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REVIEW ARTICLE

WILEY CLINICAL ORAL IMPLANTS RESEARCH

The accuracy of static computer-aided implant surgery: A systematic review and meta-analysis

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Abstract

Objectives: To assess the literature on the accuracy of static computer-assisted implant surgery in implant dentistry.

Materials and Methods: Electronic and manual literature searches were conducted to collect information about the accuracy of static computer-assisted implant systems. Meta-regression analysis was performed to summarise the accuracy studies.

Results: From a total of 372 articles. 20 studies, one randomised controlled trial (RCT), eight uncontrolled retrospective studies and 11 uncontrolled prospective studies were selected for inclusion for qualitative synthesis. A total of 2,238 implants in 471 patients that had been placed using static guides were available for review. The meta-analysis of the accuracy (20 clinical) revealed a total mean error of 1.2 mm (1.04 mm to 1.44 mm) at the entry point, 1.4 mm (1.28 mm to 1.58 mm) at the apical point and deviation of 3.5°(3.0° to 3.96°). There was a significant difference in accuracy in favour of partial edentulous comparing to full edentulous cases.

Conclusion: Different levels of quantity and quality of evidence were available for static computer-aided implant surgery (s-CAIS). Based on the present systematic review and its limitations, it can be concluded that the accuracy of static computer-aided implant surgery is within the clinically acceptable range in the majority of clinical situations. However, a safety marge of at least 2 mm should be respected. A lack of homogeneity was found in techniques adopted between the different authors and the general study designs.

1 | INTRODUCTION

Prosthetically driven implant dentistry is the optimal way to treat patients with dental implants (Katsoulis, Pazera & Mericske-Stern, 2009; Tzerbos, Sykaras & Tzoras, 2010; Zitzmann & Marinello, 1999). It requires detailed pretreatment planning to ensure a correct three-dimensional (3-D) implant position is achieved within the alveolar bone, relative to the planned prosthetic restoration (Belser et al., 2007). A 3-D model or digital file of the alveolar bone and related oral anatomy can be generated using either CT (computed tomography) or CBCT (cone beam computed tomography). CBCT offers significant radiation dose reduction with the ability to image restricted fields of view (Bornstein, Scarfe, Vaughn & Jacobs, 2014). In addition, the introduction of surface scanning technology, via either intra-oral or extra-oral scanning approaches, generates a further 3-D model of the patients' oral condition which can be superimposed on the radiographic data set, to create a realistic 3-D virtual patient.

This virtual patient can be viewed on implant planning software where the data on soft and hard dental tissue, proposed prosthetic treatment proposals and bone volume information can be visualised as different layers (Lee, Betensky, Gianneschi & Gallucci, 2015). Within the implant planning software, clinicians can perform a virtual implant placement in accordance with the future prosthetic needs, whilst respecting the existing anatomical situation. This information can be used to design and fabricate surgical drill guides, which aid the clinician to insert the implants in the planned positions. Static guidance systems are defined as systems which communicate the predetermined virtual implant position to the surgical operating area, using a rigid surgical implant template or guide (Jung et al., 2009). In an increasing manner, such static guidance systems are marketed to dental clinicians under the assumption they can produce high levels of accuracy.

Whilst these developments seem to be promising, questions have been raised about the reliability, accuracy, and the precision of these static surgical drill guides to replicate the planned implant position. Two previous ITI consensus publications on the accuracy of guided surgery were inconclusive (Jung et al., 2009; Tahmaseb, Wismeijer, Coucke & Derksen, 2014). It was recognised that each step, either solely, or in accumulation with other steps in this digital workflow, can result in inaccuracies (Tahmaseb et al., 2014). Failure

TABLE 1 Search strategy and selection criteria

Focused question (PICO)	**"What is the accuracy of static computed guided implant placement in partial and fully edentulous human subjects?"**	
Search Strategy	Population	#1 [Text Words]: ((jaw, edentulous, partially[Mesh Terms]) OR (partially edentulous) OR (partial edentulism))
	Intervention or exposure	# 2 [MeSH terms]: (Surgery, Computer-assisted) AND (Dental Implants) [Text Words]: dental AND (implant OR implants OR implantation OR implantology) AND (guide* OR computer*)
	Comparison	# 3 [Text Words]: ((((((adjusted drills) OR drill handles) OR (printed guide AND milled guide) AND (lab guide OR full guided AND partial guided) OR (depth control OR no depth control)
	Outcome	#4 [Text Words]: (1) Accuracy of placement, (2) Implant survival
	Search combination	#1 AND #2 AND #3 AND #4 #2
Database search	Language	English
	Electronic	PubMed, Cochrane
	Journals	Clinical Implant Dentistry and Related Research, Clinical Oral Implants Research, The International Journal of Oral Maxillofacial Surgery, Journal of Periodontology, Journal of Prosthetic Dentistry, Implant Dentistry, and The International Journal of Periodontics and Restorative Dentistry.
Selection criteria	Inclusion criteria	• Randomised and nonrandomised clinical studies • Case reports including at least 10 patients • Computer-guided (static) surgery in which a CT/CBCT scan was conducted for computerised planning prior to the actual implant insertion. • Studies with a primary outcome of • accuracy of computer-guided implant surgery • Clear description on accuracy measurements: distances between the • planned and actual position of the implants and/or implant angle deviations. Data on the position of actual inserted implants
	Exclusion criteria	• Cadaver, model, animal studies • Expert opinions • Dynamic computer-navigated surgery and 2D radiographic stents • Zygomatic, pterygoid and orthodontic implants • Studies with primary outcomes other than accuracy of computer-guided implant surgery • No actual insertion of the implants • Unclear description on accuracy measurements • Insufficient information on timing of implant placement after tooth extraction • Absence of objective parameters—aesthetic indices, soft tissue measurements • Multiple publications on the same patient population. • No author response to inquiry email for data clarification

of the final implant position to accurately match the virtual planned implant position can compromise the outcome.

This article aimed to review the literature in respect to the positional accuracy of implants placed using static guided implant surgery techniques in both partially and fully edentulous patients, and to assess survival rates for implants placed using static guidance systems.

2 | MATERIALS AND METHODS

2.1 | Search strategy

In accordance with PRISMA guidelines, this systematic review reports on the accuracy of implant placement and the subsequent implant survival of dental implants placed using static computer-aided guided implant surgery for partially and fully edentulous patients. The term partially edentulous patient was used to define any patient that is missing one, or more teeth, but not all teeth. A patient that is missing all teeth is defined as fully edentulous. The focused question was as follows: "What is the accuracy of static computed guided implant placement in partial and fully edentulous human subjects?"

2.2 | PICO question

Table 1 summarises the PICO question where data were sought for:

- (P) Edentulous or partially edentulous jaws,
- (I) Dental implants and computer guides,
- (C) Drill guides; printed and milled for both partially or fully guided surgery and
- (O) Accuracy of implant position and subsequent survival rate.

All electronic data resources of PubMed and Cochrane were searched as well as hand searches of the following relevant journals: Clinical Implant Dentistry and Related Research, Clinical Oral Implants Research, The International Journal of Oral Maxillofacial Surgery, Journal of Periodontology, Journal of Prosthetic Dentistry, Implant Dentistry and The International Journal of Periodontics and Restorative Dentistry.

The following terms were used for the search strategy:

MeSH terms: (Surgery, Computer-Assisted) AND (Dental Implants).

Text words: Computer Aided Surgery AND (implant OR implants) AND (dental OR oral) AND (guided surgery OR guided implant placement OR computer guided OR ((drill guide OR template) AND computer) OR surgical template OR simplant OR codiagnostix OR SMOP OR nobelguide).

The results were limited to studies written in English.

The search, electronic and manual, was limited to studies published between January 1, 2008, and December 31, 2016. Previous systematic reviews have shown that publications prior to 2008 report varying degrees of inaccuracy, possibly as a result of the limited technology available at the time (Tahmaseb et al., 2014). Therefore, the authors decided to limit the search to only include publications after 2008.

This review was registered in PROSPERO with ID number: 91834.

2.3 | Study selection

Two reviewers (A.T. and V.W.) screened all titles and abstracts independently. The reference lists of the subsequently selected abstracts and the bibliographies of the systematic reviews were searched manually. Disagreements were solved through discussion. No kappa score was calculated. Studies were screened and eliminated when either (a) group size was not clear or (b) no statistical analysis was performed. Full-text evaluation of the remaining publications was performed using the inclusion and exclusion criteria listed below:

Randomised and nonrandomised clinical studies were included for the review. Case reports were considered eligible for inclusion but must document a minimum of 10 patients. This review included only computer-guided (static) surgery in which a CT or CBCT scan was conducted for computerised planning prior to actual implant insertion in a human.

Publications containing expert opinions were excluded. Articles regarding dynamic computer-navigated surgery and 2D radiographic stents were excluded. Studies with zygomatic, pterygoid and orthodontic implants were also excluded. Data were excluded if the position of the osteotomy following computer-guided surgery was provided, but no actual implant insertion was performed. Articles were excluded if there was insufficient information on timing of implant placement.

2.4 | Data extraction

Two reviewers, A.T and V.W, independently extracted data from the included studies. Disagreements were again resolved through discussion until a consensus was reached between both reviewers. Where data were unclear or incomplete, the authors of the publication were contacted for further explanation.

The data were further analysed based on the following subgroups:

- Flapless vs. open-flap surgical procedure
- Implanted jaw: maxilla vs. mandible
- Type of edentulism: partial vs. Full
- Static Guide support: (a) mucosa, (b) tooth, (c) bone, (d) mini-pins

2.5 | Quality of the studies

A quality assessment of the included RCT was performed according to the Cochrane Handbook for Systematic Reviews of Interventions (version 5.1.0; updated March 2011 by Higgins, Altman & Sterne, 2011). Six main quality criteria were evaluated: random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data and selective reporting. Depending on the descriptions given for each individual criteria, it was rated as low, unclear or high risk of bias.

The Newcastle–Ottawa Scale (NOS) adapted by Chambrone, Chambrone, Lima and Chambrone (2010), Chambrone, Shibli, Mercurio, Cardoso and Preshaw (2015) was used to assess the risk of bias in the prospective and retrospective included studies. Thus, the following topics were used: (a) selection of study groups: sample size calculation, representativeness of the patients, description of clear selection criteria of the patients, detailed description of the surgical steps, calibration of the surgeons and assessors of outcomes (b) comparability: comparability of patients on the basis of the study design or analysis and management of potential confounders; (c) outcomes: evaluation of results; and (d) statistical analysis: validity of statistical analysis. Each included study could receive a maximum of nine stars indicating methodological quality, and therefore indicating the risk of bias. Studies with 7–9 points were arbitrarily considered as being of low risk of bias, with 5–6 points indicating medium-level risk of bias and with fewer than five points indicating high risk of bias. Table S1 in the Supporting information section shows the risk of bias per individual study.

2.6 | Statistical analysis

Statistical analysis was performed using the meta library from R, version 3.4.3. The data provided from the selected articles did not allow for the evaluation of the accuracy of different tools. Therefore, the overall accuracy of static guided implant insertion was evaluated. Differences between edentulism type were assessed by means of a random-effects meta-regression with a binary predictor, also known as a dummy variable used to investigate the difference between edentulism status

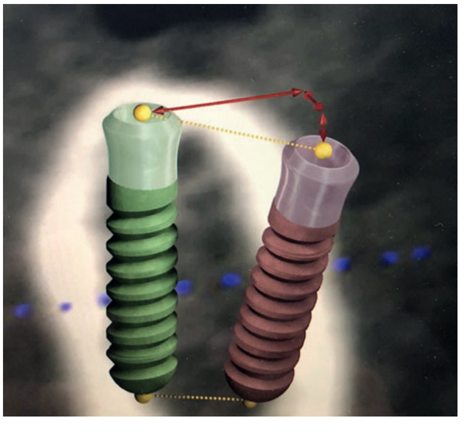

FIGURE 1 The following six outcome variables were evaluated for each selected study: 1. Deviation in entry point measured from the centre of the implant (mm). 2. Deviation in apex location measured at the centre of the implant (mm). 3. Angulation deviation. 4. Error in implant height at the entry point (mm). 5. Error in implant height at the apex (mm)

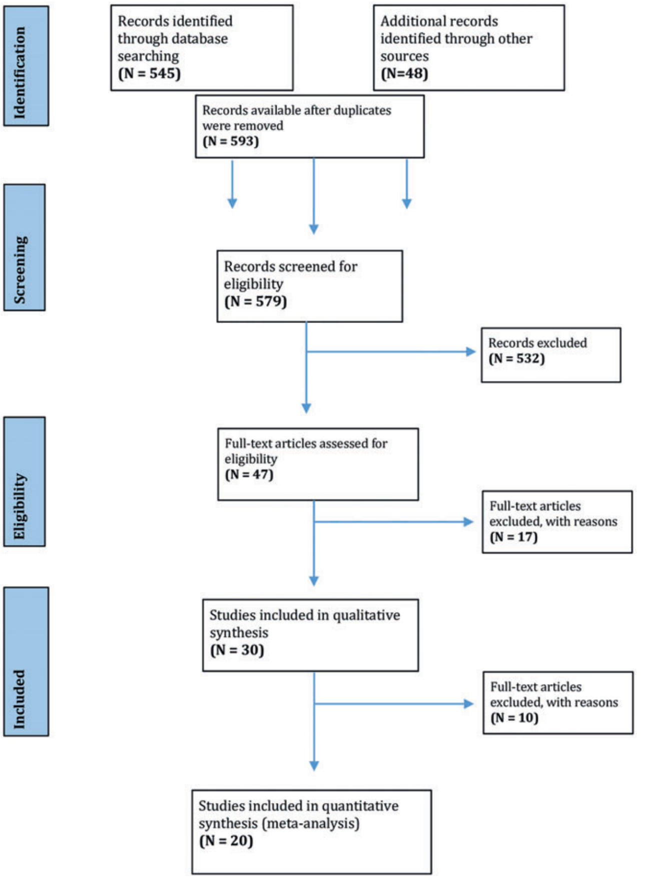

FIGURE 2 Outline of the PRISMA flow diagram for data selection and screening for eligible inclusion in the systematic review. A total of 20 articles were included for qualitative synthesis and assessment

(Hedges & Vevea, 1998). A separate analysis was performed for error at the entry point, error at the apex and angular deviation (Figure 1).

In addition, forest plots were drawn to visualise the magnitude of errors and the difference between groups. As there was evidence of heterogeneity between the articles, totals were calculated using random-effects meta-analysis for continuous variables. The significance level of the tests was 0.05. The funnel plots are demonstrated in the Supporting information Figures S1–S4.

3 | RESULTS

3.1 | Study selection

The initial electronic database search on PubMed and Cochrane database resulted in 545 articles. An additional 48 articles were identified with manual searches yielding a total of 593 articles for review. After removing duplicates, 579 were available for screening. 47 articles were selected for full-text review by two reviewers (AT, VW) independently. After prescreening, application of the inclusion and exclusion criteria and handling of the PICO question, 30 studies remained. A further 10 studies were excluded, resulting in 20 studies selected for inclusion

TABLE 2 Selected publication for meta-analysis

Authors (year)	Study design	Comparison	Software/guide system	No. of patients	No. of implants
Arisan et al. (2013)	Uncontrolled prospective clinical trial	CBCT/CT	Simplant	11	102
Cassetta et al. (2012)	Uncontrolled retrospective study	CT	Simplant/External Hex Safe	11	95
Cassetta, DiMambro et al. (2013), Cassetta, Giansanti et al. (2013) and Cassetta, Stefanelli et al. (2013)	Uncontrolled retrospective study	CT	Simplant/ SurgiGuide, External Hex Safe	20	227
Cassetta, Giansanti, Di Mambro and Stefanelli (2014)	Uncontrolled retrospective study	CT	Simplant/External Hex Safe	28	225
D'haese et al. (2012)	Uncontrolled prospective clinical trial	CT	Facilitate	13	78
Ersoy et al. (2008)	Uncontrolled prospective clinical trial	CT	Stent Cad/swissplus	21	94
Fürhauser et al. (2015)	Uncontrolled retrospective study	CBCT	NobelGuide	27	27
Geng et al. (2015)	Uncontrolled prospective clinical trial	CBCT	Simplant	24	111
Lee et al. (2013a,b)	Uncontrolled retrospective study	CT	OnDemand3D	48	102
Ozan et al. (2009)	Uncontrolled retrospective study	CT	StentCAD	30	110
Pettersson et al. (2012)	Uncontrolled prospective clinical trial	CBCT	NobelGuide	30	139
Schnutenhaus et al. (2016)	Uncontrolled retrospective study	CBCT	Swiss Media Online Planning/Camlog Guide system	24	24
Stübinger et al. (2014)	Uncontrolled prospective clinical trial	MSCT	Facilitate	10	44
Van de Wiele et al. (2015)	Uncontrolled prospective clinical trial	CBCT	Simplant	16	75
Vasak et al. (2011)	Uncontrolled prospective clinical trial	CT	Procera/ NobelGuide	18	86
Vercruyssen et al. (2014, 2015)	(RCT) randomised controlled trial	CBCT (note patients had CTs prior to CBCT to confirm eligibility)	Simplant/ Materialise Universal, Facilitate	48	209
Vercruyssen et al. (2015)	Uncontrolled prospective clinical trial	CBCT	Procera/ NobelGuide	25	150
Vercruyssen et al. (2015)	Uncontrolled prospective clinical trial	CBCT	Procera/ NobelGuide	30	104
Verhamme et al. (2017)	Uncontrolled prospective clinical trial	CBCT	Maxilim/ NobelGuide	12	72
Vieira, Sotto-Maior, Barros, Reis and Francischone (2013)	Uncontrolled retrospective study	CBCT	NobelGuide	14	62

for qualitative synthesis (Figure 2). Complete data extraction and statistical analysis were performed. From the 20 studies, one was a randomised controlled trial (RCT), eight were uncontrolled retrospective studies, and 11 were uncontrolled prospective studies. Table 2 details the article selected for inclusion and Table 3 the articles excluded from the analysis with the reasons for exclusion.

TABLE 3 The excluded papers and the reason for their exclusion

Cassetta et al.	The Influence of the Tolerance between Mechanical Components on the Accuracy of Implants Inserted with a Stereolithographic Surgical Guide: A Retrospective Clinical Study	2015	Only results on angle deviation reported
Al-Harbi and Sun	Implant placement accuracy when using stereolithographic template as a surgical guide: preliminary results	2009	Less than 10 patients included
Behneke, Burwinkel, & Behneke	Factors influencing transfer accuracy of cone beam CT-derived template-based implant placement	2012	Same cohort as Behneke et al. 2011
Behneke, Burwinkel, Knierim et al.	Accuracy assessment of cone beam computed tomography-derived laboratory-based surgical templates on partially edentulous patients	2012	Radical deviation measured instead of 3D
Cassetta, Stefanelli et al.	Accuracy of implant placement with a stereolithographic surgical template	2013	Same as Accuracy of two Stereolithographic
Cassetta, Stefanelli et al.	Accuracy of a computer-aided implant surgical technique	2013	Same as Accuracy of two stereo-lithographic 2013
Cassetta, Di Mambro et al.	Is it possible to improve the accuracy of implants inserted with a stereolithographic surgical guide by reducing the tolerance between mechanical components?	2013	Less than 10 patients included
Cassetta, Di Mambro et al.	How does an error in positioning the template affect the accuracy of implants inserted using a single fixed mucosa-supported stereolithographic surgical guide?	2013	No data error at the apex
Cassetta et al.	The influence of the tolerance between mechanical components on the accuracy of implants inserted with a stereo-lithographic surgical guide: A retrospective clinical study	2015	No data error at the entry and apex
Di Giacomo et al.	Accuracy and complications of computer-designed selective laser sintering surgical guides for flapless dental implant placement and immediate definitive prosthesis installation	2012	Only lateral deviation reported not three Dimension measurements
Farley et al.	Split-mouth comparison of the accuracy of computer-generated and conventional surgical guides	2013	No clear description on material and methods
Lee et al.	Accuracy of a direct drill-guiding system with minimal tolerance of surgical instruments used for implant surgery: a prospective clinical study	2016	No data error at the apex and angulation
Cassetta, Di Mambro et al.	The intrinsic error of a stereolithographic surgical template in implant guided surgery	2013	Same as Accuracy of two stereo-lithographic 2013
Cassetta, Stefanelli et al.	Depth deviation and occurrence of early surgical complications or unexpected events using a single stereolithographic surgi-guide	2013	Different research question
Moon et al.	Clinical problems of computer-guided implant surgery	2016	Less than 10 patients included
Naziri et al.	Accuracy of computer-assisted implant placement with insertion templates	2016	Results reported median instead of mean
Nickenig et al.	Evaluation of the difference in accuracy between implant placement by virtual planning data and surgical guide templates versus the conventional free-hand method—a combined in vivo—in vitro technique using cone-beam CT (Part II)	2010	No results reported on entry or apex in three Dimensions
Ochi et al.	Factors affecting accuracy of implant placement with mucosa-supported stereolithographic surgical guides in edentulous mandibles	2013	No results on angulation reported
Ozan et al.	Correlation between bone density and angular deviation of implants placed using CT-generated surgical guides	2011	No results reported on entry or apex in three Dimensions
Platzer et al.	Three-dimensional accuracy of guided implant placement: indirect assessment of clinical outcomes	2013	Less than 10 patients included
Shen et al.	Accuracy evaluation of computer-designed surgical guide template in oral implantology	2015	Not clear flapless? Edentulous/dentate/fully guided?
Sun, Luebbers, Agbaje, Kong et al.	Accuracy of a Dedicated Bone-Supported Surgical Template for Dental Implant Placement with Direct Visual Control.	2015	Less than 10 patients included

(Continues)

TABLE 3 (Continued)

Sun, Luebbers, Agbaje, Schepers et al.	Accuracy of Dental Implant Placement Using CBCT-Derived Mucosa-Supported Stereolithographic Template	2015	No apex results
Testori et al.	Evaluation of accuracy and precision of a new guided surgery system: A multicenter clinical study	2014	No SD
Van Assche et al.	Accuracy assessment of computer-assisted flapless implant placement in partial edentulism	2010	Less than 10 patients included
Vercruyssen et al.	Depth and lateral deviations in guided implant surgery: an RCT comparing guided surgery with mental navigation or the use of a pilot-drill template	2015	Same patient group as Vercruyssen 2014
Zhao et al.	Accuracy of computer-guided implant surgery by a CAD/CAM and laser scanning technique	2014	No results reported on entry, angulation or apex in three Dimensions

3.2 | Study characteristics

All patients in all studies were assessed prior to inclusion and reported to be suitable candidates for implant-supported prostheses. All patients were in good health at the time of implantation. Eight studies assessed the outcome of guided surgery in edentulous patients, while 12 studies reviewed the outcome for fully edentulous patients. CBCT was used for pretreatment assessment in 11 of 20 studies, whilst 9 of 20 used a medical CT device. One study used both CT and CBCT technology. The support mechanism for the surgical guides was mixed in all but one study to include, mucosa, mucosa with fixation pins, bone and tooth. Only one study evaluated tooth-supported static surgical guides (Fürhauser et al., 2015).

3.3 | Results of the individual studies

A total of 20 studies met the selection criteria for review (Table 2). This provided a total of 2,136 implants, in 460 patients which were available for review (Table 4). All studies employed a fully guided drilling sequence; however, four studies sought to compare the accuracy of fully guided implant placement with freehand implant placement following a fully guided drilling sequence and contained a cohort of implants (n = 355) which were not fully guided. A total of 1,883 implants had been placed with a static surgical guide that remained in situ following osteotomy preparation. Stabilisation of the surgical guide varied across all studies. Partially edentulous cases were completed with a mix of tooth support and tooth/mucosa support when distal extension cases were treated. Fully edentulous cases were treated with either mucosa-supported guides (9/20 studies), mucosa-supported guides stabilised with fixation pins (12/20 studies) or bone-supported guides fixed in place with stabilisation screws (7/20 studies).

A total of seven different software systems were used for pretreatment planning of the cases:(a) Simplant (7/20) (b) Facilitate (2/20) (c) Stent Cad (2/20) (d) NobelGuide (3/20) (e) OnDemand3D (1/20) (f) Swiss Media Online Planning (1/20) (g) Procera (3/20) (h) Maxilim (1/20) (Table 2). A total of 10 different guide systems were used for implant placement:(a) External Hex Safe (3/20) (b) Simplant (3/20) (c) Surgiguide (1/20) (d) Facilitate (3/20) (e) Swissplus (1/20) (f) NobelGuide (7/20) (g) OnDemand3D (1/20) (h) StentCAD (1/20) (i) CamlogGuide system (1/20) (j) Materialise Universal (Table 2). Regarding implant surgery, 12/20 studies reported on flapless surgical implant placement protocols, and 8/20 studies completed surgery with both flapless and open-flap techniques. Only one study considered the aesthetic outcomes of implant placed with static guided surgery (Fürhauser et al., 2015), demonstrating that flapless guided surgery can produce aesthetic outcomes assuming the planned implant position is realised accurately. Comparison of the planned and final implant position was performed using radiographic comparison with CT or CBCT in 19/20 studies with five different software systems being utilised. Only one study (Schnutenhaus,

TABLE 4 All publication (fully and partially edentulous) reporting on error at the entry point

Study	No of patients	No of implants
Arisan (2013)	11	102
Cassetta (2012)	11	95
Cassetta (2013)	20	227
Cassetta (2014)	28	225
D'haese (2012)	13	78
Ersoy (2008)	21	94
Fürhauser (2015)	27	27
Geng (2015)	24	111
Lee (2013)	48	102
Ozan (2009)	30	110
Pettersson (2012)	30	139
Schnutenhaus (2016)	24	24
Van de Wiele (2015)	16	75
Vasak (2011)	18	86
Vercruyssen (2014/2015)	59	311
Verhamme (2015-1)	25	150
Verhamme (2015-2)	30	104
Verhamme (2016)	12	72
Vieira (2013)	14	62
Total	461	2,194

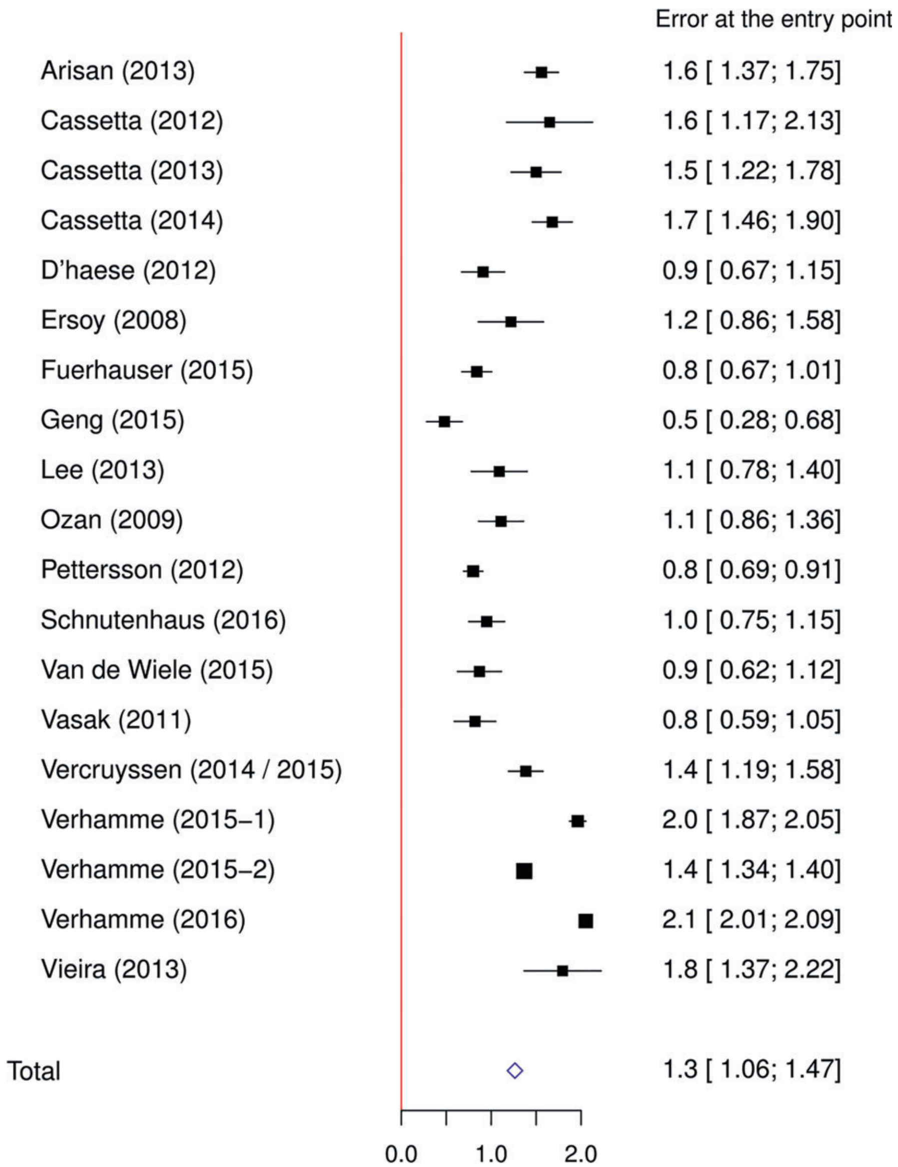

FIGURE 3 Forest plot demonstrating difference in error (mm) at the entry point between full edentulous and partial edentulous groups

Edelmann, Rudolph & Luthardt, 2016) made comparisons of the implant positions using a final impression of the actual implant location. The impression was poured in stone and the implant locations digitised and compared to the pre-treatment position using Geomagic software. In three studies, the software used for comparison of implant locations was not specified.

The majority of implants were placed using static guides, fabricated using a Rapid Prototyping SLA (stereolithography) method (2,175/2,136). A total of 63 implants were placed using acrylic guides in one study as part of a prelaunch protocol (Pettersson, Komiyama, Hultin, Näsström & Klinge, 2012).

Implant length did not seem to be correlated to positional accuracy in one RCT (Vercruyssen et al., 2015); however, one study did find larger apical deviations for longer implants placed using static guidance (D'haese, Van De Velde, Elaut & De Bruyn, 2012). Longer implants were found to have greater variation in mesio-distal angulation by one group (Verhamme, Meijer, Bergé et al., 2015; Verhamme, Meijer, Boumans et al., 2015). They recommended the use of fixation screws to reduce bucco-lingual errors. Several studies reported that right-handed surgeons had lower accuracy when treating the left side of the patient compared to the right side (Van de Wiele et al., 2015 and Vercruyssen et al., 2014). Implant placement in the anterior region was reported to be more accurate than placement in the posterior by one group (D'haese et al., 2012) which was in contrast to Verhamme et al., who found no differences (Verhamme, Meijer, Bergé et al., 2015; Verhamme, Meijer, Boumans et al., 2015).

3.4 | Quality of the studies

The 20 included studies were assessed for methodological risks analysis. Two different methods, Higgins et al. (2011) for one RCT and the Newcastle–Ottawa Scale (NOS) adapted by Chambrone

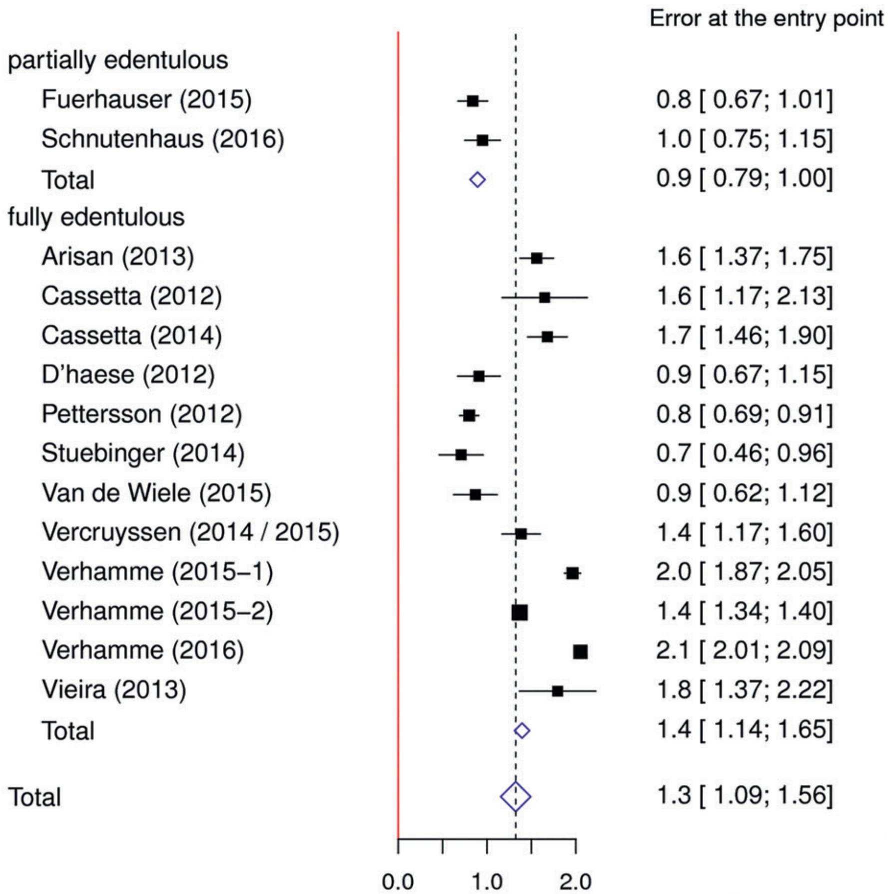

FIGURE 4 Forest plot demonstrating error (mm) at the entry point measured for all selected articles

et al. (2010, 2015) for the remaining 19 included studies, were used (Table risk of bias in the Table S1). All the included studies except the selected RCT met between 55% and 77% of the selected criteria, being considered to have a low-to-moderate level of risk of bias. The only RCT (Vercruyssen et al., 2014) met 83% of the criteria, demonstrating a low risk of bias. However, the level of the data heterogenicity and the nonstandardised measuring methods can be considered as the major limitations of this current meta-analysis.

3.5 | Synthesis of results

Only two papers reported on implant survival rate. Both studies showed 100% survival rate after at least 1 year of observation (Lee et al., 2013a,b; Pettersson et al., 2012). As not all studies reported the full detailed measurements for all outcome variables, even after authors were emailed, it was necessary to make some calculations based on only the studies which clearly demonstrated the data. Table 3 details which studies were able to be used for calculation of the outcome variables.

3.6 | Error at entry point

The mean error for entry point measured at the centre of the implant for fully edentulous cases was 1.3 mm CI:95% [1.09–1.56 mm] and 0.9 mm CI: 95% [0.79–1.00] for partially edentulous cases (Figure 3). Average error for all (partially and fully edentulous) guided surgeries was 1.2 mm, CI: 95% [1.04–1.44] (Figure 4). A significant difference was found between edentulous and fully edentulous cases treated with guided surgery with a smaller error and less deviation found in partially edentulous patients (Figure 3). Table 4 contains all publications that measured the errors at entry point. Table 5 contains all publications where a comparison between fully edentulous and partially edentulous was possible.

3.7 | Error at the apex

The mean error of apical position for partially edentulous cases was 1.2 mm CI:95% [1.11–1.20 mm] and 1.5 mm C:95% [1.29–1.62] for fully edentulous cases (Figure 5). A strongly significant difference between fully and partially edentulous was found. The average error for all cases was 1.4 mm, CI:95% CI [1.28–1.58] (Figure 6). Table 6 contains all publications that measured the errors at apical point. Table 7 contains all publications where a comparison between fully edentulous and partially edentulous was possible.

3.8 | Angular deviation

The angular deviation for partially edentulous cases was 3.3 degrees CI:95% [2.07–4.63] and 3.3 degrees for fully edentulous cases

TABLE 5 Publications specifically reporting on error at the entry point in separate groups, partial edentulous, full edentulous

Edentulism status	Study	No of patients	No of implants
Partially edentulous	Fürhauser (2015)	27	27
Partially edentulous	Schnutenhaus (2016)	24	24
Partially edentulous	Total	51	51
Fully edentulous	Arisan (2013)	11	102
Fully edentulous	Cassetta (2012)	11	95
Fully edentulous	Cassetta (2014)	28	225
Fully edentulous	D'haese (2012)	13	78
Fully edentulous	Pettersson (2012)	30	139
Fully edentulous	Van de Wiele (2015)	16	75
Fully edentulous	Vercruyssen (2014/2015)	59	311
Fully edentulous	Verhamme (2015-1)	25	150
Fully edentulous	Verhamme (2015-2)	30	104
Fully edentulous	Verhamme (2016)	12	72
Fully edentulous	Vieira (2013)	14	62
Fully edentulous	Total	249	1,413
Grand Total		300	1,464

CI:95% [2.71–3.88] (Figure 7). No significant difference between edentulous and fully edentulous. Average angular deviation for both fully and partially edentulous cases was 3.5 degrees CI: 95% [3.00–3.96] (Figure 8). Table 7 contains all publications that measured angular deviations. Table 8 contains all publications where a comparison between fully edentulous and partially edentulous was possible.

3.9 | Error in implant height at the entry point

The average error in height of the entry point is 0.2 mm, CI 95%, [−0.25 to 0.57 mm] (Figure 9).

3.10 | Error in implant height at the apex

The average error is 0.5 mm, CI:95% [−0.08 to 1.13 mm] (Figure 10).

4 | DISCUSSION

This review systematically evaluated the literature, regarding accuracy and clinical outcome of static computer-assisted implant dentistry. Static guidance systems have been previously reported to be more accurate than dynamic guidance systems, which allow the surgeon to vary the implant position in real time (Jung et al., 2009). The current systematic reviewed only implants placed in patients and not implants placed in a preclinical or cadaver studies. The average errors in entry and apex point positions were similar to the results published in a previous systematic review (Tahmaseb et al., 2014). When the 3D measurements were conducted, the vertical errors were found be statically significant inaccuracies when compared to the horizontal and angulation deviations in this present review.

Although the mean deviations seem to be in a clinically acceptable range, still some significant outliners were reported. Verhamme, Meijer, Bergé et al. (2015) and Verhamme, Meijer, Boumans et al. (2015) reported errors up to 7.8 mm at the entry point and 8.7 mm at the apical point. Verhamme et al. (2017), Verhamme, Meijer, Bergé et al. (2015) and Verhamme, Meijer, Boumans et al. (2015)reported errors up to 4.0 mm and 4.2 mm at the entry point and 3.6 mm and 4.3 mm at the apex, respectively. These results were achieved when treating fully edentulous upper jaws. The confidence interval (CI) of 95% was used to report data, in this study; therefore, the outliners were limited to a few studies. These authors also reported that the majority of the errors occurred with the implants being placed too superficially.

When considering height deviations of guided implant surgery, in this systematic review, the error in implant height was considered to be a positive valued error for implants that were not deep enough and a negative value for implants inserted below the reference line.

While the data presented in the current systematic review indicate that static guided surgery can be used to realise virtual implant planning position with reasonable accuracy, considerable errors may still occur when using static drill guides. These errors can be of a magnitude which could jeopardise the aesthetic outcome, the safety of surrounding anatomical structures or prevent the final prosthetic treatment plan from being executed as planned. Implants placed using a free-hand approach do not easily allow the clinician to make a pre- and post-treatment comparison as there is no preplanned implant position available. Vercruyssen and coworkers did seek to compare mental navigation with guided surgical approaches, where a presurgical plan was made and the operator then placed implants

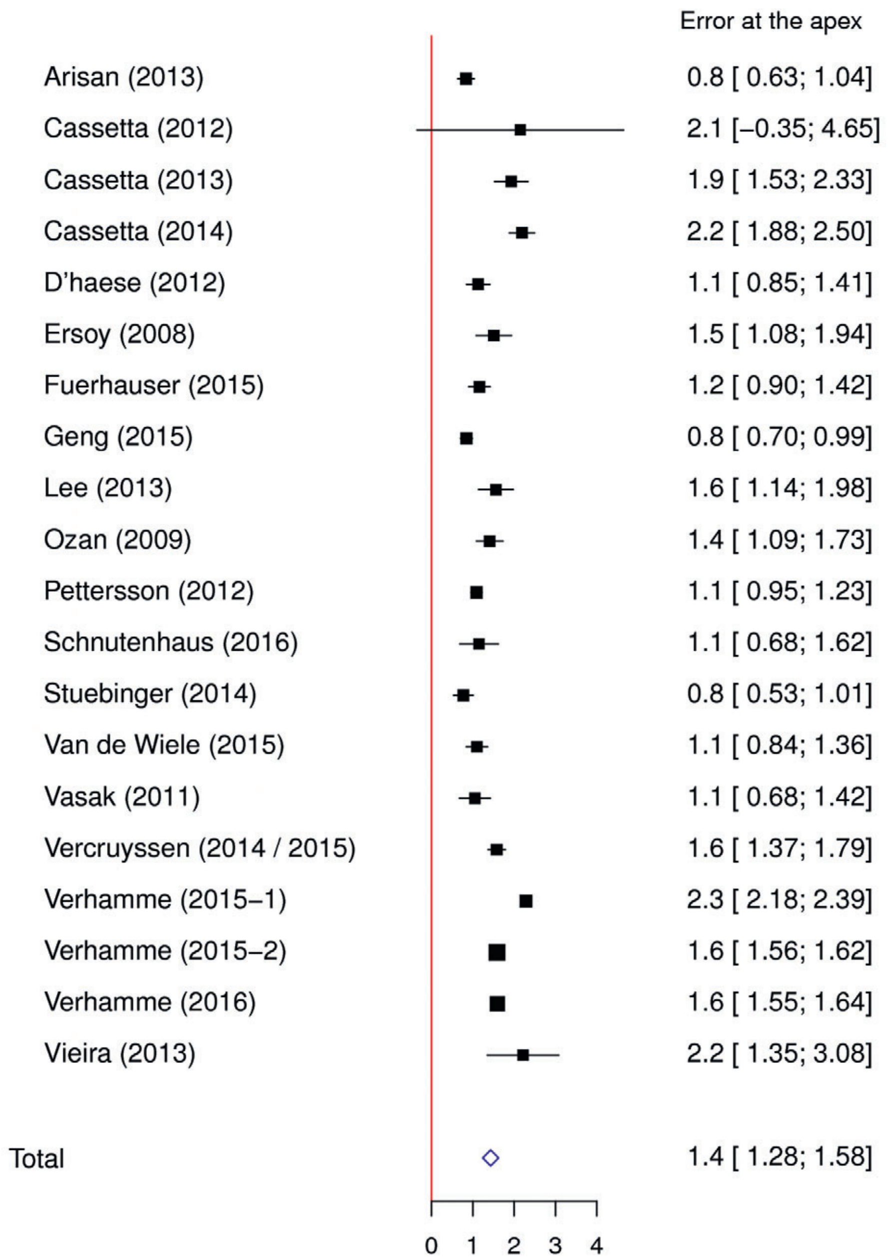

FIGURE 5 Forest plot demonstrating difference in error (mm) at the apical point between partially and fully edentulous patients

based on the mental memory or visualisation of the proposed position (Vercruyssen et al., 2014, 2015). Significantly greater variability in positional outcome was noted with this approach compared to both semiguided and guided placement.

A range of time intervals were reported from pre- to postimplant positional outcome analysis. One study performed comparison immediately after placement (Ozan, Turkyilmaz, Ersoy, McGlumphy & Rosenstiel, 2009) a further study performed analysis 10 days after implant placement (Vercruyssen et al., 2014, 2015) whilst another waited until 12 months after loading (Pettersson et al., 2012). It is quite possible that either implant abutment, or prosthesis connection, as part of immediate loading protocols, result in implant movement which is not yet osseointegrated. This effect on implant accuracy relative to the planned position has been acknowledged by D'haese et al. (2012). Future studies should seek to control this potential error more carefully.

The steps within the digital workflow sequence for guided surgery are summarised as follows: volumetric data acquisition, surface scanning procedures via intra-oral scanning or extra-oral model scanning, computer planning software, surgical guide fabrication via computer assisted milling (CAM) or 3-D printing.

In order to understand why positional errors occur for implants placed using a static guided surgical approach, the clinician must both recognise and understand the limitations within each step of the digital sequence.

From the outset, CT and CBCT volumetric data acquisition is the first potential source of error. The lower radiation dose and cost reported for CBCT compared to multislice computed tomography

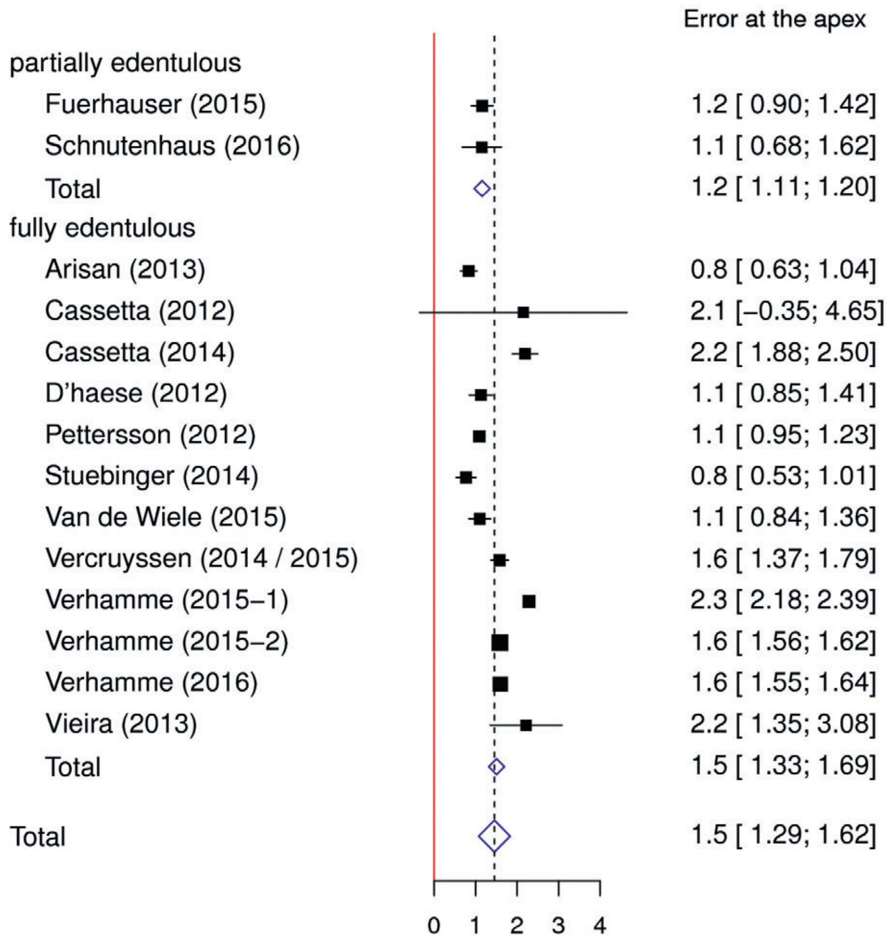

FIGURE 6 Forest plot demonstrating error (mm) at the apical point measured for all selected articles

(MSCT) are often thought to outweigh the reported disadvantages of poor soft tissue contrast with CBCT for imaging the maxillofacial region (Suomalainen, Esmaeili & Robinson, 2015). Although the linear measurements on CBCT images seem to be accurate, different parameters can influence the final results. Arisan and coworkers could not find statistically different outcomes comparing the use of CT and CBCT for planning (Arisan, Karabuda, Pişkin & Özdemir, 2013). Patient movements during the CBCT imaging process can cause image distortion and image quality degradation. Pettersson et al. showed that greater errors were found when patients moved during the CT scans compared to those that did not move (Pettersson et al., 2012). Their results demonstrated that movement resulted in a significant divergence at the level of the implant shoulder and apex. The presence of metallic restorations produces artefacts in CBCT which negatively effects image quality. Tadinada and coworkers concluded that these artefacts cause significant image degradation and often misrepresent the region of interest (Tadinada, Jalali, Jadhav, Schincaglia & Yadav, 2015). They recommend clinicians should be aware of the above limitations and understand these limitations along with normal CBCT anatomy to facilitate accurate evaluation.

Makins has also made similar statements based on their systematic review (Makins, 2014). The large number of papers included in this systematic review chose MSCT for both pre- and post-treatment implant position evaluation. The use of post-treatment imaging to precisely locate the implant position following static guided surgical placement itself represents a potential source of error, as data set segmentation and image cleaning must be performed carefully to achieve an image quality suitable enough to use for comparison. In addition, CBCT is often considered superior for producing high contrast resolution and allowing submillimetre resolution, allowing for a more accurate post-treatment implant position to be determined. Whilst these facts are known to affect imaging quality, there was insufficient data available within the current review to be able to make comparisons on the effect of the radiographic capturing technique on the outcome of guided surgery.

Surface scanning procedures allow for the capturing of soft and hard tissue intra-oral morphology. There has been a significant increase in the number of intraoral scanners (IOS) available to the clinician. Variability in IOS accuracy has been reported depending on the type of scanner used, the need to use powder application to coat the oral cavity surface and the scan acquisition sequence. Giménez et al. concluded in their study that the IOS operator affected the accuracy of measurements; however, the performance of the operator was not necessarily dependent on experience. The scanned distance affected the predictability of the scanner accuracy, and the error increased with the increased size of the scanned section (Giménez,

TABLE 6 All publication reporting on error at the apical point

Study	No of patients	No of implants
Arisan (2013)	11	102
Cassetta (2012)	11	95
Cassetta (2013)	20	227
Cassetta (2014)	28	225
D'haese (2012)	13	78
Ersoy (2008)	21	94
Fürhauser (2015)	27	27
Geng (2015)	24	111
Lee (2013)	48	102
Ozan (2009)	30	110
Pettersson (2012)	30	139
Schnutenhaus (2016)	24	24
Van de Wiele (2015)	16	75
Vasak (2011)	18	86
Vercruyssen (2014/2015)	59	311
Verhamme (2015-1)	25	150
Verhamme (2015-2)	30	104
Verhamme (2016)	12	72
Vieira (2013)	14	62
Total	461	2,194

Özcan, Martínez-Rus & Pradíes, 2015; Giménez, Pradíes, Martínez-Rus & Özcan, 2015).

In an unfortunate manner, IOS devices do not capture moveable soft tissue well. Extended edentulous or completely edentulous sites may, therefore, still require a conventional analog impression of the clinical situation which subsequently needs to be digitised. Errors can occur in the analog-to-digital conversion of a model. Whilst IOS devices are reported to be clinically efficient and highly accepted by clinicians, their precision decreases with an increasing distance between anatomical structures or implant scan bodies (Joda et al., 2017). The precision of desktop laboratory scanners is unaffected by increased distances between scan bodies, so their use is preferred for long span edentulous sites (Flügge, Att, Metzger & Nelson, 2016).

Implant planning software is used to merge the digital data sets from the radiographic and surface scanning procedures by aligning common regions on both data sets. Misalignment of the data sets may occur when there is an insufficient number of clearly identifiable common features. This can occur with metallic restorations which create artefacts or when CBCT or CT radiographs are performed with the teeth occluding. Segmentation of such radiographic data set can be complicated and compromised when such artefacts are present. Flügge and coworkers demonstrated that the mode of radiographic segmentation is highly significant for the accuracy of aligning and registering surface scan data when using a commercially available planning software (Flügge et al., 2017). They found manual segmentation of CBCT data sets was preferred to default segmentation, and the accuracy of the registration between the radiographic and surfaces scans is influenced by the presence of restorations and operator experience.

Implant manufacturers have designed the instrumentation for guided surgery such that prefabricated sleeves need to be inserted into the surgical guides. A drilling handle fits into these sleeves, ensuring that consecutive drills, with increasing diameter, can be used to prepare the surgical osteotomy. The level of tolerance between both the sleeves and drill handles, and the drill handles and drills, can cause additional inaccuracies (Cassetta, Di Mambro, Giansanti, Stefanelli & Cavallini, 2013; Cassetta, Giansanti, Di

TABLE 7 Publications specifically reporting on error at the apical point in separate groups, partial edentulous, full edentulous

Edentulism status	Study	No of patients	No of implants
Partially edentulous	Fürhauser (2015)	27	27
Partially edentulous	Schnutenhaus (2016)	24	24
Partially edentulous	Total	51	51
Fully edentulous	Arisan (2013)	11	102
Fully edentulous	Cassetta (2012)	11	95
Fully edentulous	Cassetta (2014)	28	225
Fully edentulous	D'haese (2012)	13	78
Fully edentulous	Pettersson (2012)	30	139
Fully edentulous	Van de Wiele (2015)	16	75
Fully edentulous	Vercruyssen (2014/2015)	59	311
Fully edentulous	Verhamme (2015-1)	25	150
Fully edentulous	Verhamme (2015-2)	30	104
Fully edentulous	Verhamme (2016)	12	72
Fully edentulous	Vieira (2013)	14	62
Fully edentulous	Total	249	1,413
Grand Total		300	1,464

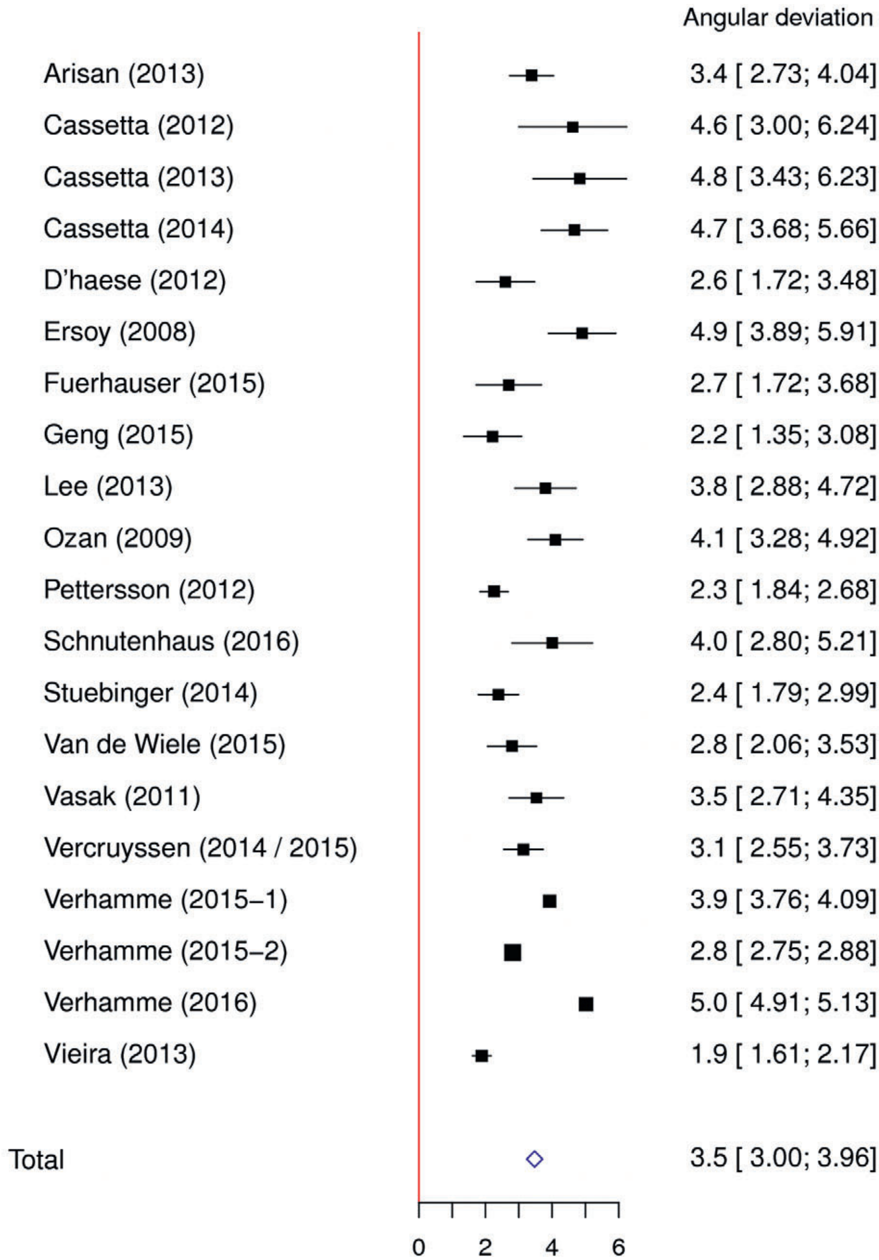

FIGURE 7 Forest plot demonstrating difference in angular error (°) between partially and fully edentulous patients

Mambro, Calasso & Barbato, 2013; Cassetta, Stefanelli, Giansanti, Di Mambro & Calasso, 2013). Schneider and coworkers, in their in vitro study, reported that the tolerance of surgical instruments and the lateral movements of the drills was significantly reduced by the use of 3-D printing with a reduced sleeve diameter (Schneider, Schober, Grohmann, Hammerle & Jung, 2015). This reduction could improve the overall accuracy in computer-assisted template-guided implant dentistry. The lateral movement of the drill can be further reduced using a shorter drill and a higher drill handle. The height and location of the sleeve must be carefully considered during implant planning and design of the surgical guide to reduce this error. One significant feature that is repeatedly highlighted was the need for adequate drill guide stabilisation during guided implant placement (Arisan et al., 2013; Cassetta et al., 2012; Cassetta, DiMambro et al., 2013; Cassetta, Giansanti et al., 2013; Cassetta, Stefanelli et al., 2013; D'haese et al., 2012; Geng, Liu, Su, Li & Zhou, 2015; Vercruyssen et al., 2015). Mucosa-supported guides were found in these studies to show micro-movement, even when multiple fixation pins were used. These authors suggested this could have contributed to inaccuracy (Cassetta, DiMambro et al., 2013; Cassetta, Giansanti et al., 2013; Cassetta, Stefanelli et al., 2013; D'haese et al., 2012).

This is in agreement with the results from a previous review by Tahmaseb and coworkers (Tahmaseb et al., 2014). The flexibility of the drill guides and lack of a physical control could be the cause of these irregularities. Tahmaseb et al. showed in a clinical trial that

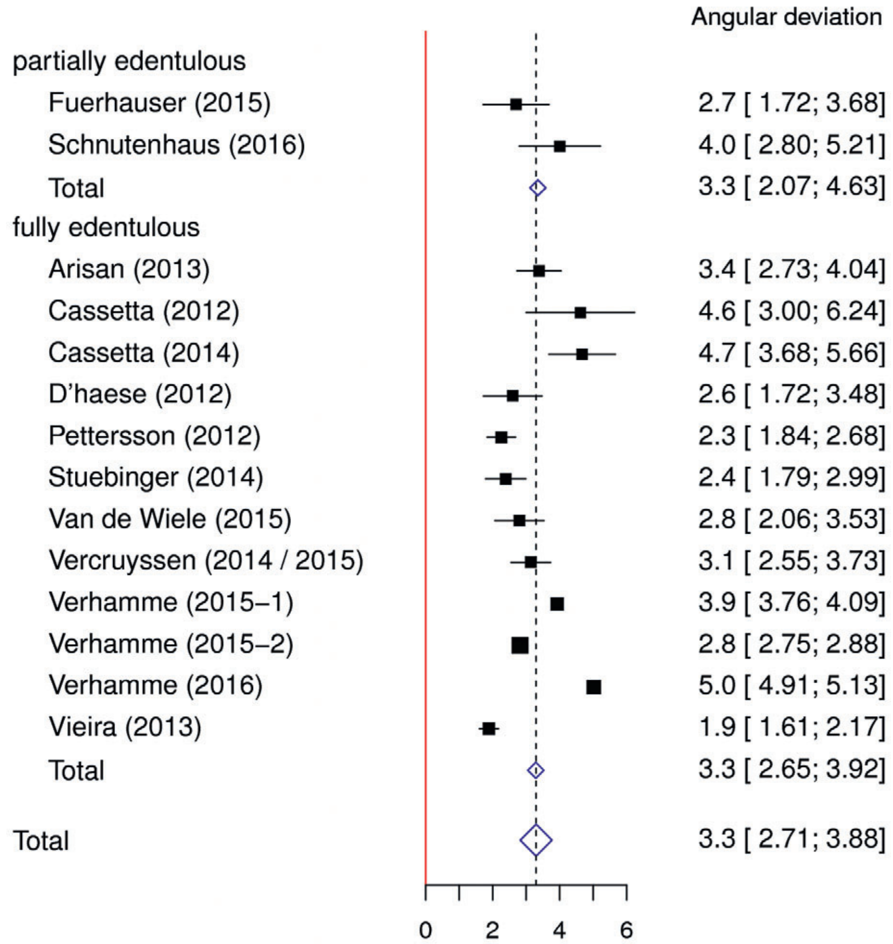

FIGURE 8 Forest plot demonstrating angular deviation (°) for all selected articles

using a novel pin device to control the vertical positioning of the implant can improve the accuracy to a level where prefabricated restoration could be inserted with an overall misfit which did not exceed 40 μm (Tahmaseb, De Clerck, Aartman & Wismeijer, 2012). Therefore, the final static drill guide design will have a significant effect on the final outcome accuracy.

Risk of bias is present in all studies where the follow-up implant position was assessed by CT or CBCT after actual implant placement. Beam hardening and radiographic artefacts create a potential source of error in comparing implant position. Arisan and coworkers noted that the CBCT images often required a manual tuning of greyscale and scatter noise deletion to allow accurate pre- and post-treatment assessment (Arisan et al., 2013). In addition, patient-related movement during scanning may also create errors in pre- and postimplant positional discrepancy. Pettersson et al. found that a large number of implants in their study needed to be removed from analysis as the rendering of the implant form in the postoperative CBCT was geometrically incorrect due to patient movements (Pettersson et al., 2012). Therefore, accurate comparisons could not be made. The number of fixation points for static guides varied between studies; some utilised three fixations screws, whilst others preferred to use 4.

The effect of smoking on mucosal thickness was evaluated by one group who found increases in tissue thickness had an effect on the accuracy (Cassetta, Stefanelli, Giansanti, Di Mambro & Calasso, 2011). Schnutenhaus et al. specified that if tissue thickness was greater than 3.5 mm a flap was raised to reduce the effect of flap thickness on the accuracy of outcome. Smoking habits were not exclusion criteria for patient enrolment within the studies (Schnutenhaus et al., 2016). In an interesting manner, some implants that were placed using a flap-less surgery protocol did not have a tissue punch procedure prior to drilling sequences (D'haese et al., 2012) As the early part of implant placement during guided surgery is unguided, the presence of thick dense tissue, which is not removed by tissue punches in a flapless approach, may alter the accuracy. Mucosal-supported guides also varied in the extent of tissue coverage. Local anaesthesia does also cause tissue swelling, which can affect the fitting and seating of a drilling guide, particularly if it is completely mucosally supported. Instability of the guides during early planning processes is also a further cause of inaccuracy (D'haese et al., 2012). Furthermore, implant abutment connection and tightening at the time of surgery for immediate loading may contribute to positional errors due to a lack of implant rotation stability.

TABLE 8 All publication reporting on angular deviation

Study	No of patients	No of implants
Arisan (2013)	11	102
Cassetta (2012)	11	95
Cassetta (2013)	20	227
Cassetta (2014)	28	225
D'haese (2012)	13	78
Ersoy (2008)	21	94
Fürhauser (2015)	27	27
Geng (2015)	24	111
Lee (2013)	48	102
Ozan (2009)	30	110
Pettersson (2012)	30	139
Schnutenhaus (2016)	24	24
Van de Wiele (2015)	16	75
Vasak (2011)	18	86
Vercruyssen (2014/2015)	59	311
Verhamme (2015-1)	25	150
Verhamme (2015-2)	30	104
Verhamme (2016)	12	72
Vieira (2013)	14	62
Total	461	2,194

The technique for radiographic data set segmentation varied considerably and was not reported in one study (D'haese et al., 2012). In addition, standardisation of the gantry angle is not known for many studies (Ersoy, Turkyilmaz, Ozan & McGlumphy, 2008). Few studies also specified the height of the guiding sleeves creating a possible error for alignment (Schnutenhaus et al., 2016). No studies prescribed an evaluation method of template fit prior to surgery nor an assessment of guide sleeve fit into the SLA produced guide. Implant diameter and length was not specified for every study.

The authors acknowledge that this systematic review is limited by the lack of homogeneity of study designs within the publications included for review. Many different surgical factors and techniques were not standardised between the studies, which serves to confound the true accuracy of guided surgery. In addition, there are many steps within the digital workflow itself, where there is a possibility of accumulating error, which also serves to mask the real accuracy of the technique. The reliance on radiographic techniques alone for comparing pre- and post-treatment positions is also considered another source of potential error and future investigations should seek to use alternative comparison methods. Furthermore, very few of the studies have focussed on the value of guided surgery in realising the intended prosthetic plan or the outcome of the final aesthetics. Whilst these limitations are acknowledged, there is a trend towards greater accuracy with a digital workflow. Also the

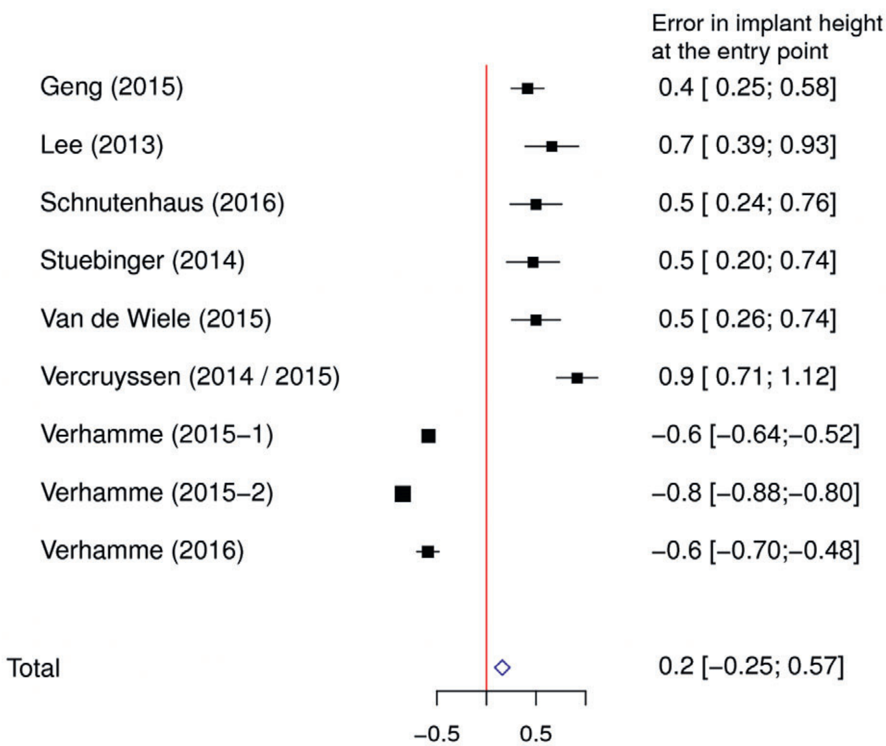

FIGURE 9 The forest plot demonstrating error (mm) in implant height at the entry point in all selected publications

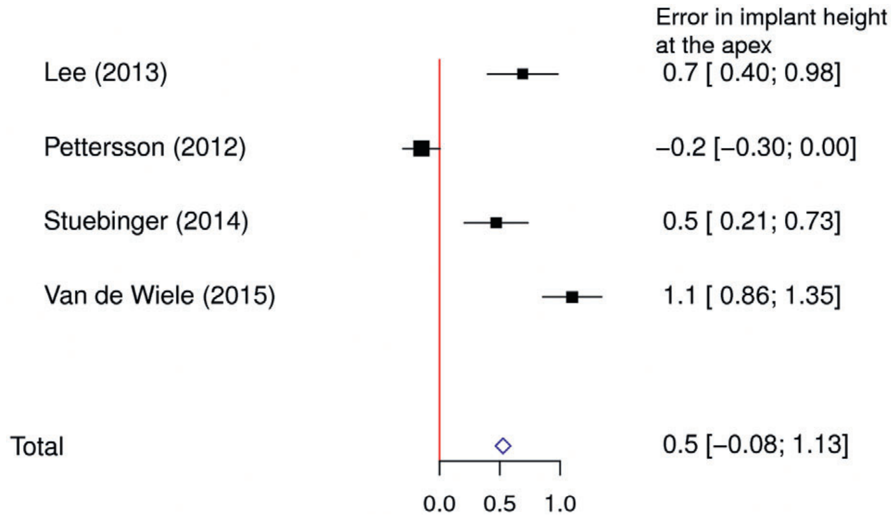

FIGURE 10 The forest plot demonstrating error in implant height (mm) at the apical point in all selected publications

TABLE 9 Publications specifically reporting on angular deviation in separate groups, partial edentulous, full edentulous

Edentulism status	Study	No of patients	No of implants
Partially edentulous	Füerhauser (2015)	27	27
Partially edentulous	Schnutenhaus (2016)	24	24
Partially edentulous	Total	51	51
Fully edentulous	Arisan (2013)	11	102
Fully edentulous	Cassetta (2012)	11	95
Fully edentulous	Cassetta (2014)	28	225
Fully edentulous	D'haese (2012)	13	78
Fully edentulous	Pettersson (2012)	30	139
Fully edentulous	Van de Wiele (2015)	16	75
Fully edentulous	Vercruyssen (2014/2015)	59	311
Fully edentulous	Verhamme (2015-1)	25	150
Fully edentulous	Verhamme (2015-2)	30	104
Fully edentulous	Verhamme (2016)	12	72
Fully edentulous	Vieira (2013)	14	62
Fully edentulous	Total	249	1,413
Grand Total		300	1,464

authors decided to review only the publications in the English language, which might result in missing information published in other languages.

5 | CONCLUSIONS

Based on the present systematic review, it can be concluded that the accuracy of static computer-aided implant surgery (s-CAIS) is within the clinical acceptable range in the majority of clinical situations. However, a safety marge of at least 2 mm should be respected. A lack of homogeneity was found in techniques adopted between the different authors and the general study designs. Better accuracy was found when partially edentulous patients were treated compared to fully edentulous patients. As a large number of factors can contribute to deviations of the actual implant position from the planned, further studies are required to investigate these factors.

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SUPPORTING INFORMATION

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