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SYSTEMATIC REVIEWS AND META-ANALYSIS

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Does a fully digital workflow improve the accuracy of computer-assisted implant surgery in partially edentulous patients? A systematic review of clinical trials

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Abstract

Background: Accurate implant placement is essential in reducing post-treatment complications and in ensuring a successful treatment outcome.

Purpose: To compare the accuracy of fully-guided static computer-assisted implant surgery (s-CAIS) using partially- and fully-digital workflows.

Materials and methods: Electronic and manual literature searches were performed to collect evidence concerning the accuracy of fully-guided s-CAIS procedures utilizing tooth-supported guides. Quantitative analysis was conducted to evaluate the accuracy of partially- and fully-digital workflows, and survival rates and complications were qualitatively analyzed.

Results: Thirteen studies, including 6 randomized controlled trials and 7 prospective clinical studies, were selected for quantitative and qualitative synthesis. A total of 669 implants in 325 patients using s-CAIS were available for review. Meta-analysis of the accuracy revealed a total mean angular deviation of 2.68° (95% CI: 2.32°-3.03°); mean global coronal deviation of 1.03 mm (95% CI: 0.88-1.18 mm); mean global apical deviation of 1.33 mm (95% CI: 1.17-1.50 mm); and mean depth deviation of 0.59 mm (95% CI: 0.46-0.70 mm). Minimal differences were found between the two different workflows. Few complications were reported, and survival rates were between 97.8% to 100% (range of follow-up: 12 to 24 months) in the available studies.

Conclusion: Similar accuracy is obtained when implants are placed in partially edentulous patients using fully-guided s-CAIS, independently of the workflow utilized.

KEYWORDS

accuracy, clinical trials, computer-aided implant surgery (CAIS), dental implants, digital impression, digital workflow, guided surgery

1 | INTRODUCTION

Accurate and prosthetically-driven implant placement is essential in reducing post-treatment complications and in ensuring the highest probability of a successful treatment outcome.[1] The incorporation of cone-beam computed tomography (CBCT) into implant treatment planning allows clinicians to assess the proximity to vital anatomy and bony morphology of the future implant site prior to placement.[2] Combining CBCT analysis with either images obtained from intra- or extra-oral digital scanning allows registration of the two datasets and is a

prerequisite in both partially- and fully-digital workflows, where a partially-digital workflow incorporates one or more traditional laboratory steps during the implant treatment planning phase. The utilization of digital workflows involves virtual planning of both the ideal implant positioning and prosthetic design in order to direct the fabrication of surgical guides. Drill guides are used by the surgeon during the osteotomies and implant insertion with the goal of transferring the implant position from the computer to the surgical site.

The implementation of computer-guided implant planning and placement in clinical practice is a relatively recent phenomenon aimed towards a more predictable and less invasive surgical procedure.[3] However, the risk for deviation remains substantial. Deviation between planned and actual implant positioning can result from transfer errors during the software planning stage as well as operator errors and numerous other sources. Results of systematic reviews suggest that tooth- or mucosa-supported guides in conjunction with fully-guided surgery demonstrate greater accuracy compared to bone-supported guides and partially guided surgery.[4-6] Ozan et al reported angular deviations of 2.91 ± 1.3°, 4.63 ± 2.6°, and 4.51 ± 2.1° from the planned position for tooth-supported, bone-supported, and mucosa-supported guided implant surgery, respectively.[7] Tooth-supported guides resulted in significantly higher accuracy during implant placement relative to bone- and mucosa-supported guides. A recent systematic review reported a significant difference in accuracy in favor of partially edentulous relative to fully edentulous cases.[8]

In vitro and ex-vivo studies are immune from many of the confounding clinical factors that can impair the accuracy of implant placement by causing movement of the guide or restriction of access during surgery.[9] Implant placement in models or cadavers is more accurate due to the lack of saliva, blood, and movement of the patient, as well as increased access, which facilitates the visual and spatial control of the surgeon during the osteotomy and implant insertion. In addition, the use of a single guide throughout an osteotomy has been recommended to reduce deviations. Integration of a depth-control mechanism in fully-guided surgery can also ensure a safe osteotomy and accurate positioning of the implants.[10]

To date, many studies have investigated the clinical accuracy of guided implant surgery utilizing a partially-digital workflow.[11-13] Recently, numerous studies have evaluated the accuracy of implant placement utilizing fully-digital approaches, with the expectation that full digitalization influences the accuracy and predictability of implant placement.[14-17] Thus, the primary aim of the present systematic review was to compare the accuracy of partially- and fully-digital workflows for static computer assisted implant surgery (s-CAIS) in fully guided tooth-supported cases.

2 | MATERIALS AND METHODS

2.1 | Study registration

The protocol of the present article has been registered in the PROSPERO database (www.crd.york.ac.uk/PROSPERO) and allocated the identification number CRD42020165213.

2.2 | Search strategy

The present systematic review followed the PRISMA guidelines for reporting on the accuracy of implant placement, survival, and complications for fully-guided s-CAIS in partially edentulous patients in order to compare partially- and fully-digital workflows. The term "partially edentulous patient" was used to define any patient that was missing one or more teeth, but not all teeth. A partially-digital workflow was defined as the inclusion of at least one laboratory step when obtaining data before digital implant planning and guide design. A fully-digital workflow was considered a sequence of procedures using only virtual imaging and designing for implant surgical planning and guide fabrication. The following PICO question[18] was formulated to address the specific aim of the study: "What is the accuracy of fully-guided s-CAIS using partially or fully-digital workflows in partially edentulous human subjects?"

- Population (P): partially edentulous patients,
- Intervention (I): fully-digital workflow for tooth-supported fully-guided s-CAIS,
- Comparison (C): partially-digital workflow for tooth-supported fully-guided s-CAIS,
- Outcomes (O): accuracy of implant positioning and subsequent survival rates and complications,
- Study design (S): randomized clinical trials (RCTs), prospective clinical studies, and case series with a minimum of 10 patients.

Electronic searches were performed in three databases—Pubmed/MEDLINE, EMBASE, and Cochrane Central for articles written in English published up to January 31, 2020. The search terms comprising the combination of key words were: ((((((((((dental implant [MeSH Terms]) OR dental implantation[MeSH Terms]) OR dental implants[Title/Abstract]) OR implants[Title/Abstract])) AND ((((computer assisted surgery[MeSH Terms]) OR computer aided surgery [MeSH Terms]) OR computer guided[Title/Abstract]) OR guided surgery[Title/Abstract]))))) AND ((accuracy[Title/Abstract]) OR deviation [Title/Abstract]).

In addition, a manual search of related articles was performed in the following relevant journals: *Clinical Implant Dentistry and Related Research*, *Clinical Oral Implants Research*, *The International Journal of Oral Maxillofacial Surgery*, *International Journal of Oral Implantology*, *Journal of Periodontology*, *Journal of Periodontal Research*, *Journal of Clinical Periodontology*, *Journal of Prosthetic Dentistry*, *Implant Dentistry*, *The International Journal of Oral and Maxillofacial Implants*, and *The International Journal of Periodontics and Restorative Dentistry*. In addition, the reference lists of the subsequently selected abstracts and the bibliographies of the systematic reviews were searched manually.

2.3 | Study selection

Two reviewers (R.S. and Z.C.) screened all titles and abstracts independently. Full-text evaluation of the remaining publications was performed using the inclusion and exclusion criteria listed below.

Inclusion criteria:

1. Randomized or nonrandomized prospective clinical studies, or case series when a minimum of 10 patients underwent surgical intervention;
2. CT or CBCT scans were used for computerized planning prior to the design of a surgical guide;
3. Intraoral scanning (IOS), tomographic templates, or extra-oral scanning of patient casts were used for data acquisition;
4. Both implant site preparation and implant insertion were performed using tooth-supported s-CAIS;
5. Deviations between planned and final implant positions were measured digitally.

Exclusion criteria:

1. In vitro or ex vivo studies, reviews, or expert opinions;
2. Implant surgery via partially-guided approaches, as defined before;
3. Studies with fully edentulous patients, as well as zygomatic, pterygoid, and/or orthodontic implants;
4. Studies reporting on dynamic computer-navigated surgery and 2D radiographic-based stents.

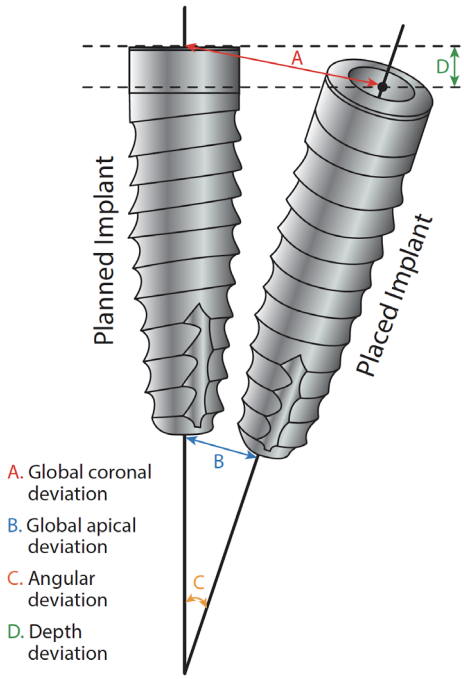

FIGURE 1 Diagram illustrating deviation measurements evaluated in this review

2.4 | Data extraction and statistical analysis

Two reviewers, R.S. and Z.C., independently extracted data from the included studies. Disagreements were resolved through discussion with a third author (M.G.) to reach a consensus. Where data was unclear or incomplete, the authors of the publication were contacted for further explanation. Data such as implant deviations, workflow utilized, implant survival, and complications were collected and systematically analyzed until a consensus was reached between both reviewers. The data was quantitatively analyzed for accuracy of implant position and qualitatively assessed for survival rates and complications.

All statistical analyses were conducted using a statistical software program (Stata software, v14.0, StataCorp, College Station, TX). The cumulative deviations in implant positioning, including global deviation at the level of the shoulder and apex, angular deviation, and depth deviation were calculated with 95% CIs using a random effects model to avoid potential bias from methodologic differences among included studies (Figure 1). Subgroup analyses were performed to compare partially and fully-digital workflow groups.

2.5 | Quality assessment

The risk of bias in the included RCTs was evaluated using the Cochrane collaboration tool.[19] Seven criteria were assessed: random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective reporting, and any other potential biases. Depending on the descriptions given for each individual criterion, a rating of low, unclear, or high risk of bias was assigned. Meanwhile, the Newcastle-Ottawa Scale (NOS) was used to evaluate the included non-randomized clinical trials.[20] Each included study could receive a maximum of nine stars to indicate methodological quality and risk of bias. Studies with 7 to 9 points were arbitrarily considered to have had a low risk of bias, with 4 to 6 points indicating a moderate risk of bias, and fewer than four points indicating a high risk of bias.

3 | RESULTS

3.1 | Study selection

The initial electronic search through Pubmed/MEDLINE, EMBASE, and Cochrane Central for articles yielded 882 articles. An additional four articles were identified with manual searches yielding a total of 886 articles for review. After removing duplicates, 717 papers were available for screening. After exclusion based on title, abstracts of 139 papers were evaluated, and 41 articles were selected for independent full-text reviews by two investigators (R.S, Z.C). After screening the remaining studies based on the inclusion and exclusion criteria as well as the PICOS question, 28 articles were excluded (Table S1), and 13 studies were ultimately selected for quantitative and qualitative synthesis (Figure 2). From these 13 studies, six were randomized controlled trials (RCTs), and seven were prospective clinical studies. Table 1 details the articles selected for inclusion. Kappa scores were

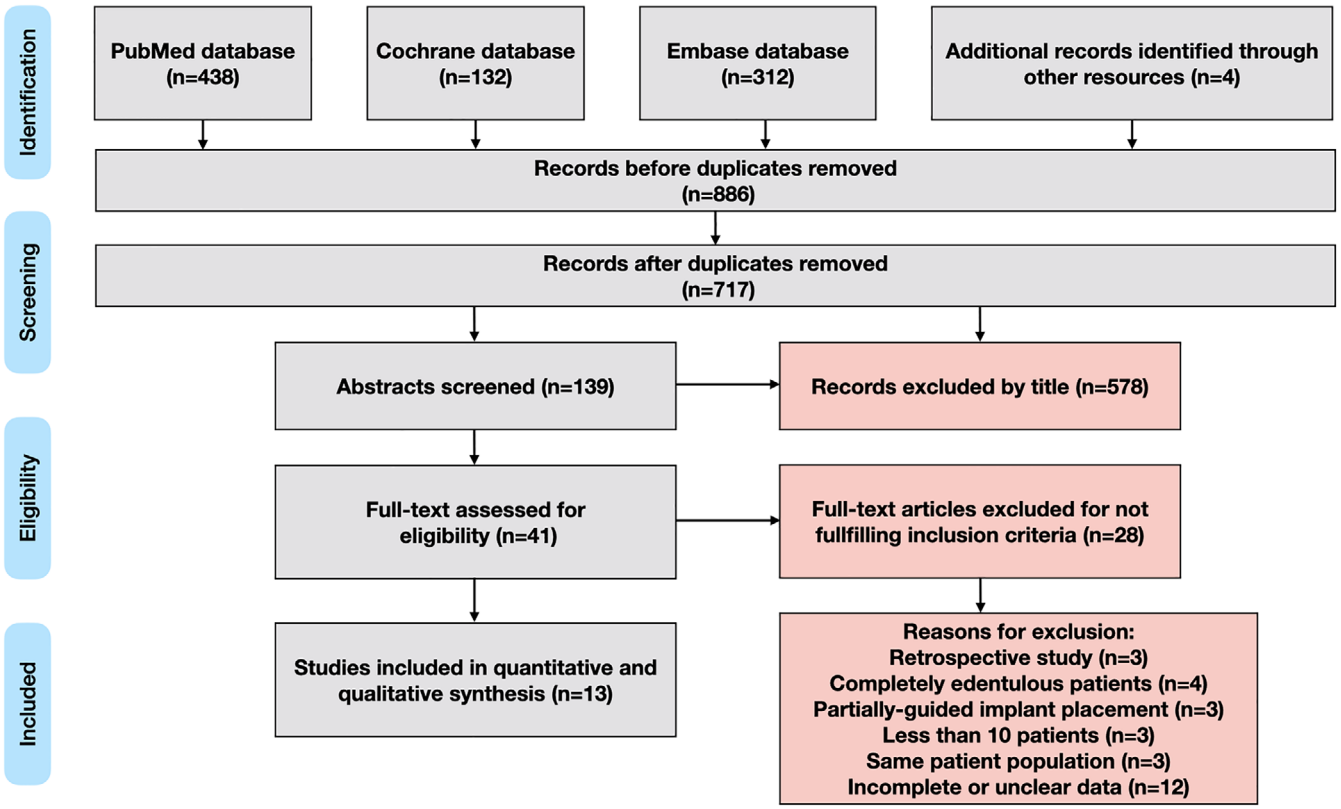

FIGURE 2 PRISMA flowchart of the screening process. A total of 13 articles were included for quantitative and qualitative assessment

calculated, yielding 0.87 in title/abstract screening and 0.92 in full text evaluation. Any disagreement was solved by discussion.

3.2 | Study characteristics

The 13 studies included in this review assessed the outcomes of fully-guided s-CAIS surgery in partially edentulous patients. All implants in all studies were virtually planned with the use of a software program and information from CBCT scans. Only data from tooth-supported guides was analyzed whereas data on other support mechanisms were excluded. Partially-digital workflow data on accuracy was extracted from nine studies. Among the nine studies, three studies[21-23] utilized laboratory-based surgical templates with a dual-scan protocol as a reference for implant planning and surgical guide design, 3 studies[10,12,24] digitized stone casts with extra-oral optical scanners to make 3D digital models for implant planning, and one study[25] utilized the CBCT scan of a conventional polyvinyl siloxane (PVS) impression to obtain 3D models for implant planning. The remaining two studies directly compared a partially-digital workflow utilizing digitized stone casts with extra-oral optical scanners vs a fully-digital workflow with models obtained via IOS.[14,26] Data for the fully-digital workflow group were extracted from the two previously mentioned RCTs[14,26] which included information on both partially- and fully-digital workflows, and four additional studies which reported solely on fully-digital workflows.[15-17,27]

3.3 | Results of the individual studies

A total of 13 studies met the selection criteria for review (Figure 2). This provided 669 implants in 325 patients. A total of eight different software systems were used for pretreatment planning of the cases: (a) coDiagnostix (3/13) (b) 3Diagnosys (2/13) (c) R2Gate (2/13) (d) Simplant (2/13) (e) Implant Studio (1/13) (f) Dental Slice (1/13) (g) Smart Guide (1/13) (h) Implant Master (1/13) (Table 1). 3Diagnosys and Implant studio were both utilized in one study.[27]

Regarding implant surgery, six out of 13 studies reported on flapless surgical implant placement, three out of 13 studies reported an open flap approach solely, and the remaining four studies completed surgery with both flapless and open-flap techniques. Regarding the comparison of the planned and final implant positions, nine studies took CBCT before and after the surgery, while four studies utilized the superimposition of information from the preoperative CBCT with the STL (Standard Tessellation Language) file obtained by postoperative IOS.

3.4 | Quality of the studies

The risk of bias in the six included RCTs was assessed and summarized in Table 2. One study[25] presented a high risk of nonrandom sequence generation, and one[26] was associated with an unclear risk. For allocation concealment, three studies[23,25,26] were found to have a high risk

TABLE 1 Publications included in the meta-analysis

Author (year)	Study design	Workflows utilized	Accuracy evaluation method	Guided system software	Number of patients	Number of implants	Implant location		Open/ Flapless
							Mand	Max	
Arisan et al (2010)	Prospective clinical study	Partially-digital: dual-scan protocol	CBCT/ CBCT	SimPlant Pro (Materialise Dental, Leuven, Belgium)	11	50	n/a		Flapless
Farley et al (2013)	Prospective clinical study	Partially-digital: dual-scan protocol	CBCT/ CBCT	Implant Master software (iDent Imaging, Foster City))	10	10	7	3	Flapless
Lee et al (2016)	Prospective clinical study	Partially-digital: stone cast digitized with desktop scanner	CBCT/ CBCT	R2Gate 1.0 (MegaGen Implant, Gyeongbuk, Korea)	11	21	12	9	Flapless
Cristache et al (2017)	Prospective clinical study	Partially-digital: stone cast digitized with desktop scanner	CBCT/STL	R2Gate 1.0 (Megagen Implant, Gyeongbuk, Korea)	25	65	33	32	Flapless
Younes et al (2018)	RCT	Partially-digital: stone cast digitized with desktop scanner	CBCT/ CBCT	Simplant (Dentsply Sirona Implants, Hasselt, Belgium)	10	21	—	21	Flapless
Magrin et al (2019)	RCT	Partially-digital: dual-scan protocol	CBCT/ CBCT	DentalSlice (Bioparts, Brasília, Brazil)	12	12	12	—	Flapless
Tallarico et al (2019a)	RCT	Partially-digital: stone cast digitized with desktop scanner Fully-digital: IOS	CBCT/STL	3Diagnosys (3DIEMME srl, Cantù,Italy)	20	57	24	33	Both (N not specified)
Tallarico et al (2019b)	Prospective clinical study	Fully-digital: IOS	CBCT/STL	3Diagnosys (3DIEMME srl, Cantù,Italy) and Implant studio (3Shape A/S, Copenhagen, Denmark)	39	119	54	65	Both (N not specified)
Derksen et al (2019)	Prospective clinical study	Fully-digital: IOS	CBCT/ CBCT	coDiagnostiX (Dental Wings Inc)	66	145	79	66	111/34
Smitkarn et al (2019)	RCT	Fully-digital: IOS	CBCT/ CBCT	coDiagnostiX (Dental Wings Inc)	26	30	10	20	Open flap
Skjerven et al (2019)	Prospective clinical study	Fully-digital: IOS	CBCT/STL	Implant studio (3Shape A/S, Copenhagen, Denmark)	20	27	6	21	Open flap
Kiatkroekkrai et al (2020)	RCT (split-mouth)	Partially-digital: stone cast digitized with desktop scanner Fully-digital: IOS	CBCT/ CBCT	coDiagnostiX (Dental Wings Inc)	47	60	20	40	Both (N not specified)

TABLE 1 (Continued)

Author (year)	Study design	Workflows utilized	Accuracy evaluation method	Guided system software	Number of patients	Number of implants	Implant location		Open/ Flapless
							Mand	Max	
Varga et al (2020)	RCT	Partially-digital: dual-scan protocol (CBCT of PVS impression and patient)	CBCT/ CBCT	Smart Guide (dicomLAB Dental, Szeged, Hungary)	28	52	37	15	Open flap

Abbreviations: CBCT, cone-beam computer tomography; IOS, intraoral scanning; Mand, mandible; Max, maxilla; n/a, data not available; *N*, number; RCT, randomized clinical trial; STL, standard tessellation language data.

TABLE 2 Risk of bias assessment for included RCTs according to the Cochrane guidelines

Study	Random sequence generation	Allocation concealment	Blinding of participants and personnel	Blinding of outcome assessment	Incomplete outcome data	Selective reporting	Other bias
Tallarico et al (2019a)	Low	Low	Low	High	Low	Low	Low
Smitkarn et al (2019)	Low	Unclear	Low	High	Low	High	Low
Younes et al (2018)	Low	Low	Low	High	Low	Low	Low
Magrin et al (2019)	Low	High	Low	Low	High	High	Low
Vagra et al (2020)	High	High	Low	Low	High	Low	Low
Kiatkroekkrai et al (2020)	Unclear	High	Low	Low	High	Low	Low

of bias, and one study[15] had an unclear risk. As for blinding of participants and personnel during outcome assessment, all included studies exhibited a low risk of bias. Additionally, three studies[14,15,24] were found to be of high risk during the assessment. According to incomplete outcome data and selective reporting, three articles showed a low risk of bias. Among all the included prospective clinical studies, there was one article[16] that attained eight stars and four articles[17,21,22,27] that received seven stars, suggesting a high standard of quality. The remaining two articles[10,12] obtained four to six stars, representing moderate quality evidence (Table 3).

3.5 | Accuracy outcomes

3.5.1 | Global deviation

Regarding global deviation at both the coronal and apical portions of the implants, valid data were provided in 10 out of 13 studies, including five RCTs[15,23-26] and five prospective clinical studies.[12,16,17,21,22] Among these studies, three articles[15-17] included a fully digital group, six articles[12,21-25] included a partially-digital group, and one article[26] had both arms. At the level of the implant shoulder, the overall weighted mean global deviation was 1.03 mm (95% CI: 0.88-1.18 mm; Figure 3). For the fully-digital group, the weighted mean deviation (coronal) was 0.89 mm (95% CI: 0.74-1.05 mm), while for the partially-digital group, this value was 1.14 mm (95% CI: 0.89-1.39 mm). At the level of the implant apex (Figure 4), the weighted mean global deviation was 1.33 mm (95% CI: 1.17-1.50 mm). In the fully-digital group, this value was 1.20 mm (95% CI: 1.02-1.39 mm) vs 1.42 mm (95% CI: 1.16-1.69 mm) for the partially-digital group.

3.5.2 | Angular deviation

Angular deviation was reported in 12 out of 13 studies, including six RCTs[14,15,23-26] and six prospective clinical studies.[12,16,17,21,22,27] The overall weighted mean angular deviation was 2.68°, with a 95% CI of 2.32° to 3.03° (Figure 5). For the fully-digital group[14-17,26,27] the mean angular deviation was 2.59° (95% CI: 1.97-3.20°), while the partially-digital group[12,14,21-26] exhibited an angular deviation of 2.76° (95% CI: 2.30-3.23°).

3.5.3 | Depth deviation

Six studies[10,12,14,15,26,27] provided depth deviation, including three studies[14,15,27] using a fully-digital approach, two studies[10,12] with

TABLE 3 Results of Newcastle-Ottawa Scale risk of bias for non-randomized clinical trials

Study	Representative of the exposed cohort	Selection of the non-exposed cohort	Ascertainment of exposure	Outcome of interest not present at start of study	Comparability of cohorts on the basis of the design or analysis	Assessment of outcome	Sufficient follow-up for outcome to occur	Adequacy of follow-up	Total
Derksen et al (2019)	★	★	★	★	★	★	★	★	8
Skjerven et al (2019)	★	★	★	★	★	☆	★	★	7
Tallarico et al (2019b)	★	★	★	☆	★	★	★	★	7
Arisan et al (2010)	★	★	★	★	★	★	★	☆	7
Farley et al (2013)	★	★	★	★	★	★	★	☆	7
Cristache et al (2017)	☆	★	★	★	★	☆	★	★	6
Lee et al (2016)	☆	☆	★	★	★	☆	★	☆	4

Note: 7 to 9 ★ high, 4 to 6 ★ moderate, and 0 to 3 ★ low quality.

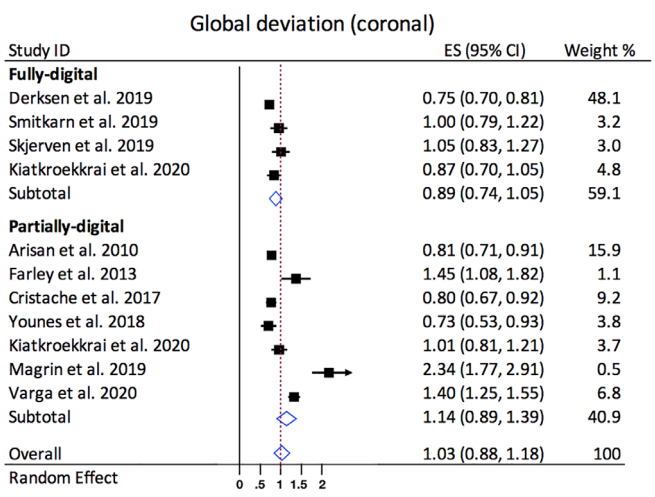

FIGURE 3 Cumulative global deviations (coronal) of partially- and fully-digital groups among selected studies (ES: effect sizes; CI: confidence interval)

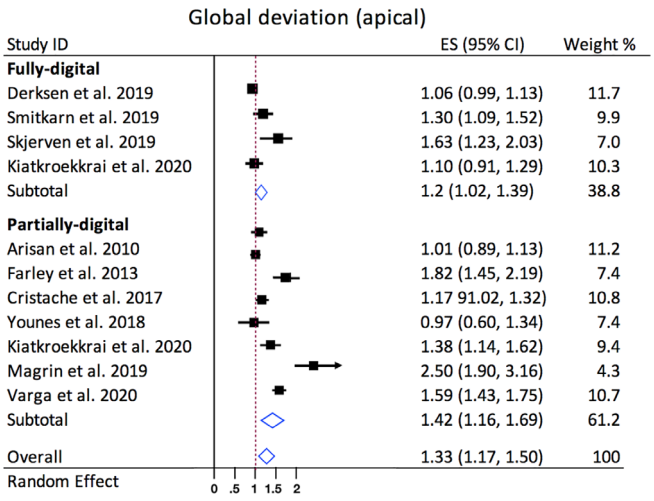

FIGURE 4 Cumulative global deviations (apex) of partially- and fully-digital groups among selected studies (ES: effect sizes; CI: confidence interval)

partially-digital approaches, and one study[26] reporting on both modalities. The weighted mean depth deviation for all the available articles was 0.59 mm (95% CI: 0.46-0.70 mm). For the fully-digital group this value was 0.55 mm (95% CI: 0.42-0.68 mm), and for the partially-digital group it was 0.62 mm (95% CI: 0.38-0.87 mm; Figure 6).

3.6 | Survival rates

An overall survival rate of 97.48-100% over a range of 12 to 24 months follow-up was reported from both groups, which is in line with previously reported outcomes regarding dental implant

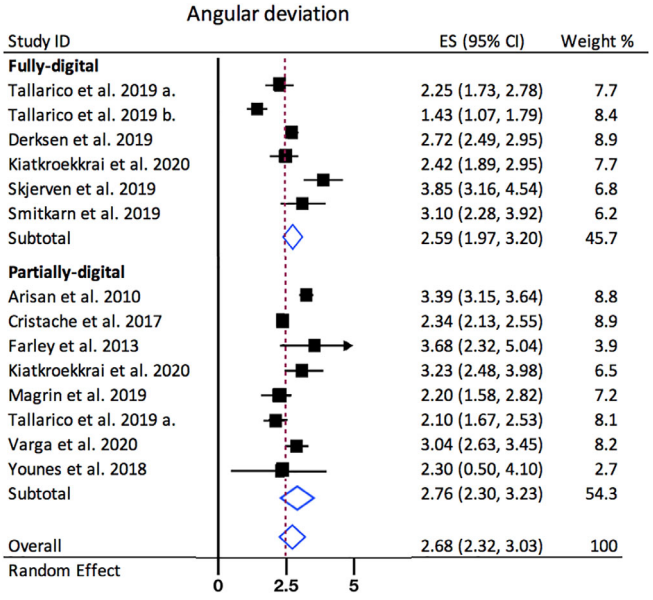

FIGURE 5 Cumulative angular deviations of partially- and fully-digital groups among selected studies (ES, effect sizes; CI, confidence interval)

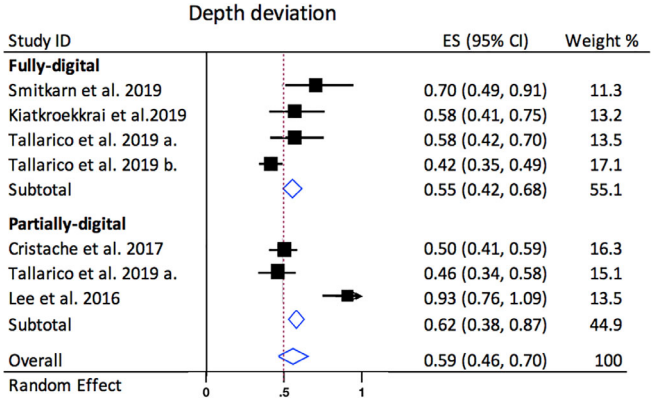

FIGURE 6 Cumulative depth deviations of partially- and fully-digital groups among selected studies (ES: effect sizes; CI: confidence interval)

treatment. In the fully-digital group, two papers reported survival rates of 99.3% after a two-year follow-up[16] and of 97.48% after 12.4 ± 7.1 months follow-up.[27] In the partially-digital group, two articles[12,21] reported implant survival rates. One study[21] reported three early failures, and one study reported 100% survival during a 1 year follow-up.[12] One study reporting on both modalities also reported 100% survival after 1 year.[14]

3.7 | Complications

Regarding intra- and post-operative complications, no nerve injuries, abnormal hemorrhages, sinus pathologies, or other complications relating to anatomical structures were reported in either group. In the fully-digital group, two studies[14,16] reported that in one case in the posterior region, the use of a surgical guide was abandoned due to limited mouth opening. In Derksen's study, they reported that nine implants placed with a flapless approach had less than 2 mm of keratinized mucosa (KM), with three implants demonstrating a complete lack of KM on the buccal aspect after prosthetic reconstruction. Two sites presented with buccal dehiscences after the final drill and simultaneous bone augmentation procedures were performed with implant placement. In the partially-digital group, two articles[22,23] reported complications. Farley and coworkers reported guide instability that required an acrylic resin reline. Magrin et al[23] reported one case with a buccal bone fracture which occurred during implant insertion, and one case with fracture of the insertion driver.

4 | DISCUSSION

The present systematic review evaluated the literature concerning the accuracy of s-CAIS utilizing partially- and fully-digital workflows. Previous studies reporting on the accuracy of s-CAIS suggested that fully-guided tooth-supported systems exhibited less deviations compared to other types of support mechanisms and partially-guided protocols.[8,16] The current review focused only on implants placed in human subjects, with the main inclusion criteria being partially edentulous patients that received implant placement through a fully-guided protocol using tooth-supported guides.

To the best of our knowledge, this is the first systematic review comparing the accuracy of partially- and fully-digital workflows, which yielded similar mean angular deviations of 2.76° (95% CI: 2.30-3.23°) and 2.59° (95% CI: 1.97-3.20°), respectively. The overall mean angular deviation for both groups encountered in the present study of 2.68° (95% CI: 2.32-3.03°) was slightly lower compared to the results of clinical studies included in previous systematic reviews.[8,28,29] Tahmaseb et al[28] reported an average angular deviation of 3.53° for fully-guided implant placement. However, there was heterogeneity in the mechanisms of guide support among the included studies, which could have contributed towards a greater deviation. Bover-Ramos et al[29] reported a higher mean angular deviation of 3.62 ± 0.29° for the included clinical studies for fully-guided implant surgery, but the majority of included studies utilized mucosa- and bone-supported guides. In a more recent systematic review, Tahmaseb et al[8] reported a mean angular deviation of 3.3°(95% CI: 2.07-4.63°) for fully-guided tooth-supported implant surgery, however, only two studies with retrospective designs using partially-digital workflows were included. Another possible explanation for the lower deviations encountered in our review is the inclusion of a study that used templates without metallic sleeves and a stopless implant driver that contributed to less angular and horizontal deviation.[27] Additionally, the evolution of 3D printing technologies may contribute to more accurate surgical templates in the recently published included studies. Despite the observation that the utilization of a fully-digital workflow resulted in a slightly smaller angular error, this

difference cannot be considered of clinical relevance. Similar conclusions were drawn in two different RCTs.[14,26] The authors conducted s-CAIS with stereolithographic guides manufactured in conjunction with either intra- or extra-oral scans and reported equal accuracy of implant positioning between the two workflows. It is worth noting that the highest mean angular deviation observed among the included studies in this review was 3.85 ± 1.83°,[17] which was substantially lower compared to earlier reports on guided surgery using both tooth- and bone-supported guides where a mean angular deviation up to 7.25 ± 2.67° was observed.[30]

For tooth-supported guides, higher deviations can be expected for cases with reduced dentition, as fewer teeth are present to support the guide. Kholy et al (2019)[31] conducted an in vitro study and reported that guides supported by a minimum of four teeth (two teeth on each side of an edentulous span) resulted in similar accuracy outcomes to full-arch-supported guides. Guides supported only by anterior teeth and distal extension scenarios were associated with significantly greater deviations. The present review included studies with heterogeneity regarding the number of single tooth gaps, distal extensions, and teeth available to support the guide. Because of variations in the number of existing teeth, it was difficult to make comparisons between the results of these studies. However, the majority of included studies acknowledged the importance of at least five teeth in two quadrants for supporting the surgical template for cross-arch stabilization.

The utilization of a fully-guided workflow has been demonstrated to increase the accuracy of implant placement relative to partially-guided surgery, where the template is removed after osteotomy preparation but prior to implant placement.[29,32] Although the present review focused only on evaluating the accuracy of fully-guided surgical procedures, two of the included studies[14,16] reported as a complication that the surgical guide had to be abandoned intra-operatively due to limited mouth opening during implant placement in the posterior region. Although not observed in this study, limited inter-arch clearance and mesiodistal spacing in single-tooth gaps may limit the use of surgical guides during osteotomy preparation. The present review reported a mean global deviation of 1.03 mm (95% CI: 0.88-1.18 mm) at the shoulder and 1.33 mm (95% CI: 1.17-1.50 mm) at the apex, which was similar between groups. Tahmaseb et al[8] reported similar mean errors of 0.9 mm (95% CI: 0.79-1.00 mm) at the entry point and 1.2 mm (95% CI: 1.11-1.20 mm) at the apex for partially edentulous cases. The magnitude of the upper limit of the confidence interval for the deviations from the studies should be considered in treatment planning and included as a safety margin.

Guided implant surgery facilitates a minimally invasive approach with conservative flap elevation or even flapless implant surgery.[33] The present review suggested both workflows can successfully incorporate a flapless approach. However, Derksen et al[16] found that 9 out of 34 implants placed using a flapless approach resulted in an inadequate zone of KM < 2 mm, with 3 implants completely lacking KM at the buccal aspect following prosthetic rehabilitation. Proper case selection and thorough treatment planning are key to avoid these potential complications.

Depth control can be achieved via indication lines or physical stoppers on the drills to aid with osteotomy preparation, guided surgical mounts with indication lines or physical stoppers to facilitate implant placement, as well as metal sleeves of varying diameters inserted in the guide.[15,16,34] During analysis of depth deviation, most included studies reported absolute values, while one study[14] took direction into consideration with positive (apical to the plan) and negative (coronal to the plan) values. This study utilized absolute values, since the use of positive and negative values during deviation analysis may result in lower deviation outcomes than actually experienced. A weighted depth deviation of 0.59 mm (95% CI: 0.46-0.70 mm) was found in the present review. For the fully-digital workflow group, this value was 0.55 mm (95% CI: 0.42-0.68 mm), compared to 0.62 mm (95% CI: 0.38-0.87 mm) in the partially-digital group. Ultimately, it is meaningful to consider depth deviation in the apico-coronal dimension in the context of long-term outcomes such as bone remodeling and pocket formation, whereas errors in implant height at the apex are more directly related to proximity to vital anatomical structures. Consequently, we suggest future studies report both absolute deviation values as well as direction.

Implant placement deviation is the cumulative result of errors which may possibly occur during all phases of s-CAIS protocols. CBCT acquisition errors include patient movement[35] and imaging artifacts.[36] It was speculated that the application of a fully-digital workflow, in contrast to earlier methods combining digital and laboratory steps, could have an influence on the accuracy of s-CAIS.[16] In the present review, deviations in the accuracy of implant placement were slightly lower for fully-digital approaches compared to the partially-digital group, but a clinically significant difference was not found. This is likely due to the fact that investigators in the partially-digital group utilized mostly stable elastomeric impression materials (polyvinylsiloxane and polyether) and followed a strict protocol adhering to manufacturer recommendations when obtaining impressions and fabricating stone casts. Also, desktop scanners can digitize stone casts or conventional impressions with high accuracy.[37] A recent investigation by Marghalani et al[38] demonstrated that the use of a specific IOS system obtained a higher level of accuracy relative to conventional impressions with polyether material, however, both resulted in clinically acceptable outcomes. On the other hand, it is logical to assume that inaccurate impressions taken with materials such as alginate with a greater propensity for deformation may lead to errors that will ultimately be incorporated into the guide and surgery. It is also possible to consider that errors could be introduced during the disinfection of the impression and pouring of the casts if adequate protocols are not followed.

A limitation of the present review involves the heterogeneity among the workflows of the included studies, including variability in the type of implant system used, the number of remaining teeth supporting the surgical template, as well as patient anatomical considerations, which made comparisons difficult between studies. Additionally, in patient-oriented dental implant research, clustered or dependent observations resulting from multiple implants placed in the same patient can potentially have a large influence on outcomes and is a common problem in this field.

The strengths of this review are as follows. The authors are unaware of a previous systematic review comparing the accuracy of implant placement between partially- and fully-digital workflows. The presence of strict inclusion criteria is an additional asset as this limited the influence of confounding variables such as different support mechanisms seen in other studies. In addition, only clinical studies were included, which increases the translatability of the results to clinical practice.

4.1 | Clinical implications

The differences found in this review were of a magnitude that would not likely jeopardize the aesthetic outcome, the safety of surrounding anatomical structures, nor the final prosthetic treatment plan from being executed as planned. However, these results should be interpreted with caution, and the maximum deviation should be taken into account as a safety margin since the involuntary contact of the implant with any critical anatomical structure can cause serious complications. Although no difference was found between partially- and fully-digital workflows, a fully-digital workflow with IOS can aid in reducing working time and improving the patient experience.[39]

4.2 | Research implications

Tahmaseb et al[8] recognized that the method used for obtaining the postoperative implant position could affect imaging quality. However, there was insufficient data available within their systematic review to be able to evaluate the effects of this on the outcome of guided surgery.[8] In our study, 9 publications used superimposition of virtually planned position and post-CBCT data, while 4 studies evaluated accuracy by obtaining post-surgical data using IOS. The differences between studies using the two methods were negligible, and comparable results were also demonstrated in a recent clinical trial comparing the two methods directly.[40] Still, few studies specifically addressed whether guided surgery can improve the likelihood of obtaining the desired prosthetic and aesthetic outcomes. In addition, another variable that remains to be further explored is whether long-term peri-implant survival and success are affected by optimal implant positioning. Although there is a current trend towards the utilization of fully-digital workflows, future research should focus on long-term follow-ups to provide further insight into the potential benefits of this approach.

5 | CONCLUSION

Within the limitations of the present systematic review, similar accuracy is obtained when implants are placed in partially edentulous patients using fully-guided s-CAIS independent of the workflow utilized for implant planning and surgical guide fabrication. Therefore, the decision to utilize either a partially- or fully-digital workflow for partially edentulous patients should take into account operator preference, cost, and patient comfort.

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CONFLICT OF INTEREST

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AUTHOR CONTRIBUTIONS

Rafael Siqueira, Zhaozhao Chen, and Hsun-Liang Chan contributed to the conception and design of the work. Rafael Siqueira, Islam Saleh, and Matthew Galli collected the data; Zhaozhao Chen led the statistics; Rafael Siqueira, Zhaozhao Chen, and Matthew Galli led the writing; Hom-Lay Wang, and Hsun-Liang Chan critically revised the manuscript.

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SUPPORTING INFORMATION

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