systematic review was reported according to the Preferred Reporting Items for systematic reviews and meta-analysis (PRISMA) guidelines [22].

The review was registered with the International Prospective Register of Systematic Reviews (PROSPERO) under number CRD420261377532.

The protocol can be accessed at: <https://www.crd.york.ac.uk/PROSPERO/view/CRD420261377532>

Focus question

The PICO (Population, Intervention, Control, and Outcome) framework in Table 1 was applied to define the eligibility criteria for all included studies in relation to the research question: “Which implant placement method - free-hand, static, dynamic, or robotic computer-assisted surgery - provides the highest dental implant placement accuracy?”

Types of publications

This systematic review included human studies

published in the English language. Studies involving case reports, *in vitro* studies, reviews, grey literature, letters, PhD thesis, editorials, studies on animals and abstracts without full-text availability were excluded.

Types of studies

Retrospective and prospective studies, clinical trials, and randomized controlled trials on humans were included in the analysis. Eligible studies had to be published between the January 1, 2016 and April 30, 2026 and report on the accuracy of free-hand and various CAIS modalities (static, dynamic, and robotic).

Information sources

The systematic search was conducted using MEDLINE (PubMed), ScienceDirect and the Cochrane Library databases.

Population

Healthy adult patients with completed skeletal maturation who were missing one, several, or all their teeth and were seeking dental implant treatment. Patients with any contraindication to implant surgery were excluded.

Literature search and screening

Searches were performed using MEDLINE (PubMed), ScienceDirect, and Cochrane Library databases. Predefined inclusion and exclusion criteria were applied to refine the search results. The keyword combinations used for the search are presented in Table 2.

Inclusion and exclusion criteria

The articles were evaluated in order to determine research eligibility based on the following inclusion and exclusion criteria:

Table 1. PICO framework

Component	Description
Population	Healthy adult patients requiring dental implant treatment with no contraindications to surgery
Intervention	Dental implant placement using free-hand, static, dynamic, and robotic computer-assisted workflows based on preoperative digital planning
Control	Free-hand implant placement
Outcomes	Accuracy of implant placement in terms of angular, apical, and platform deviations measured by postoperative imaging

Table 2. Keyword combinations used for the research (concepts 1 to 4 were combined with “AND”)

Concepts	Keywords
First	“Dental Implantation” [MeSH Terms] AND (“Accuracy” OR “Precision”) AND (“Freehand” OR “Free-hand” [tw] OR “Conventional Implant Placement” [tw] OR “Manual Implant Placement” [tw] OR “Unguided Implant Placement” [tw] OR “Non-guided Implant Placement” [tw] OR “Traditional Implant Placement” [tw] OR “Standard Implant Placement” [tw])
Second	“Dental Implantation” [MeSH Terms] AND (“Accuracy” OR “Precision”) AND (“Static Computer Assisted” [tw] OR “Static Computer-Assisted” [tw] OR “Static Computer Guided” [tw] OR “Static Computer-Guided” [tw] OR “Digital Guided” [tw] OR “Static Guided Implant Surgery” [tw] OR “Static Guided Implant Placement” [tw] OR “Surgical Guide” [tw] OR “Template Guided” [tw] OR “Static Guided” [tw])
Third	“Dental Implantation” [MeSH Terms] AND (“Accuracy” OR “Precision”) AND (“Dynamic Computer Assisted” [tw] OR “Dynamic Computer-Assisted” [tw] OR “Dynamic Computer Guided” [tw] OR “Dynamic Computer-Guided” [tw] OR “Digital Guided” [tw] OR “Dynamic Guided Implant Surgery” [tw] OR “Dynamic Guided Implant Placement” OR “Dynamic Guided” [tw] OR “Computer Navigated” [tw] OR “Computer-Aided” [tw])
Fourth	“Dental Implantation” [MeSH Terms] AND (“Accuracy” OR “Precision”) AND (“Robotic” [tw] OR “Robot-Assisted” [tw] OR “Robot Assisted” [tw] OR “Robotic Guided” [tw] OR “Robotic-Guided” [tw] OR “Robotic Surgery” [tw] OR “Robotic Implant Surgery” [tw] OR “Robotic Implant Placement” [tw] OR “Robotic Navigation” [tw] OR “Robot-Assisted Surgery” [tw] OR “Digital Dentistry” [tw] OR “Collaborative Robot” [tw] OR “Robotic System” [tw] OR “Autonomous Robotic System” [tw])

tw = text words.

Inclusion criteria

- Adult patients.
- Missing one or more teeth and requiring dental implant treatment.
- No systemic or local contraindications for dental implant surgery.
- Pre-operative and postoperative imaging data available (CBCT and/or intraoral scans).
- Studies reporting implant’s platform, apical and angular deviation.
- Implant placement accuracy assessed before osseointegration and/or prosthetic treatment.
- Studies including at least 10 implants in each group.
- Human clinical studies.
- Full-text articles published in peer-reviewed journals.

Exclusion criteria

- Patients presenting systemic or local contraindications to dental implant surgery.
- Studies without clearly defined dental implant deviation measurement methods.
- Studies with missing or incomplete outcome data.
- Deviation data not presented as mean (standard deviation).
- Studies where implant placement was performed in cadaver models.
- Studies published outside the January 2016 - April 2026 time frame.
- Case reports, reviews, *in vitro*, animal, or

transitional design studies.

- Non-English language articles.
- Abstracts without full-text availability.

Data extraction

Data withdrawn from the included articles for this study review is listed below:

- “Authors and publication year” - reveals the author and year of the study.
- “Type of study” - reveals the type of study.
- “Total number of patients” - total number of patients.
- “Number of implants placed” - the total number of implants placed and, the total number of implants placed overall, as well as the number placed in the “Free-hand” and “Test group”.
- “Age mean” - average age of the patients.
- “Implant system” - system of implant used.
- “Number of surgeons” - reveals how many surgeons performed the procedures.
- “Test group system” - computer-assisted implant surgery system of the test group.
- “Preoperative plan software” - software used for preoperative planning of implant position.
- “Postoperative measurement” - reveals when postoperative data were collected and by which method.
- “Deviation analysis software” - software used for measuring deviation.
- “Deviation” - reveals apical, platform, and angular deviations between planned and placed implants.

Selection process

The selection process was conducted in accordance with PRISMA guidelines. First, the database search retrieved all articles matching the keyword combinations (Table 2). Following duplicate removal, two independent reviewers (R.F. and P.D.), screened the titles and abstracts of the remaining records against the predefined eligibility criteria. Potentially eligible articles were then retrieved for full-text evaluation. The full-text articles were independently assessed by two reviewers (R.F. and P.D.). Any disagreements were resolved by discussion or by involving a third reviewer (J.M.). Studies that met all inclusion criteria and were not excluded by any exclusion criterion were ultimately included

in the systematic review analysis.

Risk of bias

The risk of bias was assessed within the studies by using the Joanna Briggs Institute Critical Appraisal (JBI) checklist for the Randomized Control Trials (Table 3) and Cohort studies (Table 4) [23]. Each question was answered with a “yes”, “no”, “unclear”, or “not applicable”. Methodological quality was categorized based on the proportion of favourable ‘Yes’ responses. Studies under or equal to 49% of favourable responses were classified as high risk of bias, those of 50 to 69% were classified as moderate risk of bias, and those higher or equal to 70% were classified as low risk of bias.

Table 3. The Joanna Briggs Institute Critical Appraisal checklist for the Randomized Control Trials

Question number	Questions
Q1	Was true randomization used for assignment of participants to treatment groups?
Q2	Was allocation to treatment groups concealed?
Q3	Were treatment groups similar at the baseline?
Q4	Were participants blind to treatment assignment?
Q5	Were those delivering treatment blind to treatment assignment?
Q6	Were outcomes assessors blind to treatment assignment?
Q7	Were treatment groups treated identically other than the intervention of interest?
Q8	Was follow up complete and if not, were differences between groups in terms of their follow up adequately described and analysed?
Q9	Were participants analysed in the groups to which they were randomized?
Q10	Were outcomes measured in the same way for treatment groups?
Q11	Were outcomes measured in a reliable way?
Q12	Was appropriate statistical analysis used?
Q13	Was the trial design appropriate, and any deviations from the standard RCT design (individual randomization, parallel groups) accounted for in the conduct and analysis of the trial?

Table 4. The Joanna Briggs Institute Critical Appraisal checklist for Cohort Studies

Question number	Questions
Q1	Were the two groups similar and recruited from the same population?
Q2	Were the exposures measured similarly to assign people to both exposed and unexposed groups?
Q3	Was the exposure measured in a valid and reliable way?
Q4	Were confounding factors identified?
Q5	Were strategies to deal with confounding factors stated?
Q6	Were the groups/participants free of the outcome at the start of the study (or at the moment of exposure)?
Q7	Were the outcomes measured in a valid and reliable way?
Q8	Was the follow up time reported and sufficient to be long enough for outcomes to occur?
Q9	Was follow up complete, and if not, were the reasons to loss to follow up described and explored?
Q10	Were strategies to address incomplete follow up utilized?
Q11	Was appropriate statistical analysis used?

Synthesis of results

The data of the included studies were summarized in tables presenting study characteristics, technical parameters, and study outcomes. General characteristics of the studies included the author, year of publication, study type, and total number of patients and implants in each group. Additional variables such as age, implant system, and surgeon number were also included, where applicable. Technical parameters reported the test group systems, preoperative and deviation software, as well as the methods and timing of postoperative measurements. Study outcomes specifically reported angular, apical, and platform deviations.

Statistical analysis

Due to the high heterogeneity of the studies, meta-analysis was not performed. The mean and standard deviation (M [SD]) were used to express the parametric data and $P \leq 0.05$ was used as the statistical significance level. Studies not reporting mean and standard deviation were not included in quantitative comparisons.

Retrieved references were imported into reference management software - Zotero version 8.0.4 (www.zotero.org) for reference duplicate removal. Titles and abstracts screening were then preformed manually according to eligibility criteria.

Inter-reviewer agreement at both the title/abstract screening stage and the full-text eligibility assessment stage was quantified using Cohen's kappa (κ) coefficient. Value above 0.8 was pre-specified to indicate excellent agreement.

RESULTS

Identification of records

The initial electronic search reported 1463 publications from MEDLINE (PubMed) (n = 213), ScienceDirect (n = 1181), and the Cochrane Library (n = 69) (Figure 1). A total of 754 records remained after applying additional filters: no older than 10 years (n = 155), not written in English (n = 9), not related to medical and dental topics (n = 439), and duplicates publications (n = 106). In the screening stage, 729 titles and abstracts were removed due to irrelevance on the topic. Of the 25 full-text articles that were assessed for eligibility, 13 were excluded, leaving 12 studies to be included in the review.

Inter-reviewer agreement

The initial electronic search and subsequent screening process demonstrated strong reproducibility between the evaluators:

Title and abstract screening: the independent screening of the initial 754 records yielded

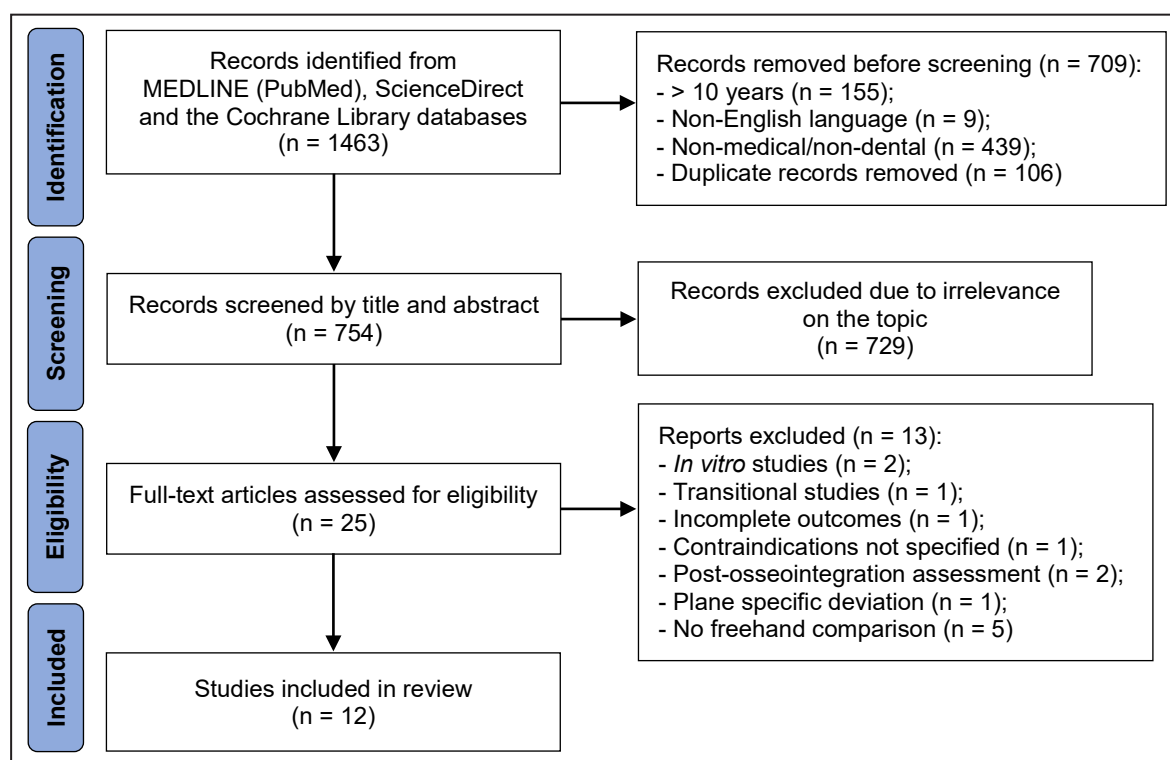


Figure 1. PRISMA flow diagram of literature search and study selection.

an excellent level of agreement between the two authors (R.F. and P.D.), with a value of $\kappa = 0.86$.

Full-text evaluation: for the 25 articles selected for full-text analysis, the inter-reviewer agreement between the two authors (R.F. and P.D.) remained exceptionally high, achieving a $\kappa = 0.91$, reflecting excellent reliability before consensus was reached on the final 12 included studies.

Study selection

Specifically, two studies were *in vitro* investigations [24,25], and one was a transitional design study [19]. One article did not report all required outcome measurements [26], and another failed to meet the patient contraindication criterion for implant surgery [27]. Two studies assessed implant placement accuracy during or after osseointegration rather than before [28,29]. One article provided only plane-specific deviation measurements for platform and apical deviations [30]. Finally, five articles compared different computer-assisted implant placement techniques, but lacked a free-hand control group [31-35]. After applying all inclusion and exclusion criteria, 12 records were ultimately included in the systematic review. The PRISMA flow diagram (Figure 1) summarizes the literature search and study selection process.

Quality assessment of included studies

The methodological quality of the included studies was assessed using the JBI Critical Appraisal Checklist for randomized controlled trials and cohort studies, respectively. The assessment revealed one study was of low overall quality [36], two studies were of moderate quality [37,38] and the remaining were of good overall quality [14,39-46]. A detailed summary of the individual study scores is presented in Tables 5 and 6.

Study characteristics

This systematic review comprised nine randomized controlled trials [14,36-38,40-44], one retrospective study [46], and two non-randomized prospective studies [39,45] (Table 7).

Among the twelve studies, four of them compared free-hand with sCAIS (three RCT and one non-randomized prospective study), four compared free-hand with dCAIS (three RCT and one non-randomized prospective study) and four compared free-hand with rCAIS (three RCT and one retrospective study). Overall, 586 implants were placed and analysed on 414 patients. A total of 296 implants were placed by free-hand, 117 using static computer-assisted systems, 85 using dynamic computer-assisted systems, and 77 using robotic systems.

Table 5. Quality assessment of randomized control trials using the Joanna Briggs Institute Critical Appraisal Checklist

Study	Year of publication	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13
Shi et al. [14]	2024	+	+	+	?	-	+	+	+	+	+	+	+	+
Smitkarn et al. [36]	2019	+	?	+	-	-	-	+	?	?	+	?	+	+
Schneider et al. [37]	2019	+	?	+	-	-	?	+	+	?	+	+	+	+
Varga et al. [38]	2020	+	+	+	?	-	?	+	+	?	+	+	+	+
Chen et al. [40]	2025	+	+	+	-	-	+	+	+	+	+	+	+	+
Wei et al. [41]	2022	+	+	+	+	-	+	+	+	?	+	+	+	+
Yang et al. [42]	2024	+	+	+	?	-	+	+	+	+	+	+	+	+
Jain et al. [43]	2025	+	+	+	-	-	+	+	+	+	+	+	+	+
Jorba-García et al. [44]	2023	+	+	+	-	-	+	+	+	+	+	+	+	+

? = unclear; + = yes; - = no.

Table 6. Quality assessment of cohort studies using the Joanna Briggs Institute Critical Appraisal Checklist

Study	Year of publication	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11
Huang et al. [39]	2023	+	+	+	?	+	+	+	-	+	N/A	+
Jaemsuwan et al. [45]	2023	+	+	+	+	+	+	+	+	+	N/A	+
Younis et al. [46]	2025	+	+	+	+	+	+	+	+	+	N/A	+

N/A = not applicable; ? = unclear; + = yes; - = no.

Table 7. Summary of study characteristics

Study	Type of study	Patients (n)	Gender	Mean age (years)	Implants (n)	Implant system	Surgery type	Surgeon(s)
Shi et al. [14]	RCT	20	Male: 7; female: 13	47	20	Straumann®	FH: 10; rCAIS: 10	2
Smitkarn et al. [36]	RCT	52	No data	No data	60	Straumann®	FH: 30; sCAIS: 30	1
Schneider et al. [37]	RCT	38	No data	No data	38	Straumann®; Astra Tech	FH: 16; sCAIS: 11	No data
Varga et al. [38]	RCT	54	Male: 28; female: 26	No data	107	MultiNeO™ (Alpha-Bio Tec)	FH: 55; sCAIS: 52	2
Huang et al. [39]	Non-randomized prospective study	48	No data	No data	48	Straumann®	FH: 24; sCAIS: 24	1
Chen et al. [40]	RCT	24	Male: 6; female: 18	35.5	24	Straumann®	FH: 14; rCAIS: 10	2
Wei et al. [41]	RCT	24	Male: 15; female: 9	38	24	Straumann®	FH: 12; dCAIS: 12	1
Yang et al. [42]	RCT	24	Male: 43; female: 97	35	24	Straumann®; PCC	FH: 12; rCAIS: 12	4
Jain et al. [43]	RCT	28	No data	No data	62	No data	FH: 31; dCAIS: 31	1
Jorba-García et al. [44]	RCT	29	Male: 13; female: 16	60	44	Straumann®; Zimmer	FH: 22; dCAIS: 22	1
Jaemsuwan et al. [45]	Non-randomized prospective study	9	Male: 6; female: 3	66	40	Straumann®	FH: 20; dCAIS: 20	1
Younis et al. [46]	Retrospective study	64	Male: 25; female: 40	45.9	95	Straumann®	FH: 50; rCAIS: 45	1

PCC = NobelParallel™ Conical Connection implant; n = number; RCT = randomized control trial; FH = free-hand; rCAIS = robotic computer-assisted implant surgery; sCAIS = static computer-assisted implant surgery; dCAIS = dynamic computer-assisted implant surgery.

Three included studies [37,38,45] evaluated more than two intervention groups. For consistency, only the relevant groups were included (fully guided group in the first two studies and dynamic guidance in the third). Therefore, the numbers reported in Table 7 (total number of implants and patients) reflect only the relevant groups.

In most studies, all procedures were performed by a single surgeon. Four studies [14,38,40] involved two or more surgeons [42], while one study [37] did not report the number of surgeons involved.

Different implant systems with varying lengths and diameters were used across the included studies. Implant length ranged from 8 to 14 mm, and the diameter from 3 to 5 mm. Seven studies used Straumann® implants (Straumann Holding AG; Basel, Switzerland), while three studies [37,42,44] used Straumann® in combination with another dental implant system. One study [38] used the MultiNeO™ dental implant system (Alpha-Bio Tec; Modi'in, Israel), and one study [43] did not disclose the implant system used.

Accuracy was measured using a similar workflow across studies. This involved using preoperative

CBCT data to generate a virtual implant position and plan, which was then compared with postoperative CBCT scans by using superimposition techniques. One article [40] used a combination of CBCT and intraoral scanning for postoperative measurements.

Postoperative measurements were taken to assess deviation. Three articles [36,41,45] performed these measurements 1 to 2 weeks after implant placement, whereas the remaining of the studies conducted them within 0 to 2 days postsurgery [14,37-40,42-44,46]. In all cases, postoperative measurements were taken prior to the onset of osseointegration.

A variety of preoperative planning and deviation analysis software were used across the included studies. Although some studies used identical software, no single program was consistently employed for either preoperative planning or deviation analysis. Regarding preoperative planning software, DTX Studio™ (Nobel Biocare; Gothenburg, Sweden) in combination with Cycad (Hangzhou Jianjia Medical Technology Co., Ltd.; Hangzhou, China) was the most frequently used (n = 3) [14,40,42], followed by Navident software (ClaroNav Technology Inc; Toronto, Canada) (n = 2) [43,44] and coDiagnostix® (Dental Wings,

Montreal, Canada) (n = 2) [36,45]. For deviation analysis, 3D Slicer (Harvard, Massachusetts, United States) was the most commonly employed software (n = 3) [14,40,42], followed by Evalunav (Navident - ClaroNav Technology Inc; Toronto, Canada) (n = 2) [44,45]. Furthermore, different systems were used within the static, dynamic, and robotic subgroups. Notably, within the robotic subgroup, three out of four studies [14,40,42] utilized the Theta dental robot (Hangzhou Jianjia Medical Technology Co., Ltd.; Hangzhou, China), making it the most frequently used. Similarly, in the dynamic subgroup, two out of the four studies [43,44] used the Navident dynamic navigation system (ClaroNav Technology Inc; Toronto, Canada). The digital workflows and measurement methods are summarized in Table 8.

Study outcomes

Three main outcome parameters were measured across studies: angular deviation (degrees), apical deviation (millimetres), and coronal deviation

(millimetres). The terms coronal, platform, shoulder, and crestal deviations were used synonymously in this review. Angular deviations represented the angular difference between planned and actual implant axes, while coronal and apical deviations represented linear differences at the implant platform and apex, respectively. Only global (3D) deviations at coronal and apical levels were analysed; plane-specific measurements were excluded. Global (3D) deviation represents the overall difference between the planned and actual implant positions, integrating deviations across all three axes into a single value. All outcomes were reported as mean (standard deviation) for consistent comparison.

Angular, apical, and platform deviations across the included studies are illustrated in Figures 2, 3, and 4, respectively. Corresponding mean values for the free-hand and CAIS test groups are presented in Table 9. Computer-assisted techniques consistently yielded lower deviations than free-hand placement across all three parameters, with the most pronounced reduction observed for angular deviation.

Table 8. Overview of digital workflow and measurement methods

Study	Test group	System	Preoperative plan software	Postoperative measurement timing and method	Deviation analysis software
Shi et al. [14]	rCAIS	Theta dental Robot	FH: DTX Studio™; rCAIS: Cycad	IAIS (CBCT)	3D Slicer
Smitkarn et al. [36]	sCAIS	coDiagnostiX® v9.7 (3D printed)	FH/sCAIS: coDiagnostiX® v9.7	2 weeks postsurgery (CBCT)	coDiagnostiX® v9.7
Schneider et al. [37]	sCAIS	SMOP	FH / sCAIS: SimPlant (Materialise / Dentsply Sirona)	IAIS (CBCT)	SMOP
Varga et al. [38]	sCAIS	SMART Guide® system	FH/sCAIS: SMART Guide planning software	2 (± 1) days postsurgery (CBCT)	Amira 5.4.0 (Thermo Fisher Scientific)
Huang et al. [39]	sCAIS	Materialise Magics 23.0 + UltraCraft A2D 4K	FH/sCAIS: Implant Studio (3Shape)	IAIS (CBCT)	Mimics Medical 21.0 + Implant Studio (3Shape)
Chen et al. [40]	rCAIS	Theta dental Robot	FH: DTX Studio™; rCAIS: Cycad	IAIS (CBCT + IOS)	3D Slicer
Wei et al. [41]	dCAIS	Dcarer dynamic navigation system	FH/dCAIS: Dcarer dynamic navigation	1 week postsurgery (CBCT)	Dcarer dynamic navigation
Yang et al. [42]	rCAIS	Theta dental Robot	FH: DTX Studio™; rCAIS: Cycad	IAIS (CBCT)	3D Slicer
Jain et al. [43]	dCAIS	Navident® Dynamic Navigation System	FH/dCAIS: Navident	IAIS (CBCT)	Evalunav
Jorba-García et al. [44]	dCAIS	Navident dynamic navigation system	FH/dCAIS: Navident	IAIS (CBCT)	Evalunav
Jaemsuwan et al. [45]	dCAIS	IRIS-100 Implant Real-time Imaging System	FH: coDiagnostiX® dCAIS: IRIS 100	1 week postsurgery (CBCT)	IRIS 100
Younis et al. [46]	rCAIS	Remebot	FH/rCAIS: RemebotDent	IAIS (CBCT)	RemebotDent

IAIS = immediately after implant surgery, CBCT = cone-beam computed tomography, FH = free-hand, rCAIS = robotic computer-assisted implant surgery, sCAIS = static computer-assisted implant surgery, dCAIS = dynamic computer-assisted implant surgery.

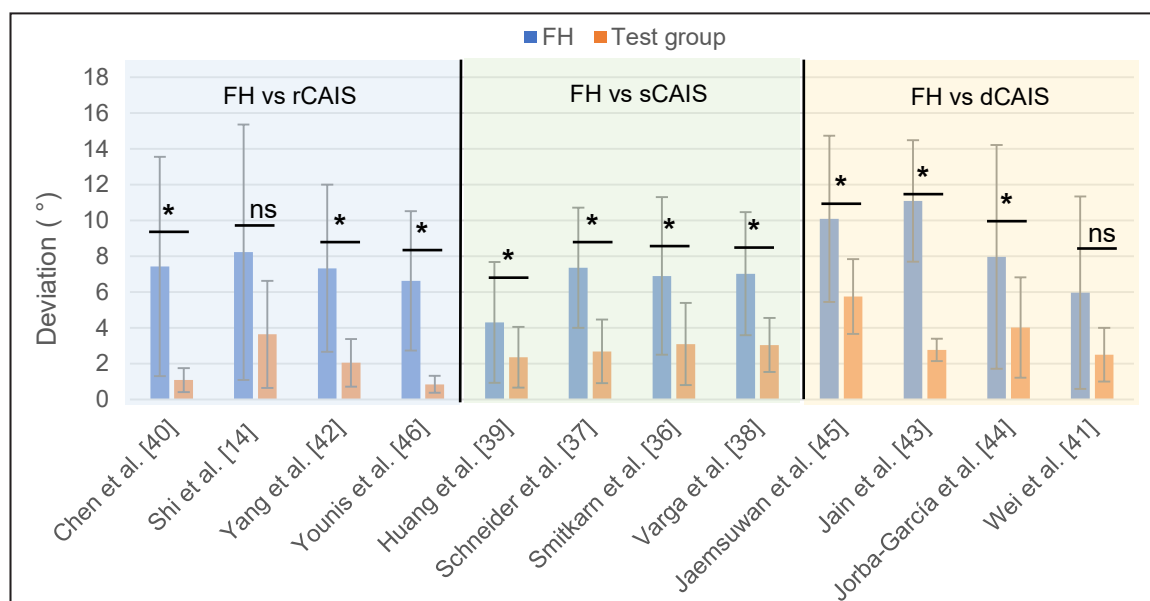


Figure 2. Mean angular deviations across the included studies, comparing free-hand and computer-assisted surgery.
*statistically significant difference between groups.

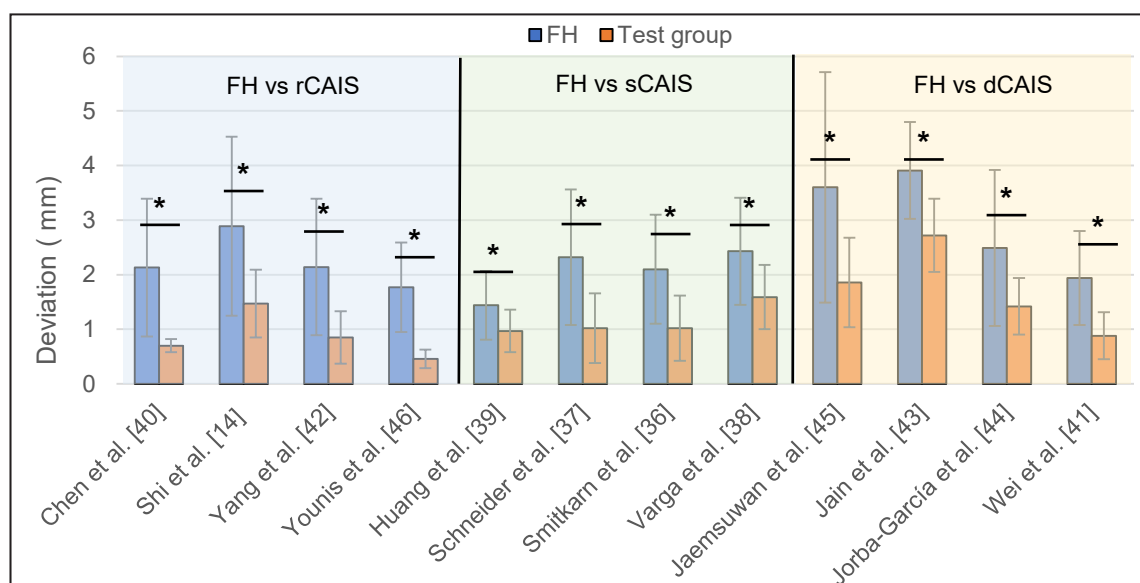


Figure 3. Mean apical deviation across the included studies, comparing free-hand and computer-assisted surgery.
*statistically significant difference between groups.

FH = free-hand; rCAIS = robotic computer-assisted implant surgery; sCAIS = static computer-assisted implant surgery; dCAIS = dynamic computer-assisted implant surgery.

This difference was particularly evident when comparing the free-hand group to robotic systems with angular deviation values ranging from approximately 6.63° to 8.23° for free-hand and 0.85° to 3.64° for rCAIS [14,40,42,46]. The static subgroup also reduced the angular deviation, with values ranging from 2.36° to 3.1°, compared with 4.31° to 7.36° for free-hand [36-39]. Dynamic computer assisted surgery demonstrated the highest interstudy variability with an angular deviation ranging from 2.51° to 5.75°, compared to 5.97° to 11.09° for free-hand [41,43-45].

Apical deviation demonstrated a similar trend, with

all computer-assisted techniques showing lower values than free-hand placement. The robotic-assisted subgroup showed the lowest apical deviations with values ranging from 0.46 to 1.47 mm comparing to 1.77 to 2.89 mm in the free-hand group [14,40,42,46]. The static subgroup demonstrated values ranging from 0.97 to 1.59 mm relative to free-hand group (1.44 to 2.43 mm) [36-39]. Similarly to angular deviation, the dynamic CAIS subgroup demonstrated the greatest interstudy variability in apical deviation, with values ranging from 0.88 to 2.72 mm, compared with 1.94 to 3.91 mm in the free-hand group [41,43-45].

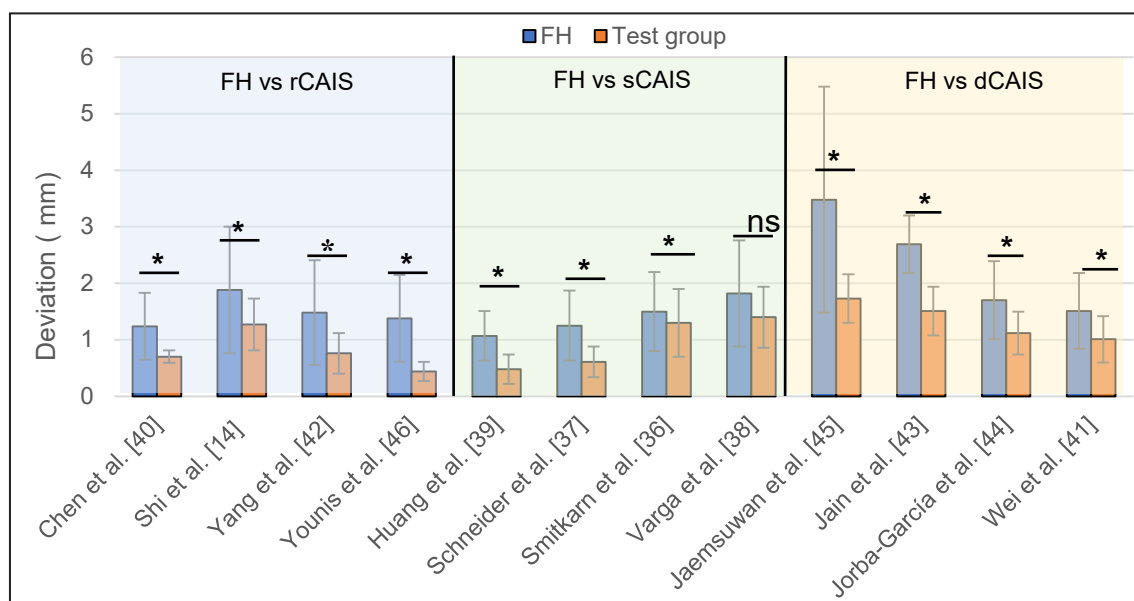


Figure 4. Mean platform deviation across the included studies, comparing free-hand and computer-assisted surgery.

*statistically significant difference between groups.

ns = non-significant; FH = free-hand; rCAIS = robotic computer-assisted implant surgery; sCAIS = static computer-assisted implant surgery; dCAIS = dynamic computer-assisted implant surgery.

Table 9. Mean values for the free-hand and CAIS test groups

Study	Test group	Angular deviation (°)		Apical deviation (mm)		Platform deviation (mm)	
		Free-hand	Test	Free-hand	Test	Free-hand	Test
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Shi et al. [14]	rCAIS	8.23 (7.14)	3.64 (2.99)	2.89 (1.64)	1.47 (0.62)	1.88 (1.12)	1.27 (0.46)
Smitkarn et al. [36]	sCAIS	6.9 (4.4)	3.1 (2.3)	2.1 (1.0)	1.0 (0.6)	1.5 (0.7)	1.3 (0.6)
Schneider et al. [37]	sCAIS	7.36 (3.36)	2.69 (1.78)	2.32 (1.24)	1.02 (0.64)	1.25 (0.62)	0.61 (0.27)
Varga et al. [38]	sCAIS	7.03 (3.44)	3.04 (1.51)	2.43 (0.98)	1.59 (0.59)	1.82 (0.94)	1.4 (0.54)
Huang et al. [39]	sCAIS	4.31 (3.37)	2.36 (1.7)	1.44 (0.63)	0.97 (0.39)	1.07 (0.44)	0.48 (0.26)
Chen et al. [40]	rCAIS	7.43 (6.12)	1.09 (0.67)	2.13 (1.26)	0.7 (0.12)	1.24 (0.59)	0.7 (0.11)
Wei et al. [41]	dCAIS	5.97 (5.37)	2.51 (1.5)	1.94 (0.86)	0.88 (0.43)	1.51 (0.67)	1.01 (0.41)
Yang et al. [42]	rCAIS	7.33 (4.67)	2.05 (1.33)	2.14 (1.25)	0.85 (0.48)	1.48 (0.93)	0.76 (0.36)
Jain et al. [43]	dCAIS	11.09 (3.39)	2.77 (0.63)	3.91 (0.89)	2.72 (0.67)	2.69 (0.51)	1.51 (0.43)
Jorba-García et al. [44]	dCAIS	7.97 (6.25)	4.02 (2.8)	2.49 (1.43)	1.42 (0.52)	1.70 (0.69)	1.12 (0.38)
Jaemsuwan et al. [45]	dCAIS	10.09 (4.64)	5.75 (2.09)	3.6 (2.11)	1.86 (0.82)	3.48 (2.0)	1.73 (0.43)
Younis et al. [46]	rCAIS	6.63 (3.9)	0.85 (0.47)	1.77 (0.82)	0.46 (0.17)	1.38 (0.77)	0.44 (0.17)

SD = standard deviation.

Platform deviation, although to a lesser extent, also demonstrated lower values with computer-assisted implant surgery than with free-hand placement. The robotic-assisted subgroup showed the lowest platform deviations, ranging from 0.44 to 1.27 mm, compared with 1.24 to 1.88 mm in the corresponding free-hand groups [14,40,42,46]. The static CAIS subgroup also demonstrated reduced platform deviation, with values ranging from 0.48 to 1.4 mm, compared with 1.07 to 1.82 mm for free-hand placement [36-39]. Dynamic CAIS similarly demonstrated lower platform deviation,

ranging from 1.1 to 1.73 mm, compared with 1.51 to 3.48 mm for free-hand placement [41,43-45].

Free-hand placement was associated with higher standard deviations in all cases.

DISCUSSION

Principal findings on deviation parameters

This systematic review compared the accuracy of traditional free-hand dental implant placement with

that of three computer-assisted techniques: static, dynamic, and robotic systems. The results of this review indicated that computer-assisted techniques generally achieved higher accuracy than free-hand placement. This finding is supported by lower angular, apical, and platform deviations reported across all included studies, with angular deviation showing the most notable difference - frequently two to three times lower than that observed with free-hand placement. For example, the study by Jain et al. [43], reported a statistically significant ($P < 0.0001$) angular deviations reduction from 11.09° in free-hand group to 2.77° in the dynamic navigation group. These findings are further supported by other systematic reviews [47,48]. However, it is important to note that not all computer-assisted methods were performed equally and under the same conditions. Consequently, variability exists across the studies and should be taken into consideration. Furthermore, the heterogeneity of the included studies should also be taken into account, as it may lead to certain limitations.

Angular deviation often showed the greatest difference between free-hand and computer-assisted techniques, highlighting its importance as a key parameter in evaluating accuracy. Angular deviation can jeopardise implant aesthetics and safety, as well as complicate restoration placement by leading to prosthetic misalignment [49]. Across the twelve included studies, free-hand placement consistently showed highest angular deviation compared to computer-assisted techniques, which significantly reduced angular errors. Additionally, the consistency of this reduction varied among the different computer-assisted techniques. The robotic system not only demonstrated the largest difference compared to free-hand placement, but also showed the lowest variability between the studies, which can imply high precision and reproducibility. In contrast, the static group showed a moderate, but relatively consistent improvement while the dynamic group, despite improving the accuracy, revealed greater variability among the studies [41,43-45], which could suggest that outcomes with dynamic navigation may be less predictable. For example, this was illustrated by Wei et al. [41], who reported a non-statistically significant reduction ($P > 0.05$) of angular deviation from 5.97° (free-hand) to 2.51° when using dynamic navigation, while Jain et al. [43] observed a statistically significant reduction from 11.09° to 2.77° ($P < 0.0001$). This variability may be explained by the differences in surgeons' experience, software systems, and clinical workflows, highlighting the potentially high heterogeneity among the studies.

Apical deviation is another important parameter

needed to assess the accuracy of an implant placement. Clinically, apical deviation is particularly important because excessive deviation may risk damaging adjacent anatomical structures, such as the inferior alveolar nerve and maxillary sinus floor. Similar to the angular deviation, all included studies showed a reduction in apical deviation values when comparing free-hand to CAIS groups. The robotic CAIS (rCAIS) group demonstrated the narrowest ranges with the least interstudy variability. Platform (coronal) deviation represents the final parameter used in this review to evaluate implant placement accuracy. A platform deviation can clinically affect a dental implant, particularly its aesthetics, prosthetic fit, and emergence profile, with greater impact in anterior regions [50]. Although the difference between free-hand and test groups was relatively small, all computer-assisted implant techniques showed better results in entry-point precision. The lowest values were predominantly observed in the rCAIS group, with a minimum value of 0.44 mm reported using Remebot® surgical robot (Beijing Ruiyibo Technology Co. Ltd.; Beijing, China) compared to 1.38 mm in the free-hand group [46]. In the sCAIS group, the differences groups were small but still present, indicating modest improvements. This was supported by Huang et al. [39], who demonstrated statistically significant ($P < 0.001$) reduction in deviation from 1.07 mm (free-hand) to 0.48 mm (sCAIS). However, some studies reported only a limited difference between the two groups. Smitkarn et al. [36] reported a marginal statistically significant ($P < 0.05$) decrease in platform deviation from 1.5 mm (free-hand) to 1.3 mm (sCAIS). Overall, sCAIS improved entry-point control, but depended heavily on the guide's fit and positioning, and its impact on deviation parameters appeared to be less pronounced than rCAIS. dCAIS also revealed consistent improvements in implant placement accuracy, with all studies reporting lower deviations in the dCAIS group compared to free-hand. A statistically significant reduction ($P < 0.05$) in deviation - by more than half - was reported by Jaemsuwan et al. [45] using the dynamic system.

Inter-study variability and technique predictability

Across all three deviation parameters, the free-hand subgroup consistently showed higher standard deviations than the corresponding computer-assisted subgroups in all included studies.

The results highlighted the low predictability of the free-hand technique and indicated its reduced reliability for achieving high dental implant placement accuracy. Additionally, among CAIS groups, inter-

study variability was most pronounced in the dynamic group [41,43-45].

In contrast, rCAIS showed narrower deviation ranges among the studies [14,40,42,46], which may suggest greater consistency. Static computer-assisted techniques showed moderate inter-study variability on deviations. Although deviation values were relatively more consistent in CAIS groups compared to free-hand, none of the investigated techniques eliminated deviation completely.

Implant-related factors, such as length and diameter, varied considerably across studies and individual patient cases, and may have influenced deviation. However, evidence from literature regarding the importance of implant length and diameter on deviation remains inconclusive. Smitkarn et al. [36] reported that implant dimensions had no significant effect on any of the three deviation parameters in either the free-hand or computer-assisted groups ($p > 0.05$). In contrast, Younis et al. [46] demonstrated that implant dimensions significantly influenced deviation in the free-hand group, with narrower implants associated with greater deviation ($P < 0.001$). The inconsistency suggests that implant-related factors may contribute to the heterogeneity observed in this review.

Clinical relevance and practical implications

The accuracy of an implant placement is important because it enables long-term survival and stability of the dental implant while avoiding anatomical damage. An accurately placed implant leads to a successful and aesthetic prosthetic restoration that is easy to clean and maintain. However, the key question is whether the observed differences in accuracy between the techniques are clinically important. According to Takács et al. [51], the maximum clinically acceptable platform deviation should be of up to 1.5 mm, while the maximum clinically acceptable angular deviation is up to 5 degrees, corresponding to approximately up to 2 mm of apical deviation [52]. When examining the results, 11 out of 12 studies [14,36-38,40-46] reported that free-hand groups exceeded the 5° angulation threshold, whereas only one [45] of the 12 test groups - using the dynamic navigation - slightly surpassed that limit (5.75 [2.09]°). Similarly, 9 out of 12 studies [14,36-38,40,42-45] reported that free-hand groups exceeded the 2 mm apical deviation threshold, while only one [43] test group (dynamic navigation) surpassed the limit (2.72 [0.67] mm). For the platform deviation, the difference was less pronounced, but still evident: 6 out of 12 studies [14,38,41,43-45] reported free-hand groups exceeding the 1.5 mm

coronal threshold, compared to only two test groups [43,45].

It is important to note that implant accuracy reflects the precision of placement and does not necessarily determine biological success. A comparison of survival rates between computer-assisted and free-hand placement performed by experienced surgeons showed high success rates in both groups, ranging between 95 to 98 % [53,54]. This suggests that accuracy might not be the primary cause of failure, which is influenced mainly by biological and prosthetic factors such as occlusal loading, the prosthetics design, personal hygiene, and the host's immune response [55,56]. Another important aspect to consider is complication reduction, which has been inconsistently reported across the literature. While some reviews reported similar complication rates across all groups, others, including D'haese et al. [10] and Block et al. [57], emphasized a reduction in iatrogenic risks - such as inferior alveolar nerve injuries and maxillary sinus floor perforations - when computer-assisted techniques were used. These authors particularly recommended CAIS approaches for complex anatomical cases.

No clinically meaningful differences were observed between groups regarding clinical outcomes, including intra-operative pain, post-operative pain, quality of life, complications, and survival rates [14,40]. Clinical outcomes were comparable across all methods used, allowing the implant to heal properly, become asymptomatic within one to two weeks, appear aesthetic and function adequately. Nevertheless, several studies suggested an increase in pain with free-hand placement compared to computer-assisted surgery [12,26].

The practical aspect of each technique and its applicability in clinical practice should also be taken into account. Each technique presents distinct advantages and limitations. Free-hand placement, although lacking digital guidance, still allows complete visibility and intra-operative adjustment of the plan at any time if needed [12]. In addition, the human hand allows full flexibility, whereas robotic hands may have difficulty reaching posterior areas because these regions are harder to access [14,19]. However, as indicated in the findings of this review, the free-hand technique carried higher deviations because it relies heavily on preoperative planning, manual drilling, and a high level of operator experience.

Robotic-assisted surgery provides real-time feedback and haptic control, which offers physical guidance and helps the operator maintain control while reducing error and fatigue [14,19]. Similarly,

dynamic navigation enables real-time tracking and intra-operative adjustment [12,14]. This represents a significant advantage over the static guided systems, where no modifications can be made once the guide is fabricated [14,19]. The clinical use of static guides can be influenced by several factors, including limited mouth opening, improper guide positioning or stabilization, and inadequate irrigation [19]. Dynamic navigation requires the surgeon's attention to be continuously shifted between the screen for real-time navigation and the surgical drill [14]. It also demands additional training and a learning curve to master the technique [14,19].

A further disadvantage of CAIS techniques is the complexity of the procedure, including registration, calibration, and verification, which can introduce error, as well as the need for numerous accessories [12]. All computer-assisted systems were associated with higher financial costs, increased equipment requirements, and greater space demands [32,50]. Free-hand placement remained the most affordable option, especially given the already high costs associated with implant therapy. In terms of surgical time, free-hand procedures were usually similar to, and occasionally shorter than, those of CAIS techniques, particularly the rCAIS [14]. The longer duration of robotic surgery was primarily attributable to preoperative calibration, registration, and intraoperative real-time navigation adjustments.

Limitations

The strengths of this systematic review included the exclusive use of *in vivo* human studies, enhancing clinical relevance. Furthermore, all studies performed postoperative evaluation prior to implant osseointegration, ensuring consistency in outcome measurements. Another strength was the use of superimposition techniques that, despite some variability in software, allowed the consistent measurement of identical parameters and anatomical planes across studies.

Several limitations of this review should be acknowledged. First, three of the included studies were non-randomized clinical trials [39,45,46], which may differ in several aspects and are associated to a higher risk of bias. In addition, variability in study design and outcomes led to inconsistency, making direct comparison more difficult. Another limitation was the small sample size reported in some of the articles, especially in the rCAIS groups [14,40,42]. A small sample size can lead to less reliable sources and unstable results that could be disproportionately influenced by just a few participants. Furthermore,

implant placement accuracy is highly dependent on operator experience and knowledge, both in free-hand and CAIS procedures. This dependency introduced additional variability and limited the generalizability of the review's findings. Moreover, different planning software, deviation analysis software, and test group systems were used across the studies. Each system and software operate differently and has its own advantages and limitations, which may lead to variations in measurement methods and outcomes.

Additional limitations were related to patient factors. Not all studies excluded patients with conditions such as poor bone or soft tissue quality, limited mouth opening, compromised periodontal status, or smoking habits, all of which can affect a host's response to implant placement and long-term outcomes. Additionally, there was heterogeneity in the clinical scenarios between patients. Some required implants in posterior regions, which are generally harder to access. Additional variability arose from the presence or absence of adjacent teeth, which could affect the ease and subsequent accuracy of implant placement, thereby reducing comparability and representing another limitation of this review.

Finally, the absence of meta-analysis limited the ability to draw a robust, generalizable conclusion regarding the superiority of any specific computer-assisted technique over the others.

CONCLUSIONS

1. Computer-assisted techniques (static, dynamic, and robotic) demonstrated higher accuracy than free-hand placement across angular, platform, and apical deviations, with the most pronounced difference observed for angular deviation. The greatest reductions were consistently achieved by robotic computer-assisted surgery.
2. Computer-assisted surgery provided superior accuracy compared to free-hand, which could lead to better aesthetics, safer procedures, and easier prosthetic placements. In addition, computer assisted implant techniques could improve control during surgery and lead to standardization of procedures.
3. Computer-assisted surgery can be useful and dominant in the future, especially in complex anatomical cases. However, improvements are still needed in its practicality, particularly in terms of cost, time consumption, and system complexity.
4. The available data lack sufficient consistency to support a unified conclusion on the superiority of

any specific computer assisted implant modality. Further randomized clinical trials with larger samples and reduced variability are required to identify the technique offering the best accuracy, reliability, and clinical practicality.

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The authors report no conflicts of interest related to this study.

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