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Systematic Review
Dental Implants

Comparison of dynamic navigation systems in dental implantology: a systematic literature review of in vitro studies

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Abstract. Dynamic navigation is an innovative technology in implant surgery that enhances the precision of implant placement through real-time guidance for clinicians. This technology allows on-the-spot adjustments during surgery, reducing the risk of complications and improving implant outcomes. The aim of this systematic review was to assess the accuracy of various dynamic navigation systems in implant placement using in vitro models. A comprehensive literature search was performed across several databases, focusing on studies published between 2016 and 2024 that reported three-dimensional (3D) and angular deviations. Seven in vitro studies were included, analysing five dynamic navigation systems (ImplaNav, Navident, Denacam, X-Guide, and DCARER), with 649 implants evaluated. Results showed mean coronal 3D deviations between 0.46 mm and 1.58 mm, while apical deviations ranged from 0.48 mm to 2.12 mm. Angular deviations varied between 1.01° and 4.24°. Maximum deviations reached up to 4.80 mm for coronal 3D deviation and 10.70° for angular deviation. All systems demonstrated high accuracy within clinically acceptable limits, with X-Guide showing the lowest numerical errors. Factors like tracking technology, calibration methods, and user experience were found to influence accuracy. Overall, dynamic navigation significantly improves implant placement accuracy compared to freehand methods but remains dependent on technical factors.

Keywords: Dental implants; Computer-assisted surgery; Image-guided surgery; Surgical navigation systems; Dental models; Systematic review.

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In contemporary dentistry, dental implants have become a widely favoured approach for replacing missing teeth, gaining notable popularity among clinicians[1]. This popularity is attributed to their long-term success, stability, aesthetic results, and relatively brief procedure duration[2]. While the success of dental implants is commonly defined as the 'survival' of a functional implant, both scientific research and clinical practice acknowledge various mechanical and biological complications that can arise in both the early and late stages of dental implantation[3]. Furthermore, achieving successful outcomes in dental implant treatment necessitates a comprehensive understanding of the various factors influencing implant success. The introduction of guided implant placement has revolutionized the field of implant dentistry, leading to significant improvements in accuracy and greater predictability in prosthetic outcomes[4]. Currently, there are two established guided surgery protocols in dentistry: static and dynamic[5].

The development of the guiding technique was made possible by the advent of cone beam computed tomography (CBCT)[6]. The ability to conduct three-dimensional (3D) spatial evaluations of bone topography and critical anatomical structures has enabled the creation of surgical templates (guides) to achieve precise implant positioning, thereby minimizing the risk of intraoperative and postoperative complications[7]. Static guided surgery is facilitated by CBCT scanning, intraoral scanning (IOS), and computer-aided design/computer-aided manufacturing (CAD/CAM) milling or 3D printing[8]. Since implant placement planning requires detailed dental and mucosal surface information, the intraoral scan integrates the surface image with CBCT data, which is then used to model prosthetic structures and determine implant positions[9].

Dynamic guided surgery, also known as dynamic navigation, represents a cutting-edge technology used for the guidance of implant placement. This technique tracks the movements of the clinician's instrument and the patient's jaw position in real time[10]. A virtual plan is created based on CBCT and IOS data, and the exact angle and position of the drill are tracked and displayed on a monitor alongside a digital image of the bone volume (CBCT) and implant plan. As the drill tip nears the preplanned implant location, the system provides cross-sectional imaging, allowing the surgeon to monitor the precise implant positioning[1]. During navigation, a registration procedure is employed to align the multi-coordinate frame of the tracker, handpiece, patient marker, and preoperative CBCT dataset[11]. Currently, the two primary registration methods in dynamic navigation systems are feature point-based registration and marker point-based registration. The mechanisms behind these methods differ: feature point-based registration relies on anatomical features of teeth and feature points of preoperative CBCT images, while marker point-based registration uses the fiducial marker plate of the navigation system[12].

Furthermore, infrared dynamic navigation systems offer two methods for tracking surgical instruments, depending on whether the instruments emit light or merely reflect it[12]. The first method, active optical tracking, utilizes infrared cameras to detect light-emitting diodes (LEDs) for device tracking. The second method, passive optical tracking, involves illumination that emits light, and a camera captures the light reflected by retroreflective markers attached to the device[13,14]. Unlike the LED in active tracking systems, passive retroreflective markers do not emit light but instead reflect infrared camera light. While both navigation methods can enhance the precision of oral implant surgery, the active dynamic navigation system combined with a marker point-based registration method should be prioritized for complex implant surgeries to improve clinical efficiency, long-term survival rates, and accuracy[12].

Given the challenges posed by anatomical complexity, large bony defects, and human error in dental implantation, dynamic navigation technology has gained widespread acceptance in recent years due to its high precision and ability to minimize complications[15]. A retrospective study by McDermott et al.[10] found an overall complication rate of 13.9%. Complications such as nerve damage, sinus insertion, periodontal ligament injury to adjacent teeth, and cortical perforation may occur during dental implantation. A meta-analysis conducted by Burstein et al.[16] indicates that the incidence of mandibular nerve injury during implant placement ranges from 0% to 13%. To address these challenges, dynamic computer-aided implant surgery (dCAIS) has recently been introduced into dental implantology concepts. dCAIS aims to minimize deviations from the pre-planned implant placement by allowing real-time adjustments and updates to the treatment plan during the surgery[17]. Moreover, dynamic navigation provides a wide field of visibility during implant placement, ensuring that the procedure remains easily controllable[18].

Although dynamic navigation is a relatively new technology, a diverse range of navigation systems with distinct technological features are currently used in clinical practice[19]. This diversity presents challenges for clinicians in selecting the most appropriate system. Furthermore, a substantial amount of research exists on the accuracy of the methodology, involving various patient samples and clinical aspects that affect outcomes. This diversity complicates the objective comparison of these systems. Consequently, image-based technologies are rapidly transitioning from research settings to clinical use, despite the limited generalized information about outcomes from model-based trials. By synthesizing in vitro studies, the review assesses the reliability and precision of dynamic navigation systems under various experimental conditions, distinct from clinical settings.

Since studies comparing dynamic navigation systems are not widely published, the objective of this review was to summarize the literature and assess the accuracy of implant position (including coronal, apical, 3D, lateral, depth, and angular deviations) within model studies assessing various dynamic navigation systems.

Materials and methods

Eligibility criteria and data items

The following question was formulated for this systematic literature review: Which dynamic navigation system is more accurate for implant placement in partially or fully edentulous in vitro models? In this literature review, the problem refers to partially or fully edentulous models; the intervention is the preparation of the implant site and the insertion of the implant using dynamic navigation; the comparison represents the planned versus the actual implant position; the outcome measures the accuracy of the dynamic navigation (including 3D, lateral, depth, and angular deviations); and the type of study refers to in vitro model studies.

This systematic review of the scientific literature was prepared in accordance with the PRISMA requirements (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)[20]. Articles were searched by one independent researcher (K.M.).

The following inclusion criteria were applied: (1) type of publication: in vitro studies; (2) study sample of at least 10 implants; (3) computed tomography (CT) scan performed to assess accuracy; (4) the results (3D and angular deviations) are clearly stated in the study; (5) the article must be written in English; (6) the article must be relevant to the topic.

Exclusion criteria were (1) literature reviews or meta-analyses, single clinical case studies, lectures, and letters; (2) in vivo studies; (3) articles investigating zygomatic, pterygoid, and orthodontic implants; (4) studies investigating static guided surgery; (5) publications older than 10 years; (6) articles not written in English.

Electronic data search strategy and selection of studies

For the systematic review of the literature, articles were searched in the electronic databases MEDLINE (PubMed), Embase (ScienceDirect), Cochrane Central Register of Controlled Trials (Cochrane Library), Springer Link, and Google Scholar. A structured search of these databases was performed, without time or other restrictions, to answer the question: Which dynamic navigation system is more accurate for implant placement in partially or fully edentulous in vitro models?

The selection of articles was started on July 5, 2022. The last search was performed on March 14, 2024. The search strategy used in PubMed was as follows: "Dental implant" [MeSH Terms] OR "Dental implantation" [MeSH Terms] AND "In vitro" [MeSH Terms] AND "Image guided surgery" [MeSH Terms] OR "Dynamic navigation" OR "Computer-aided navigation" OR "Surgical navigation systems".

Quality assessment

The quality of the selected studies was evaluated individually using the Quality Assessment Tool for In Vitro Studies (QUIN Tool). Twelve criteria were taken into account: clearly defined aims/objectives, a comprehensive explanation of the sample size calculation, a detailed description of the sampling technique, information about the comparison group, a thorough explanation of the methodology, details regarding the operators, randomization, methods of measuring outcomes, information about outcome assessors, blinding, the statistical analysis, and presentation of the results[21]. Each criterion is rated as adequately specified (score 2), not adequately specified (score 1), not specified (score 0), or not applicable (NA). The scores from the 12 criteria are then summed (total score) and used to determine the final score for each study, using the following formula: Final Score (%) = [(Total Score)/(2 × Number of Applicable Criteria)] × 100. The final score is used to classify each study as having a high, medium, or low risk of bias according to the following thresholds: > 70% = low risk of bias, 50–70% = medium risk of bias, and < 50% = high risk of bias.

Results

Selection of studies

The initial search identified 183 articles. The selection strategy is shown in Fig. 1. After removing duplicates, 123 articles were screened by title and abstract. Following this stage, 43 articles were selected for full-text reading, of which seven were finally considered eligible for inclusion in this systematic review[5,11,19,22–25]; these studies evaluated accuracy for 649 implants.

Quality assessment

The risk of bias was assessed as high in one study, medium in two studies, and low in four studies. Detailed results of the risk of bias assessment using the QUIN Tool are given in Supplementary material Table S1.

Study characteristics

The characteristics of the studies included in this review are presented in Table 1. Table 2 summarizes the key differences and similarities among the five dynamic navigation systems employed in these studies, focusing on the components and features that influence their clinical performance. A summary of the main results of the studies is provided in Table 3.

All included articles reported in vitro model studies; they were published between 2016 and 2023. The five dynamic navigation systems examined in these studies were ImplaNav (BresMedical, Sydney, Australia), Navident (ClaroNav Technology Inc., Toronto, Canada), Denacam (Mininavident AG, Liestal, Switzerland), X-Guide (X-Nav Technologies, LLC, Lansdale, PA, USA), and DCARER (Yizhime; Suzhou Digital-Health Care Co., Suzhou, China)[5,11,19,22–25]. Three studies assessed the accuracy of dynamic navigation during implant placement among surgeons with varying levels of experience[19,22,24]. Two of these studies compared implantation with dynamic navigation and freehand techniques[22,24]. Two other studies aimed to compare the accuracy of implant positioning with dynamic and static guided implantation[5,23]. One study assessed two different dynamic navigation system registration methods[11], while one assessed a single dynamic navigation system, with no comparison group[25]. Fully edentulous or partially edentulous models were used; two studies used maxilla models[5,19], four studies used mandible models[11,22–24], and one study used both maxilla and mandible models[25]. The implants were inserted after CT and virtual planning. Postoperative CT scans were aligned with the planning data to assess deviations of the actual implant position from the planned position.

The key findings presented in the tables are discussed in detail and compared with previous studies in the Discussion section.

Discussion

This review assessed the accuracy of dynamic navigation (deviations between planned and realized implant positions) in studies using in vitro models, with a focus on 3D, depth, and lateral coronal and apical deviations, and the angular deviation (Fig. 2).

The findings indicate that dynamic navigation techniques can effectively transfer the preoperative virtual implant plan to the jaw with high accuracy[26,27]. Specifically, the mean coronal 3D deviation ranged from 0.46 ± 0.20 mm to 1.58 ± 0.80 mm, while the mean apical 3D deviation ranged from 0.48 ± 0.21 mm to 2.12 ± 0.94 mm. Coronal depth deviation, analysed in four studies, ranged from 0.26 ± 0.19 mm to 0.78 ± 0.49 mm, while the mean apical depth deviation, assessed in six studies, ranged from 0.25 ± 0.19 mm to 0.88 ± 0.47 mm. Coronal lateral deviation, examined in five studies, varied from 0.33 ± 0.19 mm to 1.23 ± 0.81 mm, and the mean apical lateral deviation, analysed in four studies, from 0.36 ± 0.20 mm to 1.23 ± 0.81 mm. The mean values of angular deviation were between 1.01° ± 0.57° and 4.24° ± 2.52°. These mean deviations are considered within acceptable limits, in the dental implantology

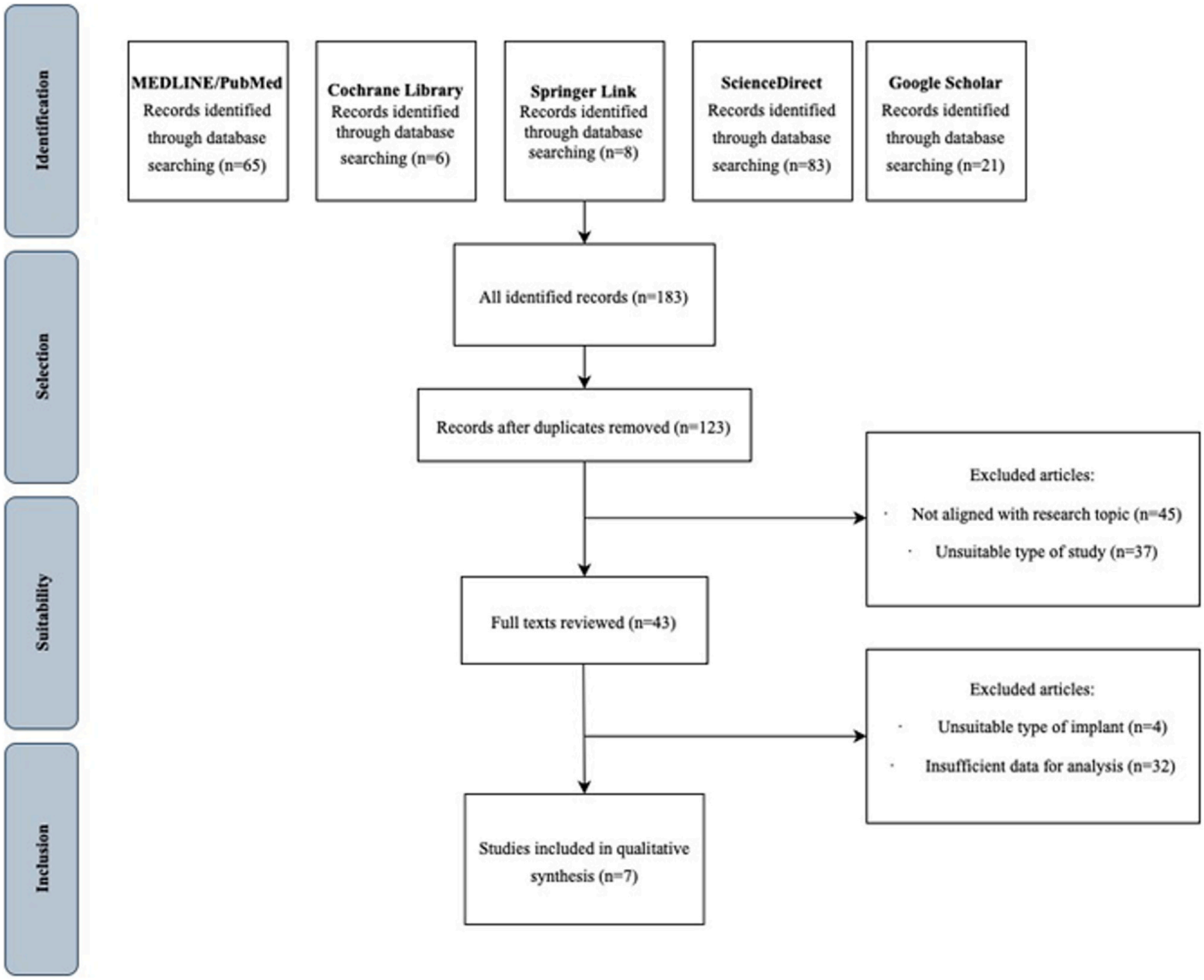

Fig. 1. Flow diagram of the search and selection process.

recommended safety zone. However, it is crucial to bear in mind the maximum deviation value to assess the risk of damage to important anatomical structures[17]. Based on the data from the reviewed studies, the maximum errors described were as follows: the maximum coronal 3D deviation ranged from 0.92 mm to 4.80 mm, apical 3D deviation ranged from 1.01 mm to 4.92 mm, coronal depth deviation ranged from 0.91 mm to 3.13 mm, apical depth deviation ranged from 0.96 mm to 3.09 mm, and angular deviation ranged from 2.47° to 10.70°.

Three studies compared implant positioning among clinicians of different experience levels[19,22,24]. Pellegrino et al.[19] reported no statistically significant difference among the four operators for the dynamic navigation system (coronal deviation, $P = 0.27$; apical deviation, $P = 0.06$). The variables showed a normal distribution (Shapiro–Wilk test, P-values > 0.05), and Levene's test indicated equal variance among groups ($P > 0.05$). Wang et al.[24] found that novice practitioners achieved comparable accuracy and confidence to experienced practitioners using the navigation approach, unlike freehand and static-guided methods. Furthermore, experienced practitioners showed slightly higher angular deviations across all approaches, but without any significant difference. Differences in entry two-dimensional (2D) deviation, apex 3D deviation, and vertical apex deviation were also not significant based on the approach, experience, or their interaction ($P > 0.05$). However, the novices took significantly longer with the navigation approach compared to the experienced practitioners. Similarly, Wu et al.[28] and Sun et al.[29] found that practitioner experience did not significantly impact accuracy with the navigation approach. Conversely, Jorba-García et al.[22] reported notable differences in deviations between the novice and experienced professionals for the freehand method, but similar deviations for the implants placed with the navigation system. They reported that dynamic navigation enhanced accuracy, particularly for novices, although they did not directly compare the accuracy between the skilled and inexperienced operators.

The most recent similar systematic literature review, on the accuracy of dynamic computer-aided implant placement by Jorba-Gracía et al.[17], was published in 2021. This previous systematic review and meta-analysis compared dynamic navigation systems to static protocol surgery. In vitro studies reported lower deviation values, including 2.01° for mean angular deviation, 0.8 mm for lateral coronal deviation, 0.46 mm for 3D coronal deviation, 0.97 mm for lateral apical

Table 1. Study characteristics and reported results.

Study	Sample size, implants	DN system	Specimens
Pellegrino et al.[19] 2020 (Italy)	112	ImplaNav (BresMedical)	Extra-hard plaster fully edentulous maxilla models
Jorba-García et al.[22] 2019 (Spain)	18	Navident (ClaroNav)	Partially edentulous mandible models (first and second premolar and first molar)
Mediavilla Guzmán et al.[5] 2019 (Spain)	20	Navident (ClaroNav)	Standardized polyurethane models of partially edentulous upper jaws (tooth positions 24, 26)
Struwe et al.[23] 2023 (Switzerland)	180[a]	Denacam system (Mininavident AG)	Polyurethane mandibular models (tooth positions 34, 33, 43, 44, 45)
Emery et al.[25] 2016 (USA)	231	X-Guide (X-Nav Technologies)	Four types (dentate and edentulous maxilla, dentate and edentulous mandible) of custom polyurethane Sawbones models
Wang et al.[24] 2022 (Belgium)	24[b]	X-Guide (X-Nav Technologies)	Acrylic-based resin mandibular models (tooth positions 36, 46)
Wei et al.[11] 2023 (China)	64[c]	*DCARER* (Yizhime)	Resin mandible models (tooth positions 35, 36, 37, 47)

Study	Outcome measure	DN technique results, mean ± SD
Pellegrino et al.[19] 2020 (Italy)	Coronal V–L deviation	0.74 ± 0.53 mm
	Coronal M–D deviation	0.87 ± 0.65 mm
	Coronal depth deviation	0.75 ± 0.74 mm
	3D coronal deviation	1.58 ± 0.80 mm
	Apical V–L deviation	0.78 ± 0.58 mm
	Apical M–D deviation	0.84 ± 0.64 mm
	Apical depth deviation	0.70 ± 0.67 mm
	3D apical deviation	1.61 ± 0.75 mm
	Angular deviation	4.24° ± 2.52°
Jorba-García et al.[22] 2019 (Spain)	Entry 3D	1.29 ± 0.46 mm
	Entry 2D	0.85 ± 0.41 mm
	Apex 3D	1.33 ± 0.5 mm
	Apex vertical	0.88 ± 0.47 mm
	Angulation	1.6° ± 1.3°
Mediavilla Guzmán et al.[5] 2019 (Spain)	Apical level	1.18 ± 0.60 mm
	Coronal level	0.85 ± 0.48 mm
	Angular level	4.00° ± 1.41°
Struwe et al.[23] 2023 (Switzerland)	Bucco-oral deviation at implant tip	0.58 ± 0.52/1.22 ± 0.8 mm
	Bucco-oral deviation at implant base	0.6 ± 0.49/1.23 ± 0.81 mm
	Mesial–distal deviation at implant tip	0.74 ± 0.84/0.49 ± 0.30 mm
	Mesial–distal deviation at implant base	0.63 ± 0.83/0.41 ± 0.30 mm
	Apical–coronal deviation at implant tip	0.62 ± 0.48/0.46 ± 0.38 mm
	Apical–coronal deviation at implant base	0.62 ± 0.48/0.45 ± 0.38 mm
	3D deviation at implant tip	1.31 ± 0.89/1.51 ± 0.73 mm
	3D deviation at implant base	1.26 ± 0.87/1.49 ± 0.74 mm
	Angular deviation	2.26° ± 1.87°/2.72° ± 1.72°
Emery et al.[25] 2016 (USA)	Angular deviation	1.09° ± 0.55°
	Entry global deviation	0.46 ± 0.20 mm
	Entry depth deviation	0.26 ± 0.19 mm
	Entry lateral deviation	0.33 ± 0.19 mm
	Apex global deviation	0.48 ± 0.21 mm
	Apex depth deviation	0.25 ± 0.19 mm
	Apex lateral deviation	0.36 ± 0.20 mm
Wang et al.[24] 2022 (Belgium)	Entry 2D deviation (horizontal drilling point deviation)	1.09 ± 0.41/1.14 ± 0.46 mm
	Apex 3D deviation (3D deviation at implant apex location)	1.55 ± 0.56/1.76 ± 0.71 mm
	Apex (V) deviation (vertical depth deviation)	0.44 ± 0.55/0.70 ± 0.58 mm
	Angular deviation	3.37° ± 1.56°/ 3.19° ± 1.89°
Wei et al.[11] 2023 (China)	Angular deviation	1.17° ± 0.47°/ 1.01° ± 0.57°
	Entry deviation (3D deviation)	1.23 ± 0.52/1.12 ± 0.56 mm
	Apex deviation (3D deviation)	2.12 ± 0.94/1.82 ± 1.00 mm
	Entry horizontal deviation	0.55 ± 0.34/0.61 ± 0.38 mm
	Apex horizontal deviation	0.74 ± 0.41/0.91 ± 0.44 mm
	Entry depth deviation	0.78 ± 0.49/0.68 ± 0.58 mm
	Apex depth deviation.	0.79 ± 0.49/0.71 ± 0.66 mm

2D, two-dimensional; 3D, three-dimensional; DN, dynamic navigation; M–D, mesial–distal vector; SD, standard deviation; V–L, bucco-lingual vector.

[a]Two groups of 90: one group with the marker in the CBCT, the other with a 3D-printed marker.

[b]Two groups: 12 experienced practitioners and 12 novice practitioners.

[c]Two groups of 32, with different methods of registration.

Table 2. Technical details of the dynamic navigation (DN) systems.

DN system	Technology	Handpiece	Markers
ImplaNav (BresMedical)	Optical tracking with infrared cameras	Standard implant handpiece with attached reflective marker	Reflective markers attached to patient and handpiece
Navident (ClaroNav)	Optical tracking with dual infrared cameras	Standard implant handpiece with X-Clip (reflective markers)	Reflective markers attached to patient and handpiece
Denacam system (Mininavident AG)	Optical tracking with single overhead camera	Standard implant handpiece with reflective markers	Reflective markers attached to patient and handpiece
X-Guide (X-Nav Technologies)	Magnetic tracking system	Handpiece with embedded magnetic sensors	Magnetic sensors embedded in stent or patient
DCARER (Yizhime)	Optical tracking with infrared cameras	Standard implant handpiece with attached reflective marker	Reflective markers attached to patient and handpiece

DN system	Camera/tracking system	Setup, calibration	Accuracy
ImplaNav (BresMedical)	Single infrared optical tracking camera	Requires calibration with reflective markers	High precision, within 0.5 mm of planned position
Navident (ClaroNav)	Dual infrared optical tracking cameras	Quick calibration using X-Clip	High precision, within 0.5 mm of planned position
Denacam system (Mininavident AG)	Single overhead optical tracking camera	Requires calibration, more sensitive to occlusions	High precision, but slightly less consistent
X-Guide (X-Nav Technologies)	Magnetic field generator (no camera needed)	Less frequent calibration, no line-of-sight issues	High precision, affected by nearby metal objects
DCARER (Yizhime)	Single infrared optical tracking camera	Standard calibration with reflective markers	High precision, within 0.5 mm of planned position

DN system	Ease of use	Special features	Clinical applications
ImplaNav (BresMedical)	User-friendly, requires careful marker placement	Compatible with partially/fully edentulous cases	Flapless surgery; Insertion of angled or zygomatic implants; Surgeries in atrophic sites and cases requiring guided bone regeneration
Navident (ClaroNav)	Slightly complex setup, but offers 360° visualization	360-degree visualization with X-Point system	Placement of dental implants; Guided endodontics; Piezotome bone surgeries
Denacam system (Mininavident AG)	More complex due to overhead camera setup	Cost-effective with basic features	Implant placement; Bone surgery and augmentation; Enables precise navigation for root canal treatments; Facilitates the removal of impacted teeth
X-Guide (X-Nav Technologies)	Easier setup, no occlusion concerns	No line-of-sight issues due to magnetic tracking	Facilitates controlled and accurate sinus lift procedures; Guided bone regeneration; Allows for on-the-spot adjustments during implant placement
DCARER (Yizhime)	Straightforward setup, but careful marker placement required	Cost-effective, compatible with various implant systems	Implant placement; Assist in navigating to the exact location of the root canal; Can be used to plan and execute precise orthodontic interventions, such as the placement of orthodontic anchors and adjustments based on real-time feedback; For procedures involving the treatment of gum diseases, can help in the precise removal of diseased tissue and placement of regenerative materials; It aids in the accurate placement and alignment of prosthetic components, ensuring that crowns, bridges, and dentures fit well and function correctly; Can guide the placement of graft materials with high precision, enhancing the success of the procedure

deviation, 0.81 mm for 3D apical deviation, 0.61 mm for depth apical deviation, and 0.76 mm for depth coronal deviation. The maximum deviations were 2.07° for angular deviation, 0.83 mm for lateral coronal deviation, 0.48 mm for 3D coronal deviation, 1.01 mm for lateral apical deviation, 0.83 mm for 3D apical deviation, 0.64 mm for depth apical deviation, and 0.84 mm for depth coronal deviation. The authors concluded that there was no significant difference between the dynamic navigation systems and that these systems were more accurate than the static guide protocol[17].

Regarding clinical studies, Block et al.[30] concluded that the dynamic

Table 3. Results of the studies; mean ± standard deviation and maximum values (maximum values are shown in brackets).

Deviation	ImplaNav (BresMedical) Pellegrino et al.[19]	Navident (ClaroNav) Jorba-García et al.[22]	Navident (ClaroNav) Mediavilla Guzmán et al.[5]	Denacam system (Mininavident AG) Struwe et al.[23]
Coronal (mm)				
3D	1.58 ± 0.80	1.29 ± 0.46	0.85 ± 0.48 (1.90)	1.31 ± 0.89 (4.8)/1.51 ± 0.73 (3.36)
Depth	0.75 ± 0.74	-	-	0.62 ± 0.48 (3.13)/0.46 ± 0.38 (1.94)
Lateral	0.74 ± 0.53	-	-	0.58 ± 0.52 (2.21)/1.22 ± 0.8 (3.23)
	0.87 ± 0.65			0.74 ± 0.84 (4.85)/0.49 ± 0.30 (1.68)
Apical (mm)				
3D	1.61 ± 0.75	1.33 ± 0.5	1.18 ± 0.60 (2.50)	1.26 ± 0.87 (4.92)/1.49 ± 0.74 (3.69)
Depth	0.70 ± 0.67	0.88 ± 0.47	-	0.62 ± 0.48 (3.09)/0.45 ± 0.38 (1.94)
Lateral	0.78 ± 0.58	-	-	0.6 ± 0.49 (2.00)/1.23 ± 0.81 (3.54)
	0.84 ± 0.64			0.63 ± 0.83 (4.82)/0.41 ± 0.30 (1.22)
Angular (°)	4.24 ± 2.52	1.6 ± 1.3	4.00 ± 1.41 (6.10)	2.26 ± 1.87 (10.70)/2.72 ± 1.72 (8.50)

Deviation	X-Guide (X-Nav Technologies) Emery et al.[25]	X-Guide (X-Nav Technologies) Wang et al.[24]	*DCARER* (Yizhime) Wei et al.[11]
Coronal (mm)			
3D	0.46 ± 0.20 (0.92)	-	1.23 ± 0.52/1.12 ± 0.56
Depth	0.26 ± 0.19 (0.91)	-	0.78 ± 0.49/0.68 ± 0.58
Lateral	0.33 ± 0.19 (0.83)	1.09 ± 0.41 (1.67)/1.14 ± 0.46 (2.02)	0.55 ± 0.34/0.61 ± 0.38
Apical (mm)			
3D	0.48 ± 0.21 (1.01)	1.55 ± 0.56 (2.77)/1.76 ± 0.71 (2.75)	2.12 ± 0.94/1.82 ± 1.00
Depth	0.25 ± 0.19 (0.96)	0.44 ± 0.55 (1.96)/0.70 ± 0.58 (2.2)	0.79 ± 0.49/0.71 ± 0.66
Lateral	0.36 ± 0.20 (0.91)	-	0.74 ± 0.41/0.91 ± 0.44
Angular (°)	1.09 ± 0.55 (2.47)	3.37 ± 1.56 (6.68)/3.19 ± 1.89 (6.54)	1.17 ± 0.47/1.01 ± 0.57

navigation method (X-Guide, X-Nav Technologies) improved the accuracy and precision of implant placement when compared to freehand placement. On the other hand, in a systematic review by Vinnakota et al.[31], it was reported that dynamic computer-assisted implant placement may not be superior to the static methods in the clinical scenario. Consequently, their null hypothesis that no significant difference exists between dynamic and static methods for implant placement deviations was not rejected.

In a systematic review by Jonaityte et al.[32], dynamic navigation, initially introduced for endodontic treatment, was shown to increase the accuracy in root canal therapy when compared to the freehand technique. However, the authors stated that further well-designed clinical trials were required to confirm the findings.

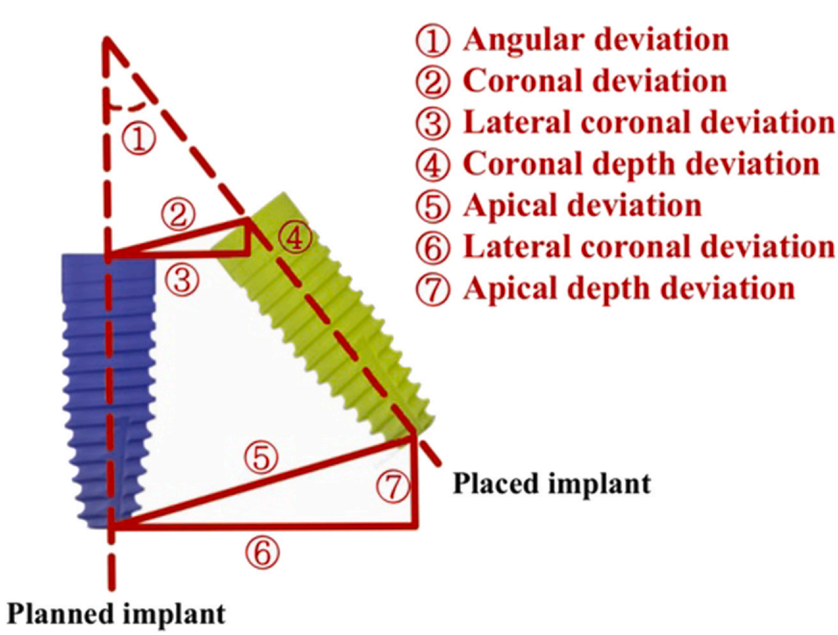

Fig. 2. Parameters used to analyse deviations between planned and inserted implants.

Despite the informative results of this review, certain limitations should be kept in mind. In vitro studies, by their design, may not fully replicate the conditions in clinical practice, and other factors such as limited visibility and access cannot be entirely accounted for. Nevertheless, the results of in vitro studies may still provide an indication of the clinically achievable accuracy of the systems reviewed. Moreover, a systematic review by Wei et al.[27] found no significant difference in accuracy between in vitro and clinical studies. During the clinical implementation of dynamic navigation, factors such as patient movement or restricted views of the operating field did not seem to worsen outcomes.

The methodological variability and potential biases also limit the findings of this review, and hindered comprehensive statistical analyses. The in vitro studies were heterogeneous, with diverse model materials being used (e.g., plaster, polyurethane, acrylic, resin).

In addition, several technical factors affect the risk of inaccuracies. This systematic review specifically included studies that used postoperative CBCT to measure the deviations, excluding those that employed intraoral scans to determine implant positions. While CBCT is a commonly used method, it is not as sensitive or accurate as intraoral or desktop scanning. IOS could offer a promising alternative for more precise evaluation of implant accuracy, potentially mitigating some of the artifacts associated with CBCT scans around implants[33,34].

Furthermore, different navigation systems were investigated, with substantial technological differences in optical tracking[19], and various implant planning programs were used: coDiagnostiX (Dental Wings GmbH), NemoScan (Nemotec), EvaluNav (ClaroNav Technology). Moreover, different implant systems were chosen: Ticare Inhex, Straumann Standard Plus, Straumann SLActive, BioHorizons, and Zimmer/Biomet 3i. Table 3 outlines the main similarities and differences among the five dynamic navigation systems evaluated. Despite their general similarities, small differences could impact clinical outcomes.

When comparing ImplaNav (BresMedical), Navident (ClaroNav), Denacam (Mininavident), X-Guide (X-Nav Technologies), and DCARER (Yizhime), it is crucial to consider the specific features, technologies, and intended uses of each system. While most systems use optical tracking, Denacam employs magnetic tracking, which can simplify the avoidance of occlusions. Optical systems like Navident, X-Guide, and ImplaNav provide enhanced visual feedback but require precise marker placement[35]. X-Guide stands out for its 360-degree visualization, although the head-mounted tracking can present a steeper learning curve[36]. Navident and Denacam are praised for their user-friendly interfaces, while X-Guide and ImplaNav excel in advanced tracking and planning capabilities[37]. All systems offer submillimetre accuracy, with Navident being slightly more precise. However, their effectiveness can vary based on the clinical setup and user experience[38].

Additionally, all systems integrate with dental practice management tools and can be combined with physical surgical guides for improved precision and workflow efficiency[39]. DCARER is particularly versatile, supporting not only implant placement but also orthodontic, prosthodontic, and gum disease treatments[40]. Each system's strengths and trade-offs make them suitable for different clinical environments and user preferences.

Intraoperative complications must also be considered, such as movement of the optical markers on the patient's jaw or handpiece, incorrect calibration of the drill axis or tip, and inaccurate manipulation. Despite these challenges, dynamic navigation presents several advantages over static guided surgery[28]. In dynamic navigation, after planning and calibration, real-time guidance is provided through visual 3D CT images, which direct the implantation to the planned position[41]. This approach helps to mitigate certain errors associated with the static navigation methods, such as those related to guide production or post-processing. According to Wang et al.[42], errors in static navigation can arise from scanning parameters, guide fabrication and application, and human factors.

Finally, integrating dental navigation systems into busy practices presents challenges due to the additional time requirements and costs. These systems have steep learning curves, which can make it difficult for the practitioner to master them without frequent use[24]. On the other hand, with increased familiarity, practitioners are likely to become more proficient, which can reduce surgical times and boost confidence in the technology. Looking ahead, as technology advances, the costs associated with these systems are expected to decrease. This will likely improve the cost–benefit ratio, making such systems more attractive and leading to their greater adoption alongside traditional dental treatments.

In summary, image-based navigation has significantly enhanced the accuracy of implant placement in dental implantology[43]. These systems enable precise virtual planning that accounts for prosthetic positioning and backward planning, facilitating prosthetically ideal implant placement during surgery[6]. While all dynamic navigation systems share core features such as real-time tracking, visual guidance, and CBCT integration, their accuracy, each use, and workflow vary. Among the systems reviewed, X-guide (X-Nav Technologies) demonstrated the lowest numerical errors, suggesting superior precision in implant insertion. However, the primary differences lie in the specific technologies employed – such as optical versus magnetic tracking – and their impact on the clinical workflow, which will ultimately influence their suitability for different clinical applications.

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Patient consent

Not applicable.

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Competing interests

None.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ijom.2025.02.005.

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