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SYSTEMATIC REVIEW

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# Accuracy of robotic computer-assisted implant surgery in clinical studies: a systematic review and meta-analysis

Zixin Luo[1,2†], An Li[3†], Alexey Unkovskiy[4,5], Jiang Li[1,2], Florian Beuer[4], Zhe Wu[1,2*] and Ping Li[1,2*]


## Abstract

**Objectives** To analyze the accuracy of the robotic system in clinical studies and assess potential factors that might affect the accuracy of robotic implant placement.

**Materials and methods** PubMed, Embase, and Cochrane Central Register of Controlled Trials were used to search for studies published from August 2014 till October 2024. Studies on robotic computer-assisted implant surgery (R-CAIS) were identified. Furthermore, manual searches were performed for selected journals. Only clinical studies were included. Subgroup analysis was performed based on robot autonomy, different dentitions, and the working principle of the camera.

**Results** Sixteen studies met the inclusion criteria, evaluating 908 implants. The meta-analysis of accuracy showed that the average global platform deviation, global apex deviation, and angular deviation were 0.69 mm (95% CI: 0.61–0.77, $I^2 = 94\%$), 0.72 mm (95% CI: 0.64–0.79, $I^2 = 93\%$), and 1.62° (95% CI: 1.34°–1.89°, $I^2 = 96\%$), respectively. In subgroup analysis, Meta-generic inverse variance analysis observed statistically significant differences in global platform deviation and apex deviation between robots using infrared and mechanical tracking ($p < 0.01$), as well as between those using visible light and mechanical tracking ($p < 0.01$). No significant differences were observed between autonomous and semi-active systems and different dentitions.

**Conclusion** The R-CAIS technology demonstrated a high level of accuracy. However, further large-scale, multi-center, randomized, controlled clinical trials are necessary to compare robotic implant placement with other techniques, and the additional factors influencing robotic implant placement must be explored.


**Keywords** Computer-assisted implant surgery, Accuracy, Dental implant, Robot-assisted surgery

†Zixin Luo and An Li contributed equally as first authors to this work.

*Correspondence:
Zhe Wu
zhewudentist@gzhmu.edu.cn
Ping Li
Pingli@gzhmu.edu.cn
[1]School and Hospital of Stomatology, Guangdong Engineering Research Center of Oral Restoration and Reconstruction, Guangzhou Medical University, Guangzhou 510182, China
[2]Guangzhou Key Laboratory of Basic and Applied Research of Oral Regenerative Medicine, Guangzhou 510182, China
[3]Department of Periodontology, Stomatological Hospital, School of Stomatology, Southern Medical University, Guangzhou 510280, China
[4]Department of Prosthodontics, Geriatric Dentistry and Craniomandibular Disorders, Charité- Universitätsmedizin Berlin, Corporate Member of Freie Universitat Berlin, Humboldt- Universität zu Berlin, Aßmannshauser Str. 4-6, 14197 Berlin, Germany
[5]Department of Dental Surgery, Sechenov First Moscow State Medical University, Bolshaya Pirogovskaya Street, 19c1, 119146 Moscow, Russian Federation

## Introduction

The precise placement of dental implants is critical to ensure long-term stable aesthetics and function. While improper implant placement can result in complications, such as impinging on adjacent anatomical structures like the maxillary sinus or the inferior alveolar nerve canal [1–3]. Digital technologies have revolutionized implant dentistry by enabling prosthetically driven implant placement, achieving a higher accuracy level, promoting treatment consistency, and decreasing intraoperative risks [4, 5]. Computer-assisted surgery can be categorized into static computer-assisted implant surgery (S-CAIS) and dynamic computer-assisted implant surgery (D-CAIS). The latest digital technology, robotic computer-assisted implant surgery (R-CAIS), is now available.

The first-generation technology is S-CAIS, which connects the virtual planning environment and the surgical field through a pre-fabricated surgical template [6]. However, S-CAIS is constrained by issues including template misalignment, limited visualization, and the absence of intraoperative adjustability. A systematic review of S-CAIS demonstrated significant deviations in accuracy, indicating a potential risk of compromising adjacent vital anatomical structures [7–9].

The second-generation technology, D-CAIS, utilizes optical tracking and real-time imaging to assist with implant placement, allowing for intraoperative adjustments and enhancing surgical flexibility [10, 11]. While some studies suggest that D-CAIS may provide higher accuracy than S-CAIS, a randomized controlled trial found no significant difference between the two methods [12, 13]. Additionally, D-CAIS requires greater technical expertise, as surgeons must actively monitor real-time feedback during procedures, and its accuracy may vary significantly based on operator experience [14–17].

Robotic surgery in dental implantology represents cutting-edge digital technology [18, 19]. R-CAIS utilizes an operational platform, visual system, and central control system to accurately identify implant sites and direct the robotic arm for implant preparation and placement according to the preoperative plan [20, 21]. Combining real-time navigation with haptic feedback, R-CAIS has shown excellent accuracy across various studies [22–24]. Both in vitro and in vivo research indicated that R-CAIS outperformed D-CAIS in terms of accuracy, particularly in complex scenarios such as edentulous jaws and immediate implant placements [25–27]. Despite the increasing number of clinical studies on R-CAIS, dedicated analyses on the accuracy of robotic systems remain limited. According to the Idea, Development, Exploration, Assessment, and Long-term monitoring (IDEAL) framework, R-CAIS has progressed through preclinical studies and proof-of-concept phases and is now rapidly advancing, highlighting the need for large-sample clinical research [28]. Therefore, it is crucial to analyze the accuracy of R-CAIS clinical applications. Current meta-analyses reveal a limited number of studies, particularly in complex cases, randomized controlled trials, and multicenter research [29, 30]. Additionally, the factors influencing robotic precision remain unclear.

This review aims to (1) investigate the accuracy of the robotic system in clinical applications, thereby providing further clinical evidence to support the development of robotic systems; (2) study potential factors that may influence the accuracy of robotic implant placement, including robot autonomy, dentitions, and visual systems.

## Materials and methods

### PICO question

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [31]. The protocol was registered in PROSPERO (CRD42024590506). The focused question of this review was: "What is the accuracy of robotic computer-assisted implant surgery?" To facilitate this investigation, the inquiry was structured using the PICO (population, intervention, comparison, outcomes) framework (Table 1).

### Eligibility criteria

The studies included in this review met the following inclusion criteria: (1) human clinical studies; (2) clinical trials with at least five patients and 10 implants; (3) studies using a robotic system to place implants; (4) studies on single-tooth loss, partially edentulous and/or fully edentulous; (5) studies using global platform deviation, global apex deviation, and angular deviation to describe accuracy; (6) studies in English; (7) studies using commercial robots.

A previous meta-analysis [32] on dynamic navigation established inclusion criteria of 10 patients and 10 implants. Considering the limited number of existing robotic clinical studies and the typical implantation range of 4 to 6 implants for complete denture patients, a study involving 5 patients could yield 20 to 30 implants, thus satisfying the statistical requirement of exceeding 10 implants. Therefore, we established the inclusion criteria to be greater than 5 patients or more than 10 implants.

The exclusion criteria were: (1) reviews, systematic reviews, expert points, and case reports with less than 10 implants or 5 patients; (2) studies that only used animals, cadavers, and in vitro studies; (3) studies that did not record the accuracy clearly; (4) studies only included tilted or zygomatic implants.

### Search strategy

The search was conducted in the following electronic databases: PubMed, Embase, and Cochrane Central

**Table 1** Search start

| **Focus question** | **What is the accuracy of robot-assisted implant surgery in partially or fully edentulous patients?** | |
|---|---|---|
| PICO | Population | Adult patients have undergone implant surgery. |
| | Intervention | Placing implant using R-CAIS. |
| | Comparison | The difference between planned positions and actual positions measured through CBCT |
| | Outcome | Implant placement accuracy measured with global platform deviation, global apical deviation, and angular deviation |
| Databases | PubMed | (((((((Robotic Surgical Procedures[MeSH Terms]) OR (robot-guided surgery[Title/Abstract])) OR (robotic guidance[Title/Abstract])) OR (robotic surgery[Title/Abstract])) OR (surgical robot[Title/Abstract])) OR (robot[Title/Abstract])) OR (robotic[Title/Abstract])) AND (((dental implants[Title/Abstract]) OR (dental implant[Title/Abstract])) OR (oral implantology[Title/Abstract]))<br>Filters: in the last 10 years |
| | Embase | #1 'robot assisted surgery'/exp<br>#2 'robotic surgical system'/exp<br>#3 robotic AND system: ab, kw, ti<br>#4 ('robot'/exp OR robot) AND assisted AND surgery: ab, kw, ti<br>#5 ('robot'/exp OR robot) AND surgery: ab, kw, ti<br>#6 'tooth implant'/exp<br>#7 ('dental''/exp OR dental)AND implant: ab, kw, ti<br>#8 oral AND implantation: ab, kw, ti<br>#9 (#1 OR #2 OR #3 OR #4 OR #5) AND (#6 OR #7 OR #8) AND [2014–2024]/py |
| | Cochrane CENTRAL | #1 MeSH descriptor: [Robotics] explode all trees<br>#2 MeSH descriptor: [Robotic Surgical Procedures] explode all trees<br>#3 (robotic surgery): ti, ab, kw OR (robotic assisted): ti, ab, kw OR (robot): ti, ab, kw<br>#4 (dental implant): ti, ab, kw<br>#5 (#1 OR #2 OR #3) AND #4 |
| Search date | | 27-Oct-24 |

Register of Controlled Trials (Table 1) for studies published from August 2014 to October 2024. The search used the terms ("robot-assisted surgery," or "robotic surgical system," or "robotic system," or "robot surgery") and ("dental implants" or "oral implantology"), limiting the language of articles to English. Furthermore, a manual search was conducted for articles published in the following journals over the past decade: Journal of Clinical Periodontology, Journal of Prosthetic Dentistry, Journal of Dentistry, Clinical Oral Implants Research, Clinical Implant Dentistry and Related Research, and Journal of Periodontology. Additionally, grey literature was searched on OpenGrey and www.greylit.org.

### Study selection

Two independent reviewers (P.L. and Z.L.) performed the screening by independently evaluating the titles and abstracts of the studies after removing duplicates. Next, two reviewers independently searched and further assessed the full text of potentially eligible studies. Appendix 1 presents the reasons for article exclusion at this stage. After the selection process, another researcher experienced in meta-analysis (A.L.) conducted an analysis and evaluation of the selected articles. Any discrepancies in the article selection process were resolved through further discussion to reach a consensus.

### Data extraction and outcome measures

Two reviewers (P.L. and Z.L.) independently collected data by organizing the article information into tables, which were then reviewed by another researcher who provided modifications and suggestions regarding any discrepancies.

The CBCT images of planned and actual placement were compared to assess the accuracy of implants by measuring three dimensions: global platform deviation, global apex deviation, and angular deviation. In this review, global platform deviation was defined as the three-dimensional coronal distance between the planned and actual implant positions, measured from the central axis point. Global apex deviation was defined as the three-dimensional apical distance between the planned and actual implant positions, also measured from the central axis point. The angular deviation was defined as the angle measured from the central axis of the planned and actual implant positions. All three accuracy variables were assessed using CBCT, as illustrated in Fig. 1.

### Risk of bias assessment

Two reviewers (P.L. and Z.L.) conducted independent assessments of the quality of the clinical studies. Any differences were resolved through discussion with the collaborator (A.L.) to reach a consensus. In randomized controlled clinical trials (RCTs), the risk-of-bias tool (RoB2) in the Review Manager 5.4.1 (Cochrane Collaboration, Oxford, UK) software was used for evaluation

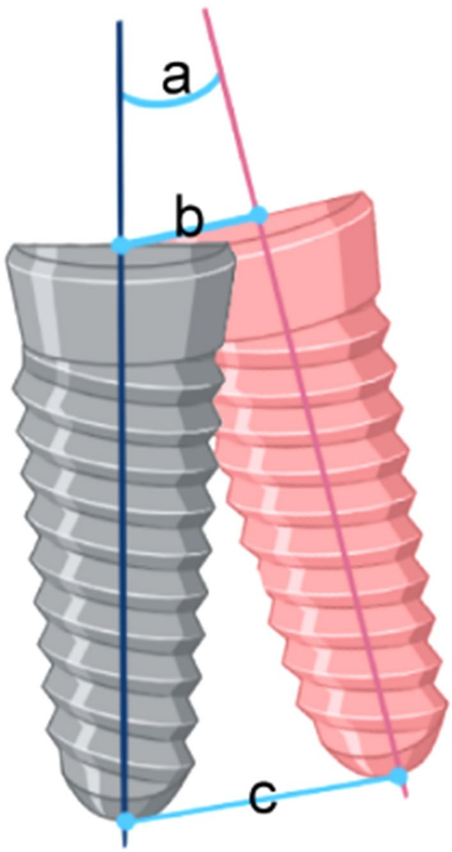


**Fig. 1** Accuracy parameters. (**a**) Angular deviation. (**b**) Global platform deviation. (**c**) Global apex deviation. The image was created with BioRender.com

following the guidelines provided by the Cochrane Handbook for Systematic Reviews of Interventions (version 6.0, updated in July 2019), and the assessment covered the following domains: (1) random sequence generation (selection bias); (2) allocation concealment (selection bias); (3) blinding of participants and personnel (performance bias); (4) blinding of outcome assessment (detection bias); (5) incomplete outcome data (attrition bias); (6) selective reporting (reporting bias); (7) other bias [33]. Prediction model risk of bias assessment tool (PROBAST) defines the overall risk of bias at low, high, and unclear levels. The publications were categorized as follows: (1) low risk of bias: trials with low risk of bias across all domains; (2) some concerns: trials that raise concerns in at least one domain for this result, without having a high risk of bias in any domain; (3) high risk of bias: trials with high risk of bias in at least one domain, or trials with some concerns in multiple domains significantly reducing confidence in the result. Non-randomized interventional studies were assessed using the Newcastle-Ottawa Scale (NOS) [34]. The NOS explores the risk of bias in three domains: selection, comparability, and outcome. Studies scoring 7–9 indicate a low risk of bias, while studies scoring 5–6 represent a medium risk. Studies scoring < 5 are considered to have a high risk of bias.

### Statistical analysis

This systematic review was conducted using Review Manager 5.4.1 software for quantitative data analysis. Global platform deviation, global apex deviation, and angular deviation were considered continuous variables for assessing the precision of implants. If the studies provided outcome data divided into subgroups, the means and standard deviations (SD) were weighted based on the respective subgroup sizes [33].

Firstly, a single-arm meta-analysis of the continuous data results was conducted from all the included articles. The mean values of each study's results were calculated and analyzed. The 95% confidence intervals (CI) were calculated in this study to assess the maximum deviation, which is crucial for preventing damage to vital anatomical structures. Next, subgroup analyses were performed based on different navigation systems, different dental arches, and different working principles of camera to explore their significant heterogeneity.

## Results

### Study selection

As shown in the comprehensive search flowchart in Fig. 2 and 211 articles were retrieved by searching three electronic databases: 81 articles from PubMed, 118 from Embase, and 12 from Cochrane CENTRAL. In addition, one article was obtained by manually searching dental journals. After eliminating duplicates, 150 papers remained. By reviewing the titles and abstracts, 128 articles were excluded, leaving 25 articles. Afterward, 9 articles were excluded after reading the full texts. Table S1 [35] presents the reasons for exclusion. The quality of the remaining 16 clinical studies was assessed using the RoB2 and NOS.

### Study characteristics

Sixteen articles that primarily focused on the past three years were finally included. Table 2 presents the study characteristics data. A total of 908 implants were included in the analysis, and the study results were evaluated by CBCT. Among the sixteen clinical studies, two were randomized controlled trials [24, 36], five were retrospective studies [26, 35, 37–39], five were case series [25, 40–43], and four were prospective single-arm studies [44–47]. All clinical studies, except for four that did not provide this information, reported no intraoperative or postoperative complications.

Among the studies included in this review, two RCTs [24, 36] compared the accuracy of freehand techniques (FH) with R-CAIS, one study compared D-CAIS with R-CAIS [37], one study compared FH, S-CAIS, and

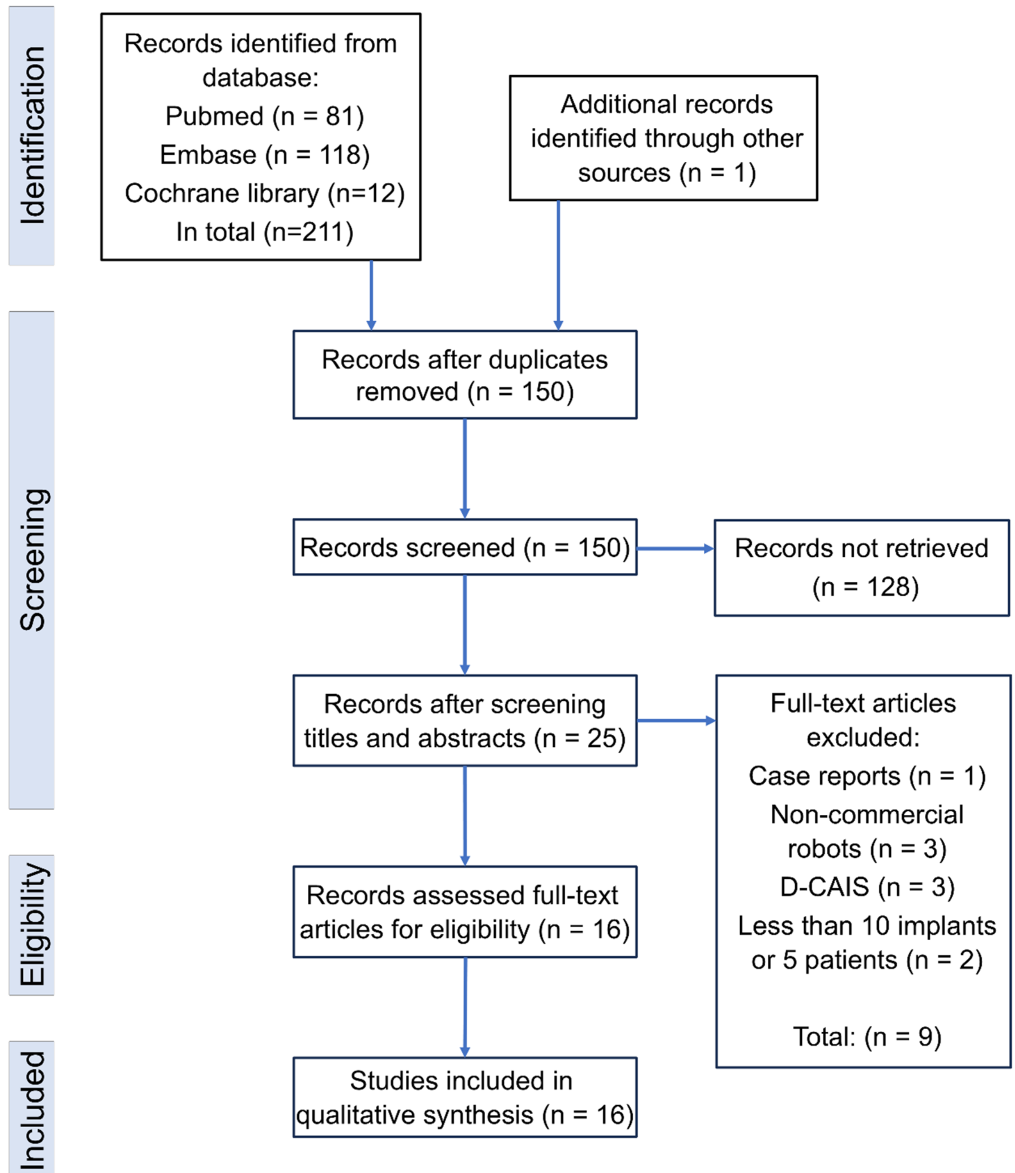


**Fig. 2** Search flow diagram

R-CAIS in the context of immediate anterior tooth implants [35], and one study compared S-CAIS, D-CAIS, and R-CAIS [46]. Additionally, two study focused on comparing S-CAIS with R-CAIS [38, 39]. Regarding the autonomous types of surgical robots, ten studies used autonomous robots [25, 26, 35, 37–39, 41, 43–45], while six used semi-active robots [24, 36, 40, 42, 46, 47]. Seven different brands of robotic systems were used. From the perspective of dentition statuses in the clinical studies, four studies focused on full edentulism [25, 38, 45, 47], three investigated patients with single tooth loss [24, 36, 43], two were conducted on partial edentulism [37, 44]. One study simultaneously assessed the implant accuracy for single tooth loss and full edentulism [40]. Apart from the Yomi based on mechanical tracking, all other robot systems' navigation is based on tracking reflective light, with Remebot's visual system based on visible light and the rest of the robot's visual systems based on infrared light.

### Quality of studies

The included clinical studies were assessed for quality. The RoB2 in the Review Manager 5.4.1 software was employed to evaluate two RCT studies [24, 36]. As shown in Fig. S1, the results indicated that the study met over 77% of the RoB2 criteria, except for one study uncertainty in outcome measurement, all other risks were classified as low levels of bias risk. The NOS was used to assess the remaining fourteen non-RCT studies with a score range

**Table 2** Description of the selected studies

| Study (year) | Study design | Robot system | The working principle of camera | Implant system | Autonomous/ semi-active | Patients /Implants | Age (years) | State of dentition | Global platform deviation (mm) | Global apex deviation (mm) | Angular deviation (°) | Complications | Control group |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fan Yang et al. (2024) [36] | Randomized clinical trial | Theta | Infrared ray | Straumann Nobel PCC | Semi-active | 70/70 | 35.6 ± 12.3 | Single tooth lost | 0.76 ± 0.36 | 0.85 ± 0.48 | 2.05 ± 1.33 | None | Freehand |
| Ningbo Zhao et al. (2024) [26] | Retrospective case series | Remebot | Visible light | Straumann BLT<br>Astra EVS<br>Nobel Replace CC<br>BEGO RSX | Autonomous | 15/20 | 32.07 ± 6.90 | Single tooth lost & partially edentulism | 0.75 ± 0.20 | 0.70 ± 0.27 | 1.17 ± 0.73 | None | / |
| Yu Wu et al. (2024) [41] | Case series | FZ-DISAS-I | Infrared ray | Straumann | Autonomous | 74/86 | 23–65 (45) | Single tooth lost & partially edentulism | 0.61 ± 0.20 | 0.79 ± 0.32 | 2.56 ± 1.10 | NR | / |
| Jun Li et al. (2024) [35] | Retrospective clinical study | Remebot | Visible light | NR | Autonomous | 21/33 | 41.14 ± 16.49 | Single tooth lost & partially edentulism | 0.62 ± 0.28 | 0.65 ± 0.27 | 1.46 ± 0.57 | NR | Freehand, S-CAIS |
| MiaoZhen Wang et al. (2024) [44] | Prospective clinical study | Yakebot | Infrared ray | NR | Autonomous | 13/20 | NR | Partially edentulism | 0.65 ± 0.32 | 0.66 ± 0.34 | 1.52 ± 1.01 | NR | / |
| Rui Xie et al. (2024) [45] | Prospective clinical study | YaZhi, YakeRobot | Infrared ray | Astra Tech EV<br>Nobel Parallel CC | Autonomous | 12/102 | 35–71 (59.8) | Fully edentulism | 0.53 ± 0.19 | 0.58 ± 0.17 | 1.83 ± 0.82 | None | / |
| Jay M. Neugarten et al. (2024) [42] | Large case series | Yomi | Mechanical tracking | Straumann BLX<br>Nobel active<br>Prima Plus<br>Paltop External Hex<br>Co-Axis | Semi-active | 108/273 | 19–92 (57) | Single tooth lost & partially edentulism & fully edentulism | 1.10 ± 0.69 | 1.12 ± 0.69 | 1.42 ± 1.53 | NR | / |
| Sihui Zhang et al. (2023) [37] | Retrospective clinical study | Remebot | Visible light | Astra TX<br>Bicon<br>Nobel active or replace (PMC)<br>Straumann BL or BLT<br>Weigo | Autonomous | 39/62 | 50.21 ± 17.82 | Partially edentulism | 0.68 ± 0.36 | 0.69 ± 0.36 | 1.37 ± 0.92 | None | D-CAIS |

**Table 2** (continued)

| Study (year) | Study design | Robot system | The working principle of camera | Implant system | Autonomous/semi-active | Patients /Implants | Age (years) | State of dentition | Global platform deviation (mm) | Global apex deviation (mm) | Angular deviation (°) | Complications | Control group |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jun-Yu Shi et al. (2023) [24] | Randomized clinical trial | Theta | Infrared ray | Straumann BLT | Semi-active | 10/10 | 47.5 (13.5) | Single tooth lost | 1.27 ± 0.46 | 1.47 ± 0.62 | 3.64 ± 2.99 | None | Free-hand |
| Ping Li et al. (2023) [25] | Case series | Remebot | Visible light | NR | Autonomous | 10/59 | 34–89 (57.3 ± 13.7) | Fully edentulism | 0.67 ± 0.37 | 0.69 ± 0.37 | 1.27 ± 0.59 | None | / |
| Wenxue Wang et al. (2023) [38] | Retrospective clinical study | Yakebot | Infrared ray | Straumann BL. | Autonomous | 5/36 | 61.20 ± 7.43 | Fully edentulism | 0.65 ± 0.25 | 0.65 ± 0.22 | 1.43 ± 1.18 | None | S-CAIS |
| Shi-Chong Qiao et al. (2023) [40] | Case series | Langyue | Infrared ray | Nobel Active or CC | Semi-active | 19/19 | 46.7 (9.9) | Single tooth lost | 0.54 ± 0.17 | 0.54 ± 0.11 | 0.79 ± 0.22 | None | / |
| | | | | | | 2/9 | | Fully edentulism | 0.53 ± 0.17 | 0.58 ± 0.17 | 0.77 ± 0.26 | | |
| Wei Chen et al. (2023) [46] | Prospective, single-arm clinical trial | Dencore, | Infrared ray | Straumann BL | Semi-active | 28/31 | NR | Single tooth lost & partially edentulism | 0.53 ± 0.23 | 0.53 ± 0.24 | 2.81 ± 1.13 | NR | S-CAIS, D-CAIS |
| Shasha Jia et al. (2023) [39] | Retrospective clinical study | Yakebot | Infrared ray | Straumann BLX | Autonomous | 20/30 | NR | Single tooth lost & partially edentulism | 0.43 ± 0.18 | 0.56 ± 0.18 | 1.48 ± 0.59 | None | S-CAIS |
| Shuo Yang et al. (2023) [43] | Case series | Remebot | Visible light | Axiom PX or REG Straumann BLT or BL Astra TX | Autonomous | 10/10 | 38.8 ± 20.3 | Single tooth lost | 0.74 ± 0.29 | 0.73 ± 0.28 | 1.11 ± 0.46 | None | / |
| Scotty L. Bolding et al. (2021) [47] | Prospective single-arm clinical study | Yomi | Mechanical tracking | NR | Semi-active | 5/38 | 47–65 (57) | Fully edentulism | 1.04 ± 0.70 | 0.95 ± 0.73 | 2.56 ± 1.48 | None | / |

NR: not reported

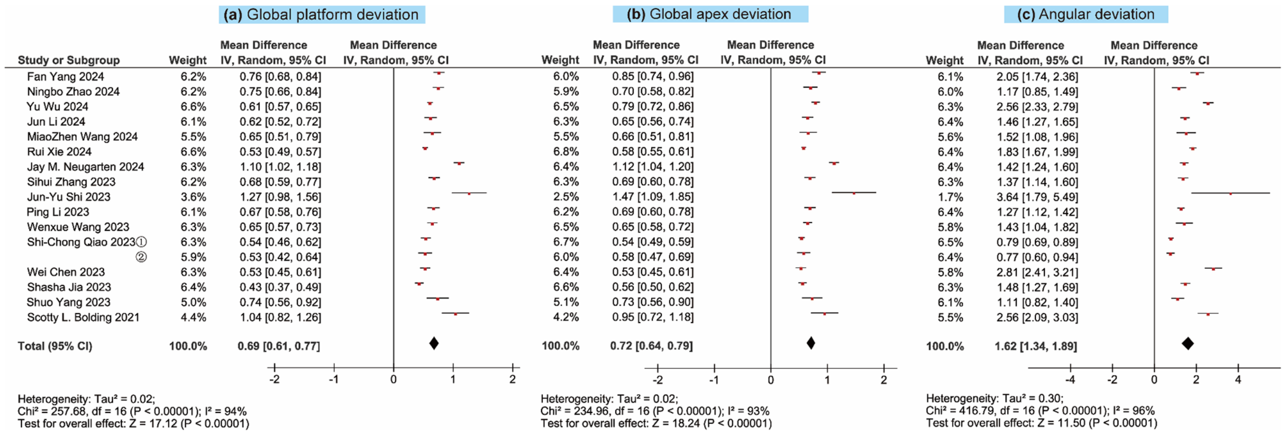


**Fig. 3** Forest plots of (**a**) global platform deviation, (**b**) global apex deviation, and (**c**) angular deviation. The 95% confidence intervals (CI) were calculated in this study

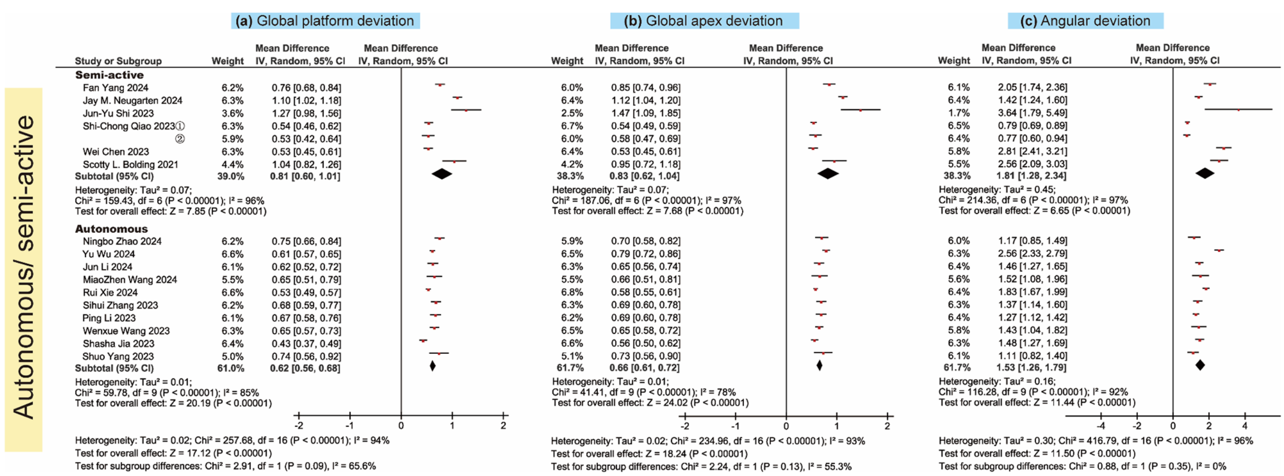


**Fig. 4** Forest plots ofautonomous/semi-active. (**a**) global platform deviation, (**b**) global apex deviation, (**c**) angular deviation. The 95% confidence intervals (CI) were calculated in this study

of 6–9, indicating a low to medium risk of bias [48]. the specific scoring details are in Table S2.

## Accuracy analysis

In all the included studies, the global platform deviation, global apex deviation, and angular deviation were 0.69 mm (95% CI: 0.61–0.77, $I^2=94\%$), 0.72 mm (95% CI: 0.64–0.79, $I^2=93\%$), and 1.62° (95% CI: 1.34°–1.89°, $I^2=96\%$) (Fig. 3).

## Subgroup analysis

A subgroup analysis was conducted to compare semi-active and autonomous robots. The global platform deviation, global apex deviation, and angle deviation of semi-active robots were 0.81 mm (95% CI: 0.60–1.01, $I^2=96\%$), 0.83 mm (95% CI: 0.62–1.04, $I^2=97\%$), and 1.81° (95% CI: 1.28°–2.34°, $I^2=97\%$), respectively, and in the autonomous robots, they were 0.62 mm (95% CI: 0.56–0.68, $I^2=85\%$), 0.66 mm (95% CI: 0.61–0.72, $I^2=78\%$), and 1.53° (95% CI: 1.26–1.79, $I^2=92\%$), respectively. There was no statistically significant difference between semi-active and autonomous robots ($P>0.05$) (Fig. 4).

A subgroup analysis was conducted to compare the dentition statuses. The global platform deviation, global apex deviation, and angle deviation of single tooth loss were 0.79 mm (95% CI: 0.58–0.99, $I^2=91\%$), 0.84 mm (95% CI: 0.58–1.09, $I^2=94\%$), and 1.54° (95% CI: 0.83°–2.25°, $I^2=96\%$), respectively, and in partial edentulism, they were 0.67 mm (95% CI: 0.60–0.75, $I^2=0\%$), 0.68 mm (95% CI: 0.61–0.76, $I^2=0\%$), and 1.40° (95% CI: 1.20°–1.60°, $I^2=0\%$), respectively. In full edentulism, these values were 0.65 mm (95% CI: 0.54–0.76, $I^2=87\%$), 0.63 mm (95% CI: 0.56–0.70, $I^2=81\%$), and 1.54° (95% CI: 1.06°–2.03°, $I^2=96\%$). There was no statistically significant difference between all the dentition statuses ($P>0.05$) (Fig. 5).

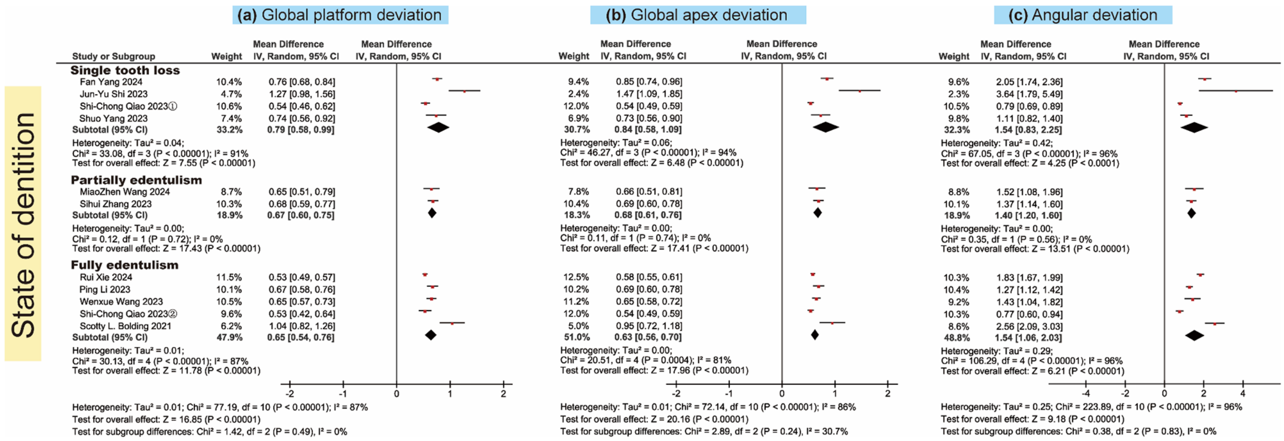


**Fig. 5** Forest plots of state of dentition. (**a**) global platform deviation, (**b**) global apex deviation, (**c**) angular deviation

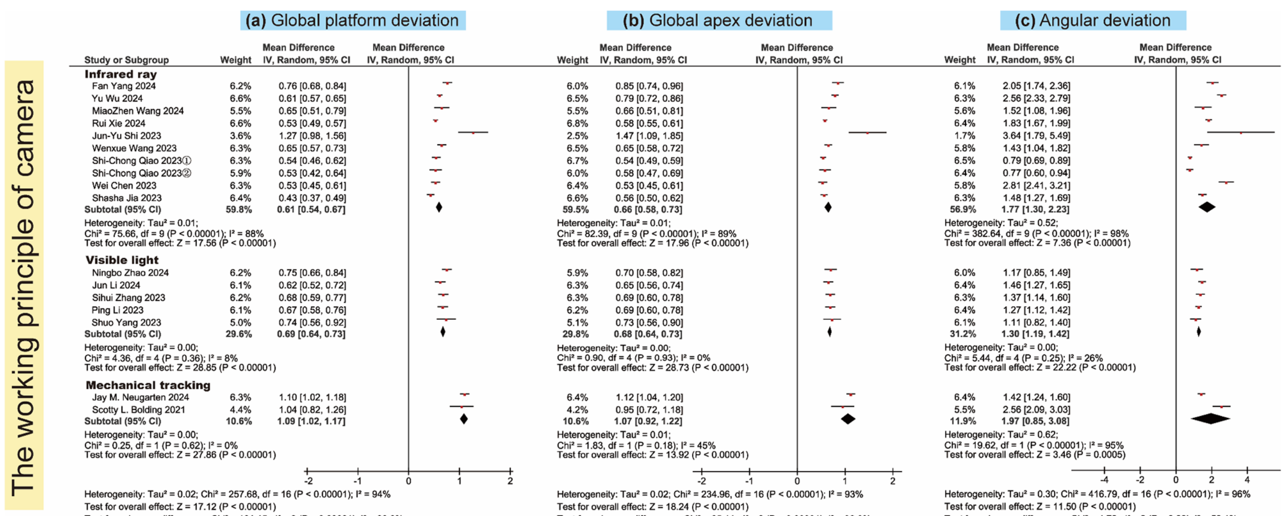


**Fig. 6** Forest plots of the working principle of camera. (**a**) global platform deviation, (**b**) global apex deviation, (**c**) angular deviation. The 95% confidence intervals (CI) were calculated in this study

A subgroup analysis was conducted to compare different robots using infrared rays, visible light, and mechanical tracking as the working principles of cameras. The global platform deviation, global apex deviation, and angle deviation of robots using infrared rays were 0.61 mm (95% CI: 0.54–0.67, $I^2=88\%$), 0.66 mm (95% CI: 0.58–0.73, $I^2=89\%$), and 1.77° (95% CI: 1.30°–2.23°, $I^2=98\%$), respectively, and in the robots using visible light, they were 0.69 mm (95% CI: 0.64–0.73, $I^2=8\%$), 0.68 mm (95% CI: 0.61–0.72, $I^2=0\%$), and 1.30° (95% CI: 1.19°–1.42°, $I^2=26\%$), respectively. and in the robots using mechanical tracking, they were 1.09 mm (95% CI: 1.02–1.17, $I^2=0\%$), 1.07 mm (95% CI: 0.92–1.22, $I^2=45\%$), and 1.97° (95% CI: 0.85°–3.08°, $I^2=95\%$), respectively. Statistically significant differences were found in global platform deviation and apex deviation between robots using infrared ray and mechanical tracking ($p<0.01$, $p<0.01$), and the global platform deviation and apex deviation between robotic utilizing visible light and mechanical tracking ($p<0.01$, $p<0.01$) (Fig. 6). No statistically significant differences were found in the other comparisons within this subgroup, except the global platform deviation between the robots using infrared rays and visible light, which recorded a p-value of 0.05; all other groups had p-values greater than 0.05.

## Discussion

Since the US Food and Drug Administration (FDA) approved the first robotic dental surgical system in 2016, research on robot-assisted implants has increased significantly [49]. This meta-analysis evaluated the accuracy of robot-assisted implants, including a total of 908 implants across 16 studies. The results indicated that the average global platform deviation, global apex deviation, and angle deviation of R-CAIS were 0.69 mm (95% CI: 0.61–0.77, $I^2=94\%$), 0.72 mm (95% CI: 0.64–0.79,

$I^2 = 93\%$), and 1.62° (95% CI: 1.34°−1.89°, $I^2 = 96\%$), respectively. The upper limit of the 95% confidence interval (CI) for the average global apex deviation (0.69 mm) was significantly below the clinical requirement of 2 mm for safe distance from the inferior alveolar nerve [50]. Previous meta-analyses reported the average global platform deviation, global apex deviation, and angle deviation for clinical studies were 0.68 mm (95% CI: 0.570.79), 0.67 mm (95% CI: 0.580.75), and 1.69° (95% CI: 1.25°2.12°) [30]. Another meta-analysis found similar deviations of 0.6 mm (95% CI: 0.50.8), 0.7 mm (95% CI: 0.60.8), and 1.6° (95%CI: 1.1°2.0°) [29]. The findings of this meta-analysis align with those of previous studies, collectively supporting the high accuracy of R-CAIS. This study is the first to specifically assess robotic accuracy in clinical trials, incorporating twice the number of clinical studies compared to prior meta-analyses. It also discusses factors influencing robotic systems and patients, including the impacts of robot autonomy, dentitions, and visual systems, with a particular focus on the effect of visual systems, which is examined for the first time in this review.

The meta-analysis in this study did not reveal significant differences between autonomous and semi-active implant systems. According to Yang's classification, autonomous surgical robots for dental implants are categorized as follows: (1) Level 1 (semi-active), where the robot provides mechanical guidance while the surgeon retains continuous control over aspects like drilling speed and force; (2) Level 2 (autonomous), where the surgeon's control over the robot is discrete, allowing the robot to perform drilling and implant insertion independently [51]. In a model study, implant robots were classified as active or semi-active based on whether their movements were independently controlled or manually guided by the surgeon, while those limited to angle locking were termed passive. This study found no significant differences in implant placement accuracy between active and semi-active robots. However, passive robots exhibited greater average global platform, apex, and angular deviations than active and semi-active types, suggesting that the arm movement method does not affect the implant process [52]. Nonetheless, hand tremors from manual control can hinder the robotic arm's autonomous adjustments, leading to reduced accuracy. The absence of significant differences between autonomous and semi-autonomous subgroups may be due to the uneven number of studies, with more data available for autonomous systems, and unaccounted heterogeneity factors such as study design and robotic brands. These limitations could have influenced the results, underscoring the need for more balanced study populations and comprehensive subgroup analyses in future research to better evaluate the impact of robotic autonomy on implant accuracy.

No significant difference was found in the implant accuracy of robotic systems across various dentition statuses. Although the complexity of implant varies with dental arch conditions—such as partial edentulism and fully edentulous cases, which often face challenges due to insufficient residual alveolar bone and lack of stable adjacent teeth for guide fixation—this study found no statistically significant differences in accuracy among single tooth loss, partial edentulism, and fully edentulism [15]. This may be attributed to the high precision of robotic systems, which minimizes the impact on various dentition statuses. An in vivo study similarly reported no significant accuracy differences between single tooth loss and fully edentulism cases with R-CAIS, which is consistent with the findings of this study [40]. In contrast, S-CAIS studies have shown higher deviations in fully edentulous patients (1.85°-8.4°), potentially due to variations in surgical guide design and fabrication, whereas robotic systems appear less affected by dental status [53–55]. This study focused solely on dentition statuses but did not account for other potentially influential factors, such as implant position (anterior vs. posterior) and jaw type (maxilla vs. mandible). Therefore, further confirmation of this viewpoint requires large-scale, multi-center, randomized, controlled clinical trials.

A comparison of the implant accuracy of different robotic systems utilizing infrared ray, visible light, and mechanical tracking as the working principles of cameras was conducted. The results indicated statistically significant differences in platform and apical deviation between the infrared and mechanical haptics groups, as well as between the visible light and mechanical haptics groups, suggesting that the tracking mechanisms and environmental adaptability of different camera principles may influence accuracy. No significant difference was observed in platform accuracy deviations between the infrared and visible light groups ($p = 0.05$), likely due to their similar optical tracking mechanisms. Previous research has indicated that haptic robotic-guided implant surgery, owing to its tactile feedback mechanisms and the high stability of robotic arms, achieved superior accuracy compared to dynamic and static navigation systems [47]. However, direct comparative studies between haptic robots and other vision-based robotic systems are lacking. Additionally, dynamic navigation studies suggest that infrared technology may enhance accuracy by reducing natural light interference, although this hypothesis requires further validation [56]. It is important to note the significant heterogeneity present in clinical studies, where confidence intervals may sometimes be adjusted to 90% ($p < 0.1$) [57]. This meta-analysis is the first to discuss the impact of robotic visual system principles on implant accuracy, although other components, such as robotic arms and user interfaces may also influence the overall performance of robotic systems [58]. Future studies with larger sample sizes and multi-brand comparative clinical trials are needed to further validate these findings.

S-CAIS utilizes surgical templates and specialized instruments to improve accuracy by physically restricting the implant position. However, it has several limitations: (1) Errors can accumulate from CBCT imaging, mechanical inaccuracies in 3D-printed templates, and mismatches between sleeves and drills [55, 59]. (2) The template only restricts the crown side of the drill, allowing for greater deviation at the implant apex [47]. (3) The implant strategy cannot be modified intraoperatively [60]. D-CAIS uses optical tracking for real-time visual guidance, enabling intraoperative adjustments to the implantation plan. Nonetheless, there are still some drawbacks to consider: (1) Manual intervention is still necessary, which can introduce linear errors of up to 0.25 mm and angular errors of up to 0.5° due to hand instability [61]. (2) D-CAIS heavily relies on the surgeon's manipulative skills and requires a learning curve [62, 63]. (3) Frequent shifts in focus between screens and the surgical site may lead to oversight of important details or fatigue [23]. R-CAIS combines a real-time dynamic optical tracking with a mechanical arm, enabling precise control of the drilling axis and achieving high accuracy [25]. This study showed superior accuracy of R-CAIS compared to conventional S-CAIS andD-CAIS [15, 53]. Previous clinical studies have consistently shown R-CAIS to be more precise than both S-CAIS and D-CAIS [37, 38]. Furthermore, a recent clinical study on immediate implant placement in the anterior region revealed that R-CAIS achieved greater accuracy than both freehand techniques and S-CAIS, highlighting the high precision of robotic assistance in complex implant procedures [35]. The high accuracy of robotic-assisted implant surgery holds significant clinical importance. It reduces the risk of damage to adjacent critical anatomical structures, such as nerves and blood vessels, while optimizing the initial stability of implants and promoting osseointegration, thereby enhancing long-term success rates [10]. Additionally, robotic technology minimizes the dependence on surgeon experience, improving the reproducibility and standardization of surgical procedures [64]. However, R-CAIS is not without its limitations.

First, in clinical studies of R-CAIS, many factors could potentially affect the accuracy of the implants, including the quality of CBCT, implant robot systems, operator skills, patient bone quality variations, and implant positions. The errors in CBCT need to be seriously considered as all implant outcomes are assessed by CBCT. The error of CBCT can come from the differences in layer thickness, voxel size, and threshold segmentation [48, 65]. Additionally, implants in CBCT scans can produce artifacts, leading to inaccurate imaging and interfering with accuracy assessment. Human factors such as the operator's proficiency in capturing images or patient movement during imaging can also impact the assessment of implant positions [66]. It is necessary to research and explore better measurement methods to reduce errors, such as intraoral scanning. Second, the advantages of R-CAIS over D-CAIS remain unclear, as there is currently insufficient evidence to support the clinical replacement of dynamic navigation by robotic systems [30]. More RCTs are needed to provide a comprehensive analysis that includes surgical duration, postoperative responses, and cost considerations. Third, the preparation process for R-CAIS is relatively lengthy, involving the creation of intraoral guides and the calibration of the patient and the robotic arm during the procedure, which extends the overall surgical time [67]. Fourth, the operational workflow of R-CAIS is complex and not yet standardized, and the learning curve associated with its use remains undefined [26].

This review conducted a quality assessment of the included clinical studies. Two RCT studies met over 77% of the RoB2 criteria (Figure S1), with only the outcome assessment being deemed as unclear levels of bias risk out of the 7 criteria [24, 36]. Due to the surgeons must be aware of the implant surgical details, it is difficult to implement blinding for the primary researchers. The fourteen non-RCT studies assessed using the NOS were found to have a low to medium risk of bias (Table S2). The main limitation was the lack of control experiments. In addition, some experiments were not assessed by an independent blinded researcher during outcome measurements. However, the accuracy of most articles on implants is measured repeatedly by one professional who evaluates the accuracy, or the average of the results measured by two professionals, which to some extent improves the reliability of the results. In conclusion, all the included studies met the criteria.

The limitations of this review include the insufficient number of large-scale, multicenter, randomized, controlled clinical trials on R-CAIS. This review only encompasses two RCTs, with the majority being case series of lower evidence levels, potentially affecting the validity of the meta-analysis [24, 36]. Future research should focus on conducting large-scale multicenter RCTs comparing S-CAIS, D-CAIS, and R-CAIS to establish the clinical advantages of R-CAIS. Additionally, relatively few control studies were included in the analyses, which precludes a meta-analysis comparing S-CAIS, D-CAIS, and R-CAIS. In addition, the included studies are primarily from Asia, with limited external validity. Besides the subgroups discussed in this review, several variables that can influence implant accuracy (e.g., the CBCT, types of implants, surgical details, and patient bone quality) are also worth researching and discussing. The observed high heterogeneity may stem from varying surgical techniques, different types of robotic systems, and the experience levels of operators. The subgroup analysis in this study did not comprehensively encompass and elucidate these sources of variability. Future research should focus on standardizing these parameters to enhance the reliability and applicability of findings regarding robotic-assisted dental implant procedures. Currently, robotic implant research is in stage 2a of the IDEAL Robotics Colloquium proposes recommendations for evaluation during development. There is a lack of randomized controlled trials in existing clinical studies, with design flaws, reporting biases, methodological heterogeneity, limited patient numbers, and surgical team experience [28]. Due to incomplete information provided in the included article, this review did not include all information about different robotic systems such as robotic arms or registration methods, and did not obtain all detailed surgical data such as CBCT images or surgical time. The included studies only reported short-term postoperative conditions. Long-term survival rates and complications studies are needed to determine the long-term efficacy of R-CAIS.

## Conclusion

Based on this systematic review, the average global platform deviation, global apex deviation, and angle deviation of the robot in clinical studies were 0.69 mm (95% CI: 0.61−0.77, $I^2 = 94\%$), 0.72 mm (95% CI: 0.64−0.79, $I^2 = 93\%$), and 1.62° (95% CI: 1.34°−1.89°, $I^2 = 96\%$), respectively. A preliminary conclusion drawn from this study is that R-CAIS has high accuracy. Besides the statistical differences observed in platform deviation and apical deviation between the infrared and mechanical haptics groups, as well as the visible light and mechanical haptics groups, no statistically significant differences were observed in autonomous vs. semi-active robots, or dentition statuses. More large-scale, multi-center, randomized, controlled clinical trials are warranted to further compare the differences between R-CAIS and S-CAIS or D-CAIS and explore more factors influencing R-CAIS.

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12903-025-05837-2.

Supplementary Material 1

Supplementary Material 2

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### Author contributions

Zixin Luo: Methodology, Investigation, Validation, Formal analysis, Writing– review & editing.An Li: Conceptualization, Software, Investigation, Formal analysis, Writing– original draft.Lvhua Guo: Software, Formal analysis, Visualization, Writing– original draft.Jiang Li, Methodology, Data curation, Writing– review & editing, Supervision, Project administration, Funding acquisition. Zhe Wu: Writing– original draft, Visualization, Resources, Investigation. Ping Li: Conceptualization, Methodology, Investigation, Resources, Formal analysis, Writing– review & editing, Supervision.

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### Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

## Declarations

### Ethics approval and consent to participate

Central Committee on Research Involving Human Subjects concluded that no ethical approval was required for data collection for this purpose. Furthermore, The protocol was registered in PROSPERO (CRD42024590506).

### Consent for publication

Not applicable.

### Competing interests

The authors declare no competing interests.

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