Clinical Oral Investigations
https://doi.org/10.1007/s00784-021-03833-8

REVIEW

Accuracy assessment of dynamic computer–aided implant placement: a systematic review and meta-analysis

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Received: 6 November 2020 / Accepted: 5 February 2021

Abstract

Objectives To assess the accuracy of dynamic computer–aided implant surgery (dCAIS) systems when used to place dental implants and to compare its accuracy with static computer–aided implant surgery (sCAIS) systems and freehand implant placement.

Materials and Methods An electronic search was made to identify all relevant studies reporting on the accuracy of dCAIS systems for dental implant placement. The following PICO question was developed: "In patients or artificial models, is dental implant placement accuracy higher when dCAIS systems are used in comparison with sCAIS systems or with freehand placement? The main outcome variable was angular deviation between the central axes of the planned and final position of the implant. The data were extracted in descriptive tables, and a meta-analysis of single means was performed in order to estimate the deviations for each variable using a random-effects model.

Results Out of 904 potential articles, the 24 selected assessed 9 different dynamic navigation systems. The mean angular and entry 3D global deviations for clinical studies were 3.68° (95% CI: 3.61 to 3.74; $I^2 = 99.4\%$) and 1.03 mm (95% CI: 1.01 to 1.04; $I^2 = 82.4\%$), respectively. Lower deviation values were reported in in vitro studies (mean angular deviation of 2.01° (95% CI: 1.95 to 2.07; $I^2 = 99.1\%$) and mean entry 3D global deviation of 0.46 mm (95% CI: 0.44 to 0.48 ; $I^2 = 98.5\%$). No significant differences were found between the different dCAIS systems. These systems were significantly more accurate than sCAIS systems (mean difference (MD): −0.86°; 95% CI: −1.35 to −0.36) and freehand implant placement (MD: −4.33°; 95% CI: −5.40 to −3.25).

Conclusion dCAIS systems allow highly accurate implant placement with a mean angular of less than 4°. However, a 2-mm safety margin should be applied, since deviations of more than 1 mm were observed. dCAIS systems increase the implant placement accuracy when compared with freehand implant placement and also seem to slightly decrease the angular deviation in comparison with sCAIS systems.

Clinical Relevance The use of dCAIS could reduce the rate of complications since it allows a highly accurate implant placement.

Keywords Dynamic computer-assisted surgery · Navigation systems · Computer-guided implantology · Dental implants

Introduction

Nowadays, dental implants are a predictable treatment option for treating both partially or totally edentulous patients [1]. However, some complications can occur, leading to implant failure. The risk factors associated with these complications can be related to the surgical technique, the patient, the restoration, and the implant itself [2].

Implants may become osseointegrated and be considered successful despite not attaining an ideal prosthetically driven position. However, this optimal position should be a treatment goal since it facilitates restoration and maximizes esthetics.

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Published online: 26 February 2021

Indeed, achieving an ideal three-dimensional (3D) implant position prevents surgical complications (such as sinusitis, nerve injuries, or bleeding), esthetic problems (i.e., buccal dehiscence due to the resorption of the buccal plate), prosthetic complications (i.e., difficulty in inserting a restoration), and marginal bone loss [3–7]. It is estimated that around 7% of complications might be related to implant malposition [8]. Moreover, another study has reported that the distance to the neighboring teeth/implant was incorrect in almost 1/5 of the implants and that one third of the implants presented perforation of adjacent structures [9].

Cone-beam computed tomography (CBCT) has become a widely used examination technique for adequate planning of any implant surgery [10–12]. Furthermore, CBCTs make it possible to simulate a prosthetically driven implant placement with specific software. This information, in turn, can be transferred to the patient, facilitating more accurate implant positioning.

Computer-aided implant surgery (CAIS) has recently been introduced into dental implantology to reduce deviations from the virtually planned implant position. According to Hämmerle et al. [13], static computer–aided implant surgery (sCAIS) systems use stereolithographic templates supported by teeth, bone, or mucosa during drilling and insertion of the implant, while dynamic computer–aided implant surgery (dCAIS) systems perform real-time tracking of the drills and implants through an optimal marker and relate this information to the 3D preoperative virtual plan drawn up with CBCT [13–16]. In 2009, Jung et al. [14] published a systematic review in which dCAIS delivered promising results. However, at that time, the available information on this technology was scarce and most published studies used an "in vitro" setting [14].

Considering the rapid development of these technologies and the large number of studies on navigation systems published in recent years, it is of great importance to gather together all the information related to the accuracy of the available dCAIS systems. Hence, the main aim of this meta-analysis was to determine the accuracy of dCAIS systems for dental implant placement in relation to the position planned preoperatively. The secondary objective of this review was to compare dCAIS systems with sCAIS systems and freehand placement.

Methods

This systematic review complied with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement [17]. The protocol was registered in PROSPERO (CRD42020175829).

The following PICO questions were formulated:

- Population: Patients or artificial models treated with dental implants placed using a dCAIS
- Intervention: Implant placement using dCAIS
- Comparison: Implant placement using sCAIS and/or freehand
- Outcome: Accuracy of dental implant placement measured with the angular deviation between the central axes of the planned and final position of the implant
- Studies: Randomized or non-randomized controlled trials, retrospective or prospective cohort studies, case-control studies, case series with more than 10 patients, and "in vitro" studies

Eligibility criteria

All primary studies including clinical (i.e., randomized clinical trials (RCTs), prospective and retrospective cohort studies, case-control studies, and case series with more than 10 patients), "in vivo", and "ex vivo" studies that reported the accuracy of dynamic computer–assisted implant systems were included. Only studies reporting the exact amount of deviation between the presurgical planning and the final implant position were included. No language restriction was applied.

Case reports and studies assessing virtual augmented reality were excluded. Studies evaluating sCAIS systems without comparing them with dCAIS systems were also excluded. Likewise, studies involving accuracy assessment in zygomatic or pterygoid implants and papers published before 2010 were excluded. The date restriction was applied to avoid including potentially outdated systems.

The main outcome variable was the angular deviation of the implant, defined as the largest angle between the longitudinal axis of the planned implant position and the placed implant position, measured in sexadecimal degrees (°). The secondary variables were entry global (3D) and lateral (2D) deviations (i.e., deviation at the implant connection), apex global (3D) and lateral (2D) deviations (i.e., deviation at the implant apex), and deviation in depth both at the apex and at the implant connection (Fig. 1).

Search strategy

An electronic search in MEDLINE (PubMed), the Cochrane Library, Scopus (Elsevier), and Web of Science (Thomson Reuters) databases up to December 13, 2020 was performed to identify all potentially eligible articles regarding dCAIS accuracy. The search strategy can be observed in Table 1.

Additionally, OpenGrey and www.greylit.org were searched for gray literature and ClinicalTrials.gov for relevant unpublished data, and manual screening of articles published in the last 10 years was carried out in the following journals: *Clinical Oral Implants Research*,

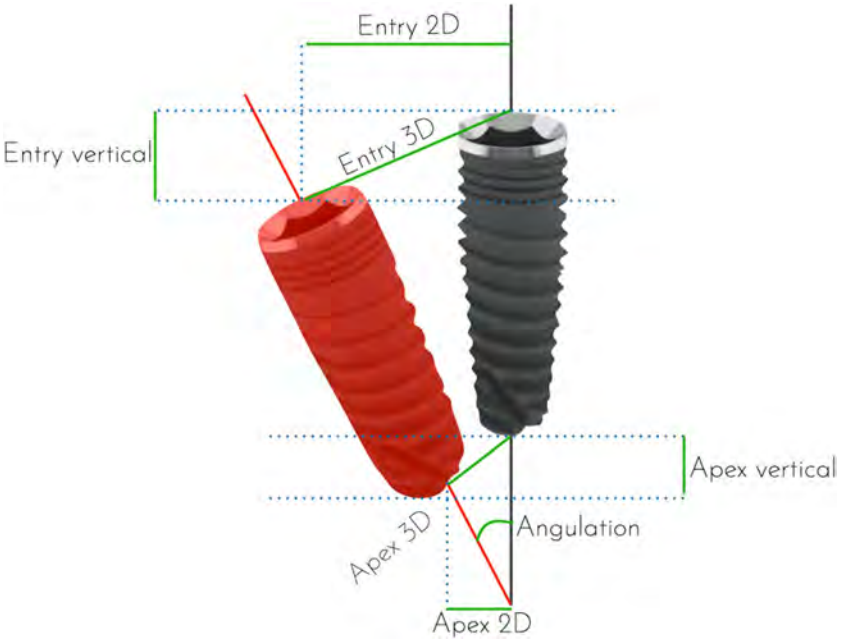

Fig. 1 Deviation outcomes: deviation between the planned position and the final position. 2D: two dimensions (lateral); 3D: three dimensions (global). Entry 2D: deviation of the implant platform in the *x* and *y* dimensions of space in an occlusal view, without taking deviation in depth (*z*-axis) into account, in millimeters (mm). Entry 3D: deviation of the implant platform in the three dimensions of space (*x*, *y*, and *z*), in millimeters (mm). Entry vertical: deviation of implant platform depth (*z*-axis), in millimeters (mm). Apex 2D: deviation of the implant apex in the *x* and *y* dimensions of space in an occlusal view, without taking deviation in depth (*z*-axis) into account, in millimeters (mm). Apex 3D: deviation of the implant apex in the three dimensions of space (*x*, *y*, and *z*), in millimeters (mm). Apex vertical: deviation of implant apex depth (*z*-axis), in millimeters (mm). Angulation: angular deviation between the central axes of the planned position and the final position, in sexadecimal degrees (°)

Table 1 Search strategy for each database

PubMed

("Surgery, Computer-Assisted"[Mesh] OR "navigation system" OR "navigation systems" OR "dynamic computer aided" OR "dynamic computer guided" OR "dynamic computer assisted") AND (dental implants OR dental implant OR "Dental Implants"[Mesh] OR implantology)

Scopus

TITLE-ABS-KEY ("Surgery, Computer-Assisted" OR "navigation system" OR "navigation systems" OR "dynamic computer aided" OR "dynamic computer guided" OR "dynamic computer assisted") AND TITLE-ABS-KEY (("dental implants" OR "dental implant" OR implantology))

Web of Science

TOPIC: (("Surgery, Computer-Assisted" OR "navigation system" OR "navigation systems" OR "dynamic computer aided" OR "dynamic computer guided" OR "dynamic computer assisted") AND ("dental implants" OR "dental implant" OR implantology))

Cochrane Library

#1: "Surgery, Computer-Assisted"[Mesh]
#2: "navigation system" OR "navigation systems" OR "dynamic computer aided" OR "dynamic
computer guided" OR "dynamic computer assisted"
#3: "Dental Implants"[Mesh]
#4: "dental implants" OR "dental implant" OR implantology
(#1 OR #2) AND (#3 OR #4)

International Journal of Oral & Maxillofacial Implants, *Journal of Oral and Maxillofacial Surgery*, *Clinical Implant Dentistry and Related Research*, and *European Journal of Oral Implantology*. The references in the selected articles and reviews were also searched. Finally, the bibliography recommended by the main manufacturers of navigation systems was analyzed.

Study selection

Two examiners with experience in meta-analysis (A.J-G. and A.G.-B.) independently selected the studies in accordance with the inclusion criteria. Initially, duplicates were merged and two reviewers (A.J-G. and A.G-B.) independently read the titles and abstracts of the potential studies to exclude irrelevant publications. After this stage, the reviewers individually assessed the full-text articles to decide on the eligibility of the remaining articles. The studies removed at this stage and the reasons for their exclusion were recorded. Any disagreement was resolved by consensus. If no consensus was achieved, a third reviewer with broad experience in statistics and meta-analysis (O.C.-F.) decided on the eligibility of the article. Cohen's kappa coefficient was calculated and showed a high degree of agreement between the reviewers (kappa= 0.977).

Data extraction

Two reviewers (A.J-G. and A.G-B.) independently used a data extraction table to gather the relevant data from the articles included. The tables were evaluated by a third reviewer (O.C.-F.), and in the event of inconsistencies, the item was referred back to the reviewers to confirm or correct data. The data included the following: (1) study characteristics: authors, year, country, and study design and settings; (2) participants' characteristics: number of patients/models, number of implants, age, gender, and type of edentulism; (3) intervention: dCAIS system, operator experience, and assessment of implants or holes; (4) comparison; and (5) outcomes of interest: deviations. The declared conflicts of interest were also registered for each individual study.

Authors were contacted in case of missing information or a need for clarification. If the reviewers identified multiple reports on the same patients, only the study with the largest sample was included.

Quality and risk of bias assessment

As part of the data extraction process, 2 reviewers (A.J.-G. and A.G.-B.) independently assessed the quality of the clinical studies.

For the RCTs, the Cochrane's risk-of-bias tool (RoB 2) was used according to the method described in the Cochrane Handbook for Systematic Reviews of Interventions (version 6.0) [18]. Hence, the following domains were evaluated: (1) randomization process, (2) deviations from intended interventions, (3) missing outcome data, (4) measurement of the outcome, and (5) selection of the reported result. The publications were grouped into the following categories: low risk of bias if the trial is judged to be at low risk of bias for all domains, some concerns if the trial is judged to raise some concerns in at least one domain for this result without having high risk of bias for any domain, and high risk of bias when the trial is judged to be at high risk of bias in at least one domain or is judged to have some concerns for multiple domains in a way that substantially lowers confidence in the result [18].

The quality assessment for observational studies was assessed using the Newcastle-Ottawa scale [19]. The following items were evaluated: (1) selection, (2) comparability (taking into consideration the type of edentulism and implant site location), and (3) outcome, and the maximum score for each study was 9 points.

Summary measures and synthesis of results

A descriptive analysis of the articles included was performed, and the following data were recorded in a descriptive summary: (1) author, (2) year, (3) country, (4) study design, (5) clinical setting, and (6) details of population, interventions, comparison, and outcomes.

The following outcome variables were analyzed (Fig. 1):

- Entry (2D) lateral: deviation between the planned position and the final position of the implant platform in the x and y dimensions of space in an occlusal view, without taking deviation in depth (z-axis) into account, in millimeters (mm)
- Entry (3D) global: deviation between the planned position and the final position of the implant platform in the three dimensions of space (x, y, and z), in millimeters (mm)
- Entry depth: vertical distance (depth) between the planned position and the final position of the implant platform (z-axis), in millimeters (mm)
- Apex (2D) lateral: deviation between the planned position and the final position of the implant apex in the x and y dimensions of space in an occlusal view, without taking deviation in depth (z-axis) into account, in millimeters (mm)
- Apex (3D) global: deviation between the planned position and the final position of the implant apex in the three dimensions of space (x, y, and z), in millimeters (mm)
- Apex depth: vertical distance (depth) between the planned position and the final position of implant apex (z-axis), in millimeters (mm)
- Angulation: angular deviation between the central axes of the planned position and the final position of the implant, in sexadecimal degrees (°)

If the studies reported the outcome data by subgroups, the mean and standard deviation (SD) were weighted by the size of each subgroup as recommended in the Cochrane Handbook for Systematic Reviews, version 6.0 [18].

The single mean meta-analysis involved estimating the mean deviations for each variable using a random-effects models based on the inverse variance method. Stratified analyses were made based on the type of study (i.e., clinical and "in vitro") and navigation system. The mean deviations and 95% confidence interval (95% CI) of each study were reported as well as the overall values. Subgroups ("in vitro" and "in vivo" studies) were isolated and subjected to linear meta-regression with adjustment for multiple comparisons (i.e., random permutations based on Monte Carlo simulation) to identify them as possible sources of covariance.

Pairwise meta-analyses were used to compare the accuracy of dCAIS with sCAIS and freehand implant placement, respectively. Meta-analyses were only performed when studies compared similar techniques and reported the same outcome measures. Stratified analysis was made based on the type of study (i.e., clinical and "in vitro"). Mean differences (MD) were combined using random-effects models.

Statistical heterogeneity was estimated by means of χ^2 (Q value) and I^2 analyses. A χ^2 P-value of <0.10 and an I^2 value of >50% were interpreted as significant heterogeneity [20].

Statistical analysis was carried out with Stata 14 software (StataCorp, College Station, TX, USA), and forest plots were performed with another software package (Review Manager version 5.3; The Cochrane Collaboration, Copenhagen, Denmark). The level of significance was set at $P < 0.05$ for all analyses.

RESULTS

Out of 907 potential articles, 24 were included in the quantitative and qualitative analysis. Twenty-two reports were excluded after full-text assessment [21–42]. Figure 2 shows the complete flowchart of the study selection process. Of the 24 articles, 10 reported on clinical studies involving humans [43–52] and 14 reported on preclinical "in vitro" studies [53–66]. The types of studies included for each system can be observed in Table 2.

In the final screening stage, the study by Kang et al. [21] testing the Cbyon system (CBYON, Inc., Mountain View, CA, USA) was excluded because the surgical technique and employed instruments were not comparable to all other studies. Furthermore, the software used in this study had important limitations (for example, it did not have a visual accuracy tool to enhance the guidance).

Nine navigation systems were evaluated. One system was not identified, and another study only reported the brand of the optical system used. Navident (Navident®, ClaroNav Technology Inc.®, Toronto, Canada) was assessed by 10 studies (5 of which were clinical studies), followed by AqNavi (AQNavi, TITC Ltd, Kaohsiung, Taiwan) with 4 studies. ImplaNav (ImplaNav; BresMedical, Sydney, Australia), AqNavi (AQNavi, TITC Ltd, Kaohsiung, Taiwan), and X-guide (X-Guide, X-Nav Technologies, LLC, Lansdale, Pa) were each used in 1 clinical study, whereas the remaining systems were only tested in an "in vitro" setting.

Table 2 Types of studies included, by system

System	Human	"In vitro"	Total
Navident	5	5	10
Iris-100	2	0	2
ImplaNav	1	1	2
AqNavi	1	3	4
X-Guide	1	1	2
Polaris Vicar	0	1	1
StealthStation Treon	0	1	1
Yizhimei	0	1	1
Others	0	1	1
Total	10	14	24

One randomized clinical trial (RCT) with a split-mouth design compared the accuracy of the Navident system with freehand implant placement [45], while two RCTs (2 parallel groups) assessed the Iris-100 system and compared it with a static guided system [47, 52].

The quality and risk of bias assessments are summarized in Table 3 and Fig. 3. The main limitations detected in the non-randomized clinical studies were limited sample sizes, which may hamper the generalization of the results [45, 49, 50], and that some articles did not specify whether the outcomes were assessed by an independent blinded researcher [20, 46–48]. Regarding the included RCT, the main limitations were associated with the allocation concealment and the blinding of the outcome assessor [47, 52].

Summarized descriptions of the studies included are presented in Table 4 and Table 5 for clinical and preclinical studies, respectively. The mean overall angular deviations were 3.68° (95% CI: 3.61 to 3.74; $I^2 = 99.4\%$) in clinical studies and 2.01° (95% CI: 1.95 to 2.07; $I^2 = 99.1\%$) in "in vitro" settings. The global (3D) entry deviation was 1.03 mm (95% CI: 1.01 to 1.04; $I^2 = 82.4\%$) in "in vivo" scenarios and 0.46 mm (95% CI: 0.44 to 0.48 ; $I^2 = 98.5\%$) in the papers that used "in vitro" designs. The mean overall accuracy of dCAIS for all the variables retrieved is summarized in Table 6. Meta-regression only revealed statistically significant differences between preclinical and clinical studies in the apex depth deviation variable ($P = 0.047$), while for all the other outcome variables, no significant differences between preclinical and clinical studies were found ($P > 0.05$ for all analyses). The forest plots can be observed in Figs. 4, 5, 6 and 7.

All dCAIS systems had similar results regarding deviations ($P>0.05$). The lowest angular deviations (mean angulation deviation of less than 2°) were achieved with the Yizhimei (Yizhimei, Suzhou, China), the StealthStation Treon (Medtronic, Minneapolis, MN), and the X-guide (X-Guide, X-Nav Technologies, LLC, Lansdale, Pa) systems in "in vitro" settings. In a clinical scenario, the highest deviations were reported by Pellegrino et al. [46] and Aydemir and Arisan [44], using ImplaNav (ImplaNav; BresMedical, Sydney, Australia) and Navident (Navident®, ClaroNav Technology Inc.®, Toronto, Canada), respectively. Navident (Navident®, ClaroNav Technology Inc.®, Toronto, Canada), Iris-100 (IRIS-100, EPED Inc., Kaohsiung, Taiwan), and AqNavi (AQNavi, TITC Ltd, Kaohsiung, Taiwan) reported similar mean angular deviations of around 3°. Finally, the ImplaNav system (ImplaNav; BresMedical, Sydney, Australia) had a mean angular deviation of 4.38° (95% CI: 3.92 to 4.83; $I^2 = 81.3\%$). The forest plot can be observed in Fig. 4b.

The angular deviation was used to compare dCAIS, sCAIS, and freehand implant placement, since this variable was reported in all studies. Only 10 papers reported data from a control group that could be analyzed in a meta-analysis [45, 47–49, 52, 54, 55, 59, 63, 66]. MD meta-analysis comparing

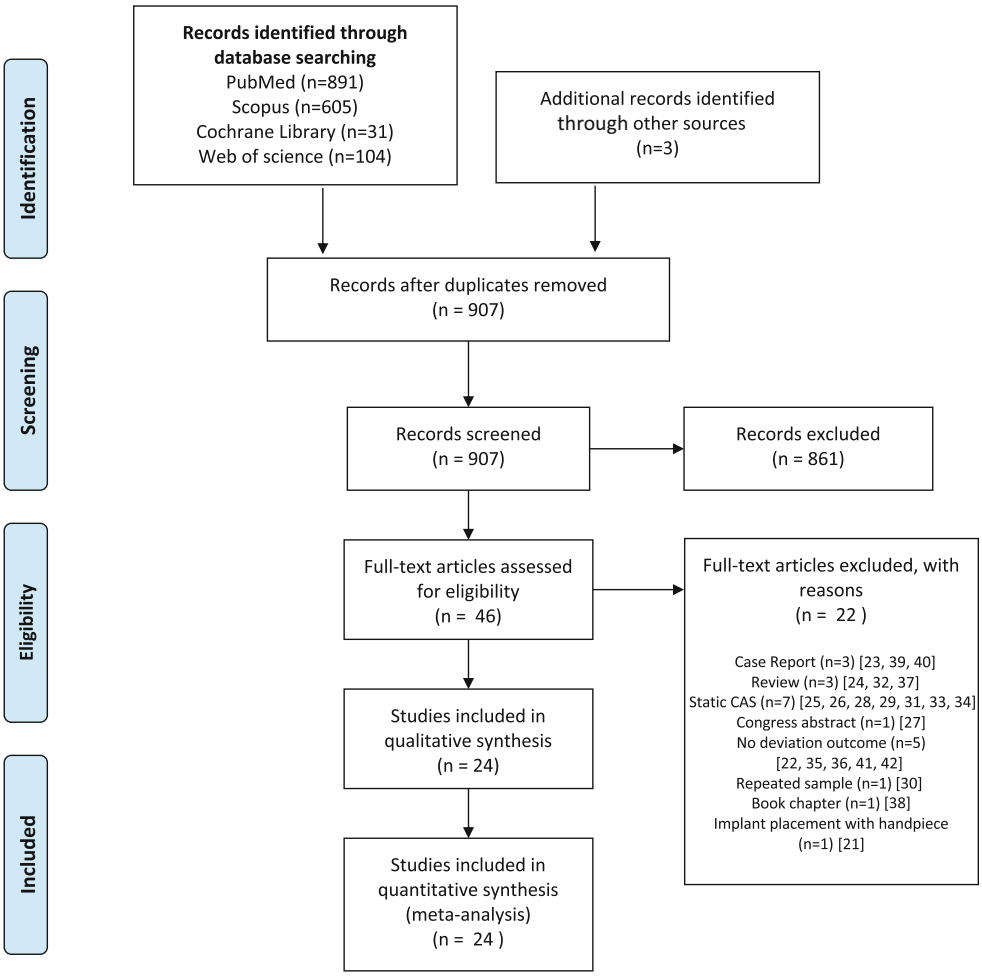

Fig. 2 Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) flowchart summarizing the screening process [17]

dCAIS with freehand implant placement reported statistically significant differences favoring dCAIS (MD: −4.33°; 95% CI: −5.40 to −3.25; $P < 0.001$; $I^2 = 97\%$). On the other hand, statistically significant differences were also found between dynamic and sCAIS systems (MD: −0.86°; 95% CI: −1.35 to −0.36; $P < 0.001$; $I^2 = 88\%$). These differences were only

Table 3 Quality assessment of the selected non-randomized studies

Study	Selection				Comparability	Outcome			TOTAL
	Representativeness of the exposed cohort (Maximum: ★)	Selection of the non-exposed cohort (Maximum: ★)	Ascertainment of exposure (Maximum: ★)	Demonstration that outcome of interest was not present at start of study (Maximum: ★)	Comparability of cohorts on the basis of the design or analysis (Maximum: ★★)	Assessment of outcome (Maximum: ★)	Was follow-up long enough for outcomes to occur (Maximum: ★)	Adequacy of follow up of cohorts (Maximum: ★)	
Stefanelli 2020c [29]	★	-	★	★	--	★	★	★	6★
Stefanelli 2020b [28]	★	-	★	★	--	★	★	★	6★
Sun 2020 [27]	★	★	★	★	★★	-	★	★	8★
Stefanelli 2020a [22]	★	-	★	★	--	★	★	★	6★
Pellegrino 2019 [24]	★	-	★	★	--	★	★	★	6★
Stefanelli 2019[21]	★	-	★	★	--	-	★	★	5★
Block 2017 [26]	★	★	★	★	★-	-	★	★	7★

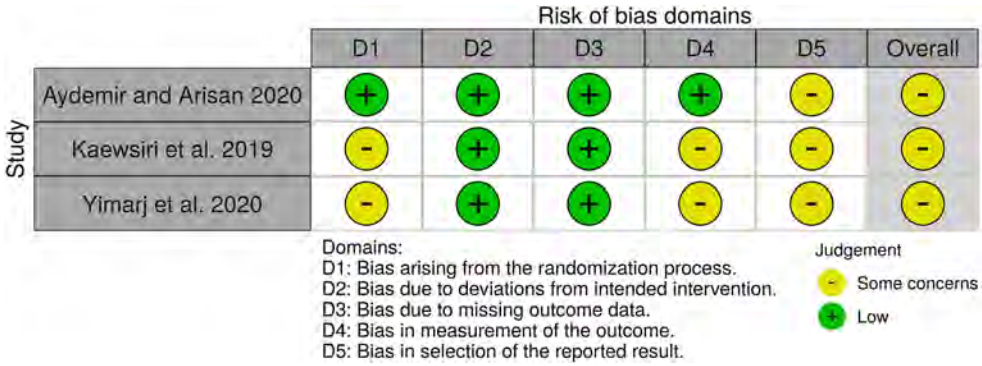

Fig. 3 Risk of bias of the selected randomized clinical trials

significant in the "in vitro" studies (MD: −1.12°; 95% CI: −1.97 to −0.28; $P = 0.009$; $I^2 = 82\%$), while clinical reports found no significant differences between groups (MD: −0.52°; 95% CI: −1.58 to 0.54; P = 0.34; $I^2 = 89\%$) (Fig. 8).

Discussion

dCAIS systems for implant dentistry have been developed to help clinicians obtain a more accurate match between implant placement and the preoperative plan. The results of the present review demonstrate that these systems are reliable and achieve clinically undetectable angular deviations (95% CI: 2.84° to 2.93°). However, it is important to stress that a 2-mm safety margin should always be applied when implants need to be placed near important anatomic structures like the inferior alveolar nerve, since deviations of slightly over 1 mm were registered on some occasions. The present meta-analysis also showed that both dCAIS and sCAIS systems are predictable options that allow clinicians to place dental implants accurately.

Comparing the different systems, Navident was assessed in 5 clinical [43–45, 50, 51] and 5 "in vitro" studies [53, 54, 57, 59, 60]. Nevertheless, it should be taken into account that 4 of the 5 clinical studies [43, 44, 50, 51] were conducted by the same research group. A similar situation was found for several systems (AqNavi system [49, 59, 62], Iris-100 system [47, 52], and ImplaNav [46, 53]) since most published studies were performed by the same authors. X-guide (X-Guide, X-Nav Technologies, LLC, Lansdale, Pa) had the largest cohort of patients (almost 500 cases with more than 700 implants placed) [48], and some clinical data was also available for AqNavi (AQNavi, TITC Ltd, Kaohsiung, Taiwan) and ImplaNav (ImplaNav; BresMedical, Sydney, Australia), as they each had at least one clinical study.

Some variables might increase inaccuracies and therefore should be controlled. Misfit of the radiological fiducial markers (which are usually tooth-supported), movements of the patient or of the fiducial markers during CBCT imaging, low quality/resolution of the CBCT, or problems during registration of the radiological markers by the planning software are possible sources of inaccuracies. Some intraoperative complications, such as movement of the optical markers placed on the patient's jaw or on the handpiece, incorrect calibration of the drill axis or tip, and imprecise manipulation of the drills, should also be considered. Finally, postoperative assessment errors (distortion of the CBCT caused by the implant and inaccuracies when overlapping the pre- and postoperative CBCTs) might affect the outcomes of the studies, although usually they are not clinically relevant. Thus, it is of utmost importance to ensure accuracy at each step, since errors accumulate.

A dCAIS system that does not need radiological fiducials has recently become available [44]. It registers the CBCT by tracing at least 3 predefined points on the remaining teeth. This could reduce inaccuracies caused by movement of the radiological fiducials. Furthermore, this system allows the clinician to register the CBCT again in case of errors. Nevertheless, it is important to stress that the available data on this system are quite scarce and further research is needed.

The results of the present review were similar to those of previous systematic reviews assessing the accuracy of sCAIS [21, 66]. These papers reported slightly higher angular and linear deviations at the entry and apex points, whereas depth deviations were lower [67, 68]. Nevertheless, their results must be interpreted with caution since Tahmaseb et al. [67] only included clinical studies, which generally report slightly higher deviations in comparison to "in vitro" studies. On the other hand, Bover-Ramos et al. [68] included both clinical (22 studies) and preclinical (12 studies) studies. The findings of both reviews are summarized in Table 7.

Our report shows that dCAIS had more accurate results compared with sCAIS only in "in vitro" settings and both systems seemed to provide similar results in a clinical scenario. Thus, in our opinion, sCAIS systems should be considered the first-line option in guided implant surgery due to the available scientific data and the reduced cost of the equipment. Nonetheless, dCAIS systems also have some advantages that need to be taken into consideration:

Table 4 Description of the selected clinical studies

Study	Country	Settings	Study design	Edentulism	N patients	N implants	Age (years)	Gender male/female	Operator experience	Intervention (dCAIS system)	Comparator	Conflict of interest
Yimarj P 2020 [52]	Thailand	University	RCT parallel	Partial (two neighboring implants)	30	60 (30/30)	60	7/23	Trained surgeon	Iris-100	sCAIS (VisiJet MP200)	No
Stefanelli 2020 c [51]	Italy	University	Case series	Fully edentulous	13	77	68.15 (SD=9.22)	7/6	Trained surgeon	Navident 2.0 TaP	None	No
Stefanelli 2020 b [50]	Italy	University	Retrospective case series	Fully edentulous	14	56	NR	NR	Trained surgeon	Navident 2.0 TaP	None	No
Sun 2020 [49]	Taiwan	NR	Non-RCT	NR	NR	128 (32/32/32/32)	NR	NR	Trained surgeon	AqNavi	- sCAIS - d+sCAIS Freehand	Yes
Stefanelli 2020a [44]	Italy	Private practice	Retrospective case series	Partial	59	136	NR	NR	Trained surgeon	Navident 2.0 TaP	None	Partial yes
Aydemir 2020 [44]	Turkey	University	Split-mouth RCT	Partial (posterior bilateral edentulism)	30 (15/15)	86 (43/43)	48.4 (21-78)	7/25	Trained surgeon	Navident	Freehand	NR
Pellegrino 2019 [46]	Italy	University	Case series	Partial and total (8/2)	10	18	57 (38-69)	3/7	NR	ImplaNav	None	Yes
Kaewsiri 2019 [47]	Thailand	University	RCT parallel	Single tooth missing	60 (30/30)	60 (30/30)	53 (21–74)	16/44	Trained surgeon	Iris-100	sCAIS (VisiJet MP200)	NR
Stefanelli 2019[43]	Italy	Private practice	Retrospective observational	Partial and total (61/28)	89 (arches)	231	NR	NR	Trained surgeon	Navident	None	No
Block 2017 [48]	USA	Private practice	Prospective cohort	Partially edentulous	478	714 (219 FG; 373 PG; 112 FH)	59 (21-89)	242/236	Trained surgeons	X-Guide	Freehand	Yes

SD standard deviation, *TaP* trace and place, *NR* not reported, *RCT* randomized clinical trial, *dCAIS* dynamic computer–aided implant surgery, *sCAIS* static computer–aided implant surgery, *FG* fully guided, *PG* partially guided, *FH* freehand

Table 5 Description of the selected preclinical studies

Study	Country	Phantom	Type of model	Edentulism	N models	N implants	Operator experience	Intervention (dCAIS system)	Comparator	Conflict of interest
Zhou 2020 [21]	China	Yes	Resin 3D printed	Partial	20 (10/10)	80 (40/40)	NR	Yizhimei	sCAIS (VisiJet M3)	No
Pellegrino 2020 [53]	Italy	No	Plaster	Total	16	112	4 operators • Experienced in implantology and dCAIS • Experienced in implantology • Experienced in dCAIS No experience	ImplaNav	None	Yes
Jorba-García 2019 [54]	Spain	Yes	Resin	Partial	6	36 (18/18)	2 operators • Experienced in implantology • No experience	Navident	Freehand	No
Sun 2019 [59]	Taiwan	No	Plaster	Partial	30	150	5 operators without dCAIS experience but with different degrees of implantology experience	AqNavi	None	No
Golob Deeb 2019 [61]	USA	Yes	Polymethylmethacrylate 3D printed	Partial	84	294	14 dental students (no experience in implantology or dCAIS)	Navident	None	NR
Mediavilla Guzman 2019 [60]	Spain	No	Polyurethane	Total	20 (10/10)	40 (20/20)	NR	Navident	sCAIS (NemoStudio®/ProJet 6000)	No
Jiang 2018 [62]	China	No	3D printed	Total	12 (6/6)	96 (48/48)	NR	dCAIS NR	Augmented reality	No
Sun 2018 [63]	Taiwan	Yes	Plaster	Partial	50	150	NR (but calculating the learning curve implies no experience with dCAIS)	AqNavi	None	No
Chen 2018 [64]	Taiwan	NR	Plaster	Partial	30 (10/10-/10)	150 (50/50/-50)	NR	AqNavi	sCAIS Freehand	No
Emery 2016 [65]	USA	Yes	Polyurethane	Partial and total	27	47	One surgeon experienced in CAIS	X-Guide	None	Yes
Kim 2015 [66]	Korea	Yes	Model	Partial	20	110	NR	Polaris Vicar (camera)	None	NR
Somogyi-Ganss 2015 [55]	Canada	Yes	Resin	Partial	50	2000 (400/16-00)	Surgeons experienced in sCAIS	Navident	4 sCAIS • Straumann • Nobel • Simplant Laboratory	Yes
Widmann 2010 [57]	Austria	No	Plaster	Total	14	104 (only osteoto-my)	NR	StealthStation Treon Plus	None	Yes
Golob Deeb 2020 [58]	USA and Slove-nia	NR	Polyurethane	Partial	12	42 (21/21)	Two residents experienced in dCAIS	Navident (Drills)	Navident (Trephine)	No

NR not reported, *dCAIS* dynamic computer–aided implant surgery, *sCAIS* static computer–aided implant surgery, *CAIS* computer-aided implant surgery

Table 6 Overall mean deviations grouped by the type of study

	Angular (°) Mean [95% CI]	Lateral (2D) entry (mm) Mean [95% CI]	Global (3D) entry (mm) Mean [95% CI]	Lateral (2D) apex (mm) Mean [95% CI]	Global (3D) apex (mm) Mean [95% CI]	Apex depth (mm) Mean [95% CI]	Entry depth (mm) Mean [95% CI]
"In vitro"	2.01 [1.95 to 2.07]	0.8 [0.77 to 0.83]	0.46 [0.44 to 0.48]	0.97 [0.94 to 1.01]	0.81 [0.79 to 0.83]	0.61 [0.59 to 0.64]	0.76 [0.68 to 0.84]
Clinical	3.68 [3.61 to 3.74]	0.69 [0.67 to 0.72]	1.03 [1.01 to 1.04]	0.9 [0.83 to 0.97]	1.34 [1.32 to 1.36]	0.73 [0.7 to 0.76]	0.50 [0.43 to 0.57]
Overall	2.84 [2.80 to 2.89]	0.74 [0.72 to 0.76]	0.75 [0.73 to 0.76]	0.96 [0.93 to 0.99]	1.09 [1.08 to 1.11]	0.66 [0.64 to 0.68]	0.61 [0.56 to 0.67]
	P=0.453	*P*=0.197	*P*=0. 163	*P*=1	*P*=0.7	*P*=0.047*	*P*=0.487

the preoperative planning and surgical procedures can be performed on the same day, there is no need to take an intraoral impression, and the dental laboratory is not involved. Furthermore, dCAIS allows real-time verification of position accuracy, clinicians can adapt their surgical planning during surgery, there is no need for a specific set of drills or instruments, and the surgeon's perception of the drilling sequence and implant placement is not affected by a splint. Another important advantage is related to the fact that these systems can be used in almost all patients, whereas static systems might not be suitable in cases with limited mouth opening. Some authors have also used dCAIS systems to place zygomatic and pterygoid implants with good results [50, 69]. This might be an interesting indication for dCAIS systems, since these implants can be associated with important complications.

On the other hand, dCAIS technology also presents some drawbacks. Expenditure increases due to the cost of the equipment and the license needed to plan each case. In addition, these systems require a certain degree of experience since the learning curve plateau is not reached until the surgeon has placed at least 15 dental implants with these systems [62]. Other important limitations are that the surgical time increases and that, in the present authors' opinion, these dCAIS tools are not at all suitable for treating fully edentulous patients.

The professional's experience is a key factor for increasing the success rate of most treatments in implant dentistry. Even though the present review did not analyze the role of the

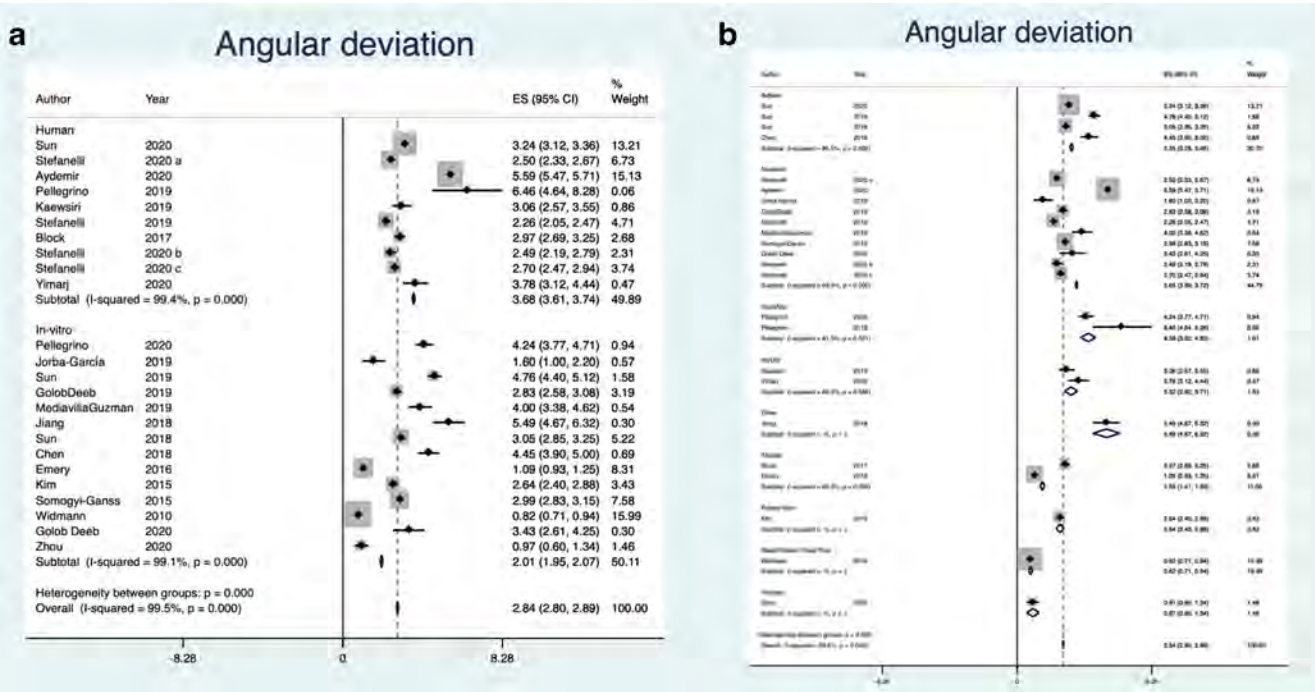

Fig. 4 Forest plot showing angular deviation measured for all selected articles. **a** Grouped by clinical and "in vitro" studies. **b** Grouped by dCAIS system. dCAIS dynamic computer–aided implant surgery

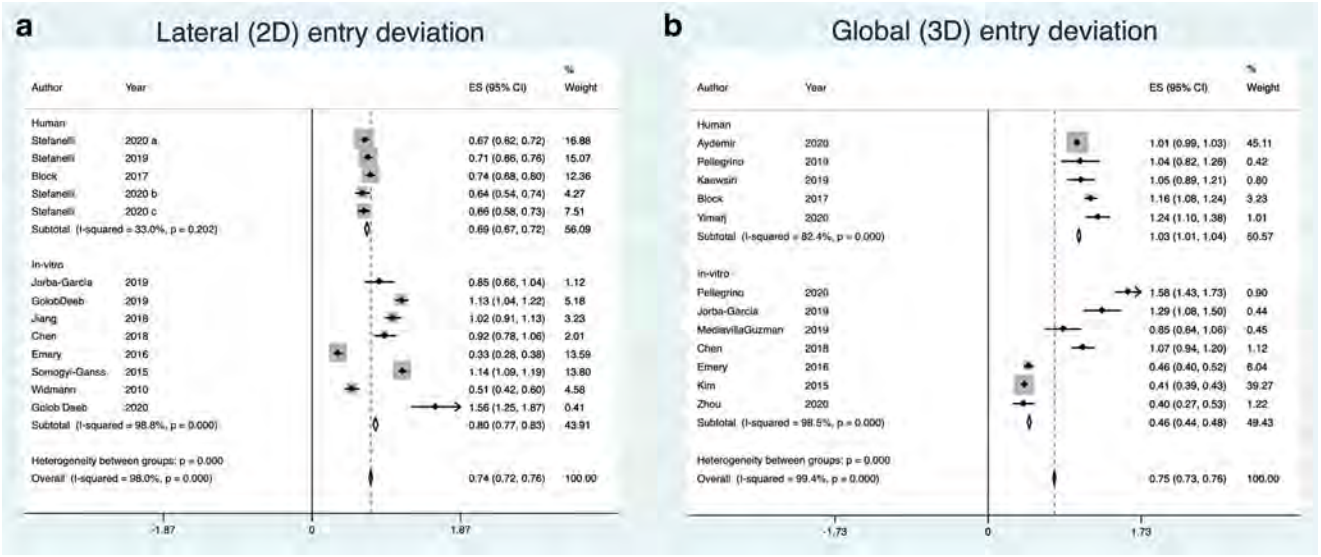

Fig. 5 Forest plot showing **a** lateral (2D) and **b** global (3D) entry deviation measured for all selected articles grouped by clinical and "in vitro" studies

surgeon's experience, some "in vitro" studies have reported that these systems might be especially useful for novice clinicians, since both experienced and novice professionals obtained a similar degree of accuracy with this technology [53, 54, 58, 60].

Despite the recommendation to use patient-reported outcome measures (PROMs) in all clinical studies dealing with rehabilitation with dental implants, they were not reported for any of the clinical studies included [70]. One systematic review included 14 studies that evaluated PROMs in patients undergoing sCAIS implant placement, but the authors were unable to issue recommendations due to the heterogeneity of the studies regarding PROM measurement, treatment modalities, and trial designs [71].

The short-term outcomes of the implants placed using dCAIS seem to be excellent. Jokstad et al. [22], after 1 year of follow-up, observed that all implants could be restored without any adverse event or prosthetic complication after loading. Furthermore, the mean marginal bone loss was less than 1 mm, and the probing depth was less than 2 mm for all sites. To confirm that these results are stable over time, further studies with longer follow-ups are needed.

New technologies have been developed every day. Augmented reality (AR) eyeglasses have already been used by clinicians to view the dCAIS computer screen next to the patient's mouth [72]. AR has also been employed to project the virtual implant plan onto the patient's jaw [61, 73]. Very recently, in 2020, robot-assisted dental implant placement has been performed with promising results, with small deviations (apical global deviation of 0.8 mm, coronal global deviations of 0.9 mm, and an angular deviation of 0.53°)[74].

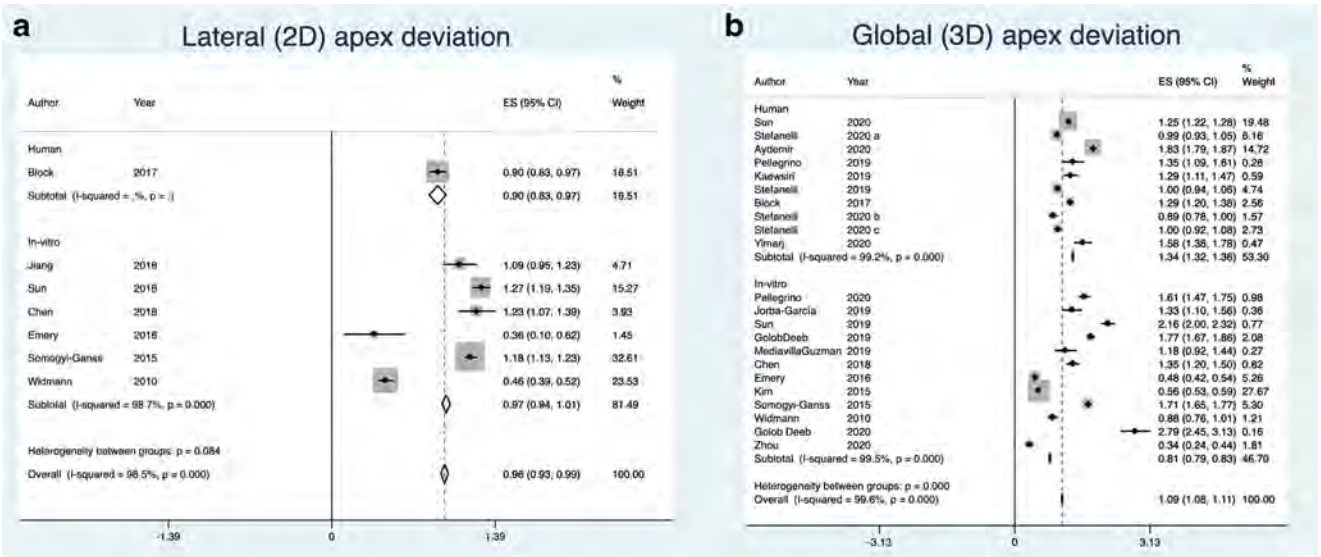

Fig. 6 Forest plot showing **a** lateral (2D) and **b** global (3D) apex deviation measured for all selected articles grouped by clinical and "in vitro" studies

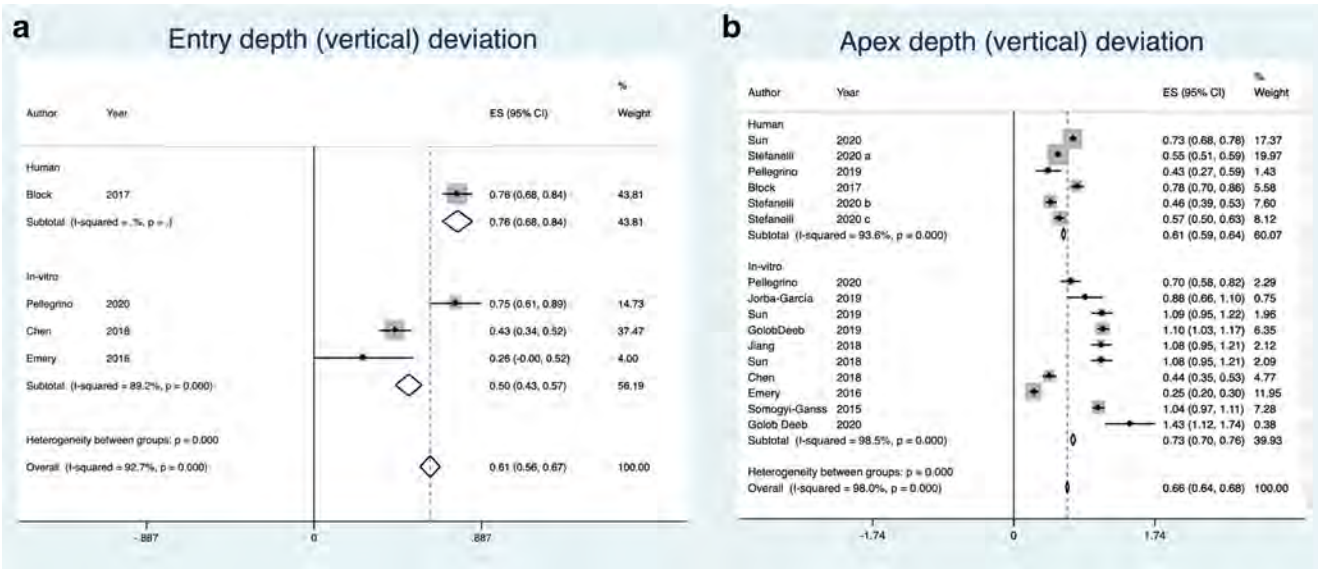

Fig. 7 Forest plot showing **a** entry depth and **b** apex depth deviation measured for all selected articles grouped by clinical and "in vitro" studies

The present review presents some limitations that need to be considered. The low number of clinical studies and the lack of homogeneity of the papers included make it difficult to determine the real accuracy of dCAIS systems. More clinical trials that evaluate patient satisfaction through the use of PROMs and have longer follow-up times are necessary to confirm the published "in vitro" data. Finally, the results related with the secondary aim (comparisons between dCAIS, sCAIS, and freehand placement) should be interpreted with caution due to the high heterogeneity found.

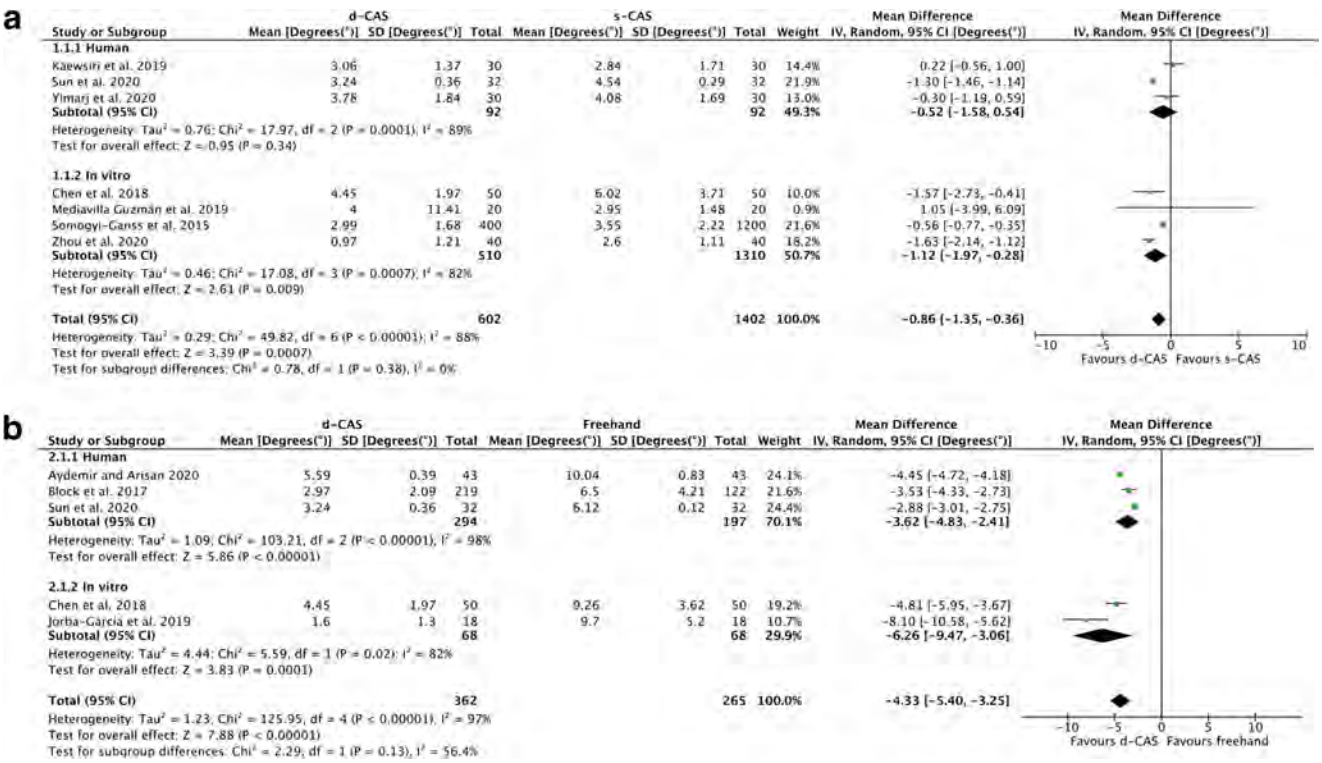

Fig. 8 Forest plots for angular deviation comparing **a** dCAIS versus sCAIS and **b** dCAIS versus freehand implant placement. sCAIS static computer–aided implant surgery, dCAIS dynamic computer–aided implant surgery, SD standard deviation, CI confidence interval

Table 7 Summary of results of meta-analysis of sCAIS

	Angular (°) Mean [95% CI]	Lateral (2D) entry (mm) Mean [95% CI]	Global (3D) entry (mm) Mean [95% CI]	Lateral (2D) apex (mm) Mean [95% CI]	Global (3D) apex (mm) Mean [95% CI]	Apex depth (mm) Mean [95% CI]	Entry depth (mm) Mean [95% CI]
sCAIS (clinical setting) Tahmaseb et al. 2018 [67]	3.5 [3.00 to 3.96]		1.3 [1.09–1.56]		1.4 [1.28 to 1.58]	0.5 [−0.08 to 1.13]	0.2 [−0.25 to 0.57]
sCAIS (clinical and "in vitro" settings) Bover-Ramos et al. 2018 [68]	3.48 [2.96 to 3.99]	1.03 [0.88 to 1.18]		1.29 [1.11 to 1.48]		0.64 [0.47 to 0.82]	

sCAIS static computer–aided implant surgery

Conclusion

dCAIS systems allow highly accurate implant placement with a mean angular deviation of less than 4°. However, a 2-mm safety margin should be applied, since deviations of more than 1 mm were observed in some studies. Most of the dCAIS systems tested achieved similar performance levels. Also, dCAIS systems increase the implant placement accuracy when compared to freehand implant placement and also seem to slightly decrease the angular deviation in comparison with the sCAIS systems.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00784-021-03833-8.

Acknowledgements The authors wish to thank Mary Georgina Hardinge for her English language editing assistance.

Author contribution Adrià Jorba-García and Albert González-Barnadas: Conception of the review; literature search and data acquisition; article drafting; approval of the final version of the manuscript and agreement to be accountable for all aspects of the work.

Octavi Camps-Font: Conception of the review; analysis and interpretation of the data; critical review of the article; approval of the final version of the manuscript and agreement to be accountable for all aspects of the work.

Rui Figueiredo and Eduard Valmaseda-Castellón: Conception of the review; interpretation of the data; critical review of the article; approval of the final version of the manuscript and agreement to be accountable for all aspects of the work.

Funding The research was not supported by any source of funding.

Declarations

Ethics approval This article does not report on any studies with human participants or animals performed by any of the authors.

Informed consent For this type of study, formal consent is not required.

Conflict of interest The authors have no direct financial or other interests in the products or information mentioned in this paper. Adrià Jorba-Garcia and Albert González-Barnadas declare no conflicts of interest. Dr. Octavi Camps-Font reports grants from Avinent (Santpedor, Spain) and has participated as a sub-investigator in clinical trials sponsored by Mundipharma (Cambridge, UK) and Menarini Richerche (Florence, Italy).

Dr. Rui Figueiredo reports grants, personal fees, and non-financial support from MozoGrau (Valladolid, Spain) and from Avinent (Santpedor, Spain) and personal fees from BioHorizons Iberica (Madrid, Spain), Inibsa Dental (Lliçà de Vall, Spain), Dentsply implants Iberia (Barcelona, Spain), and ADIN Implants (Afula, Israel) outside the submitted work. Dr. Figueiredo has also participated as a principal investigator in a randomized clinical trial sponsored by Mundipharma (Cambridge, UK) and in another clinical trial as a sub-investigator for Menarini Richerche (Florence, Italy). Dr. Eduard Valmaseda-Castellón reports personal fees and non-financial support from MozoGrau (Valladolid, Spain) and from Avinent (Santpedor, Spain) and personal fees from BioHorizons Iberica (Madrid, Spain), Inibsa Dental (Lliçà de Vall, Spain), and Dentsply implants Iberia (Barcelona, Spain) outside the submitted work. In addition, Dr. Valmaseda-Castellón has also participated as a sub-investigator in a randomized clinical trial sponsored by Mundipharma (Cambridge, UK).

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