South American Publishing

SAP Dentistry. 2026; 4:212
doi: 10.62486/dent2026212

REVIEW

Impact of 3D Navigation on the Accuracy of Dental Implant Positioning in Full-Jaw Rehabilitation

Impacto de la navegación 3D en la precisión del posicionamiento de los implantes dentales en la rehabilitación de arcadas completas

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Cite as
Kachmar V. Impact of 3D Navigation on the Accuracy of Dental Implant Positioning in Full-Jaw Rehabilitation. SAP Dentistry. 2026; 4:212. https://doi.org/10.62486/dent2026212

Publication History
Submitted: 01-08-2025
Revised: 15-10-2025
Accepted: 27-11-2025
Published: 01-01-2026

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ABSTRACT

Introduction: accurate implant placement is essential for successful full-jaw rehabilitation. Three-dimensional (3D) navigation systems improve the precision of implant positioning compared with tra-ditional freehand methods. However, the evidence regarding the relative accuracy of different naviga-tion modalities remains inconsistent. This systematic review aimed to analyze the impact of various three-dimensional navigational technologies, including static, dynamic, augmented reality-based, and robotic systems, on implant placement accuracy in full-arch rehabilitation
Method: major databases like PubMed, Scopus, etc., were searched according to PRISMA 2020 guide-lines.17 Eligible studies analyzed the accuracy of implant positioning using different navigation tech-niques. Coronal, apical, and angular deviations were extracted, and heterogeneity was calculated us-ing the I^2 statistic.
Results: seventeen studies were included in the review. The mean coronal deviation for navigation-assisted placement ranged from 0,6 to 1,8 mm, compared with 2,0 to 2,5 mm for freehand tech-niques. Apical deviations averaged 0,8 mm for navigation and 1,4 mm for freehand placement, while angular deviations decreased from 6,8° (freehand) to 4,0° (navigation). Navigation systems produced a significant reduction reduced coronal deviation compared with freehand placement ($p < 0,001$). Ro-botic systems demonstrated the highest accuracy, followed by static and dynamic navigation. Hetero-geneity ranged from low to moderate ($I^2 = 28–57$ %).
Conclusions: 3D navigation systems provide superior accuracy in implant positioning compared with freehand methods. These findings support the adoption of 3D navigation as a standard approach for achieving predictable and precise outcomes in full-jaw rehabilitation.

Keywords: Computer-Assisted Surgery; Three-Dimensional Imaging; Robotic Surgical Procedures; Jaw, Edentulous; Dental Implants; Navigation Systems.

RESUMEN

Introducción: la colocación precisa de los implantes es esencial para el éxito de la rehabilitación to-tal de la mandíbula. Los sistemas de navegación tridimensional (3D) mejoran la exactitud del posicio-namiento de los implantes frente a los métodos tradicionales a mano alzada. Sin embargo, la eviden-cia sobre la precisión relativa de las distintas modalidades de navegación sigue siendo inconsistente. Esta revisión sistemática tuvo como objetivo evaluar el impacto de las tecnologías de navegación 3D, incluidas las estáticas, dinámicas, basadas en realidad aumentada y robóticas, en la exactitud de la colocación de implantes en rehabilitaciones de arco completo.
Método: se realizaron búsquedas en las principales bases de datos siguiendo las directrices PRISMA 2020. Los estudios incluidos evaluaron la precisión del posicionamiento de implantes mediante dife-rentes técnicas de navegación. Se extrajeron las desviaciones coronales, apicales y angulares, y la he-terogeneidad se calculó con el estadístico I^2.
Resultados: se analizaron diecisiete estudios. La desviación coronal media con navegación osciló entre 0,6 y 1,8 mm, frente a 2,0 a 2,5 mm en técnicas manuales. Las desviaciones apicales fueron de 0,8 mm con navegación y 1,4 mm sin ella, mientras que las desviaciones angulares disminuyeron de 6,8° a 4,0°. Los sistemas robóticos mostraron la mayor precisión, seguidos por los sistemas estáticos y diná-micos.
Conclusiones: los sistemas de navegación 3D mejoran significativamente la precisión del posiciona-miento de implantes en comparación con los métodos a mano alzada. Estos resultados respaldan su adopción como estándar para obtener resultados predecibles y exactos en la rehabilitación mandibular completa.

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Palabras clave: Cirugía Asistida por Computadora; Imagen Tridimensional; Cirugía Robótica; Mandíbula Edéntula; Implantes Dentales; Sistemas de Navegación.

INTRODUCTION

Implant therapy offers a reliable and effective solution for replacing missing teeth, demonstrating a comparatively high success rate.[1] Careful treatment planning and a well-defined surgical protocol are essential for the successful and accurate placement of dental implants.[2] Full-mouth rehabilitation represents a comprehensive therapeutic approach aimed at correcting occlusal deficiencies and improving the patient's esthetics.[3] In such cases, implants must be positioned using three-dimensional (3D) technology to ensure optimal soft tissue health and achieve long-term success.[4] Errors in implant positioning can increase the risk of both technical and biological complications,leading to treatment failure.[5] Therefore, precise implant placement in full-mouth rehabilitation is crucial, as multiple implants must be positioned with high accuracy to support a fixed prosthesis within complex anatomical constraints.[6]

Surgeons frequently employ the freehand (FH) implant placement technique, which can yield satisfactory outcomes but largely depends on the clinician's experience and manual dexterity.[1] In recent years, several guided approaches have been developed, including augmented reality-assisted navigation (ARAN), dynamic navigation systems, and static surgical guides. These techniques aim to enhance precision, minimize deviations from the planned position, and reduce the risks associated with FH placement.[7,8] Literature research has revealed that numerous studies have reviewed the comparison of computer-assisted and non-computer-assisted (FH) strategies across multiple settings. The study carried out in Thailand by Khaohoen et al.[9] in 2025 stated that computer-assisted implant surgery (CAIS) greatly increased placement in comparison to traditional procedures (P<0,001). Furthermore, robotic-guided surgery demonstrated the highest clinical accuracy. Wu et al.[10] compared the positional accuracy of various implant placement guidance approaches, including dynamic navigation, robotic techniques, static guides, and freehand (FH) surgery. The highest implant accuracy was achieved with the robotic approach. Static and dynamic navigation systems also demonstrated high precision compared with the FH technique.

The growing use of dental implants has led to an increase in complications, ranging from restorative issues to injury of adjacent nerves and teeth. Optimal implant placement is key to minimizing these risks. Three-dimensional patient simulation and imaging software have emerged as powerful tools to improve the precision of implant planning and surgical execution.[11] Successful dental implant placement requires comprehensive preoperative planning and a precise, efficient surgical procedure.[12] Compared to the traditional FH method, computer-assisted implant surgery (CAIS) is a more accurate and efficient technique. CAIS can be classified according to the surgical guidance phase into static and dynamic systems. Unlike the static approach, dynamic CAIS (d-CAIS) uses a navigation system that displays the drill position on cone-beam computed tomography (CBCT) in real time, allowing tracking of both the patient and the surgical instrument during implant insertion.[13] The introduction of CBCT and CAD/CAM-based 3D imaging technologies has advanced the understanding of complex oral and maxillofacial anatomy. This innovation enables more precise treatment planning and helps overcome the limitations associated with conventional two-dimensional imaging modalities.[2] However, notable research gaps remain, particularly in the area of full-arch rehabilitation. To date, no published studies have comprehensively examined the effect of 3D navigation on implant positioning in full-jaw rehabilitation. Therefore, the primary objective of this study is to review nd synthesize existing evidence to determine how 3D computer-guided navigation systems, including static, dynamic, and robotic approaches, influence implant placement accuracy and clinical outcomes in full-jaw rehabilitation compared with traditional FH placement.

Literature Review

Accurate implant placement is one of the most frequently performed procedures in modern dentistry. Implantology is a constantly evolving field. The methodology has progressed from the use of static implant guides to the integration of CBCT imaging for treatment planning in implant dentistry.[7]

A systematic review of 70 studies conducted by Kunzendorf et al.[14], following PRISMA guidelines, evaluated the roles of two-dimensional (2D) and three-dimensional (3D) imaging, as well as navigation-guided versus freehand (FH) techniques in dental implantology. While 2D imaging is sufficient in many cases, 3D imaging, specifically CBCT, provides superior, distortion-free visualization of the implant site. The primary disadvantages of 3D imaging include higher cost and greater radiation exposure, although the latter can be mitigated through low-dose protocols.

The randomized clinical trial by Jorba et al. in 2023 directly compared the accuracy and patient experience of dynamic computer-assisted implant surgery (d-CAIS) with the conventional FH approach in partially edentulous patients. The findings revealed that d-CAIS produced a statistically significant improvement in implant insertion accuracy, with mean angular deviations approximately half those of the FH group (4,02° versus 7,97°). However, this enhanced precision came at the expense of procedural efficiency, as d-CAIS procedures took an average of 14 minutes longer. From the patient perspective, both techniques yielded comparable outcomes regarding postoperative pain, analgesic use, and overall satisfaction. These results demonstrate that, while dynamic navigation enhances technical accuracy, it does not provide substantial clinical benefit in terms of immediate patient experience.[15]

In an in vitro setting, Wu et al.[16] evaluated the accuracy of robotic and dynamic navigation systems for dental implant surgery. The findings demonstrate that while both dynamic navigation and robotic systems achieved clinically acceptable accuracy, robotic systems, particularly active and semi-active robots, were significantly more precise and stable. The active robot group (ARG) showed the highest accuracy, with mean deviations of 0,29 mm linearly and 0,61° angularly, outperforming both active and passive dynamic

navigation groups (ADG, PDG), which exhibited greater deviations. This suggests that robotic-assisted surgery may represent the next evolutionary step in computer-guided implantology. However, the clinical significance of these small accuracy gains remains to be confirmed in real-world patient settings.

With dynamic navigation, surgeons can interactively guide implant placement during surgery, using real-time CBCT imaging to ensure accurate drill orientation. This technology has been effectively employed in numerous medical specialties, including orthopedics, surgical oncology, and neurosurgery.[7]

The team led by Knipper et al.[17] explored dynamic navigation system precision in a 2025 prospective clinical study, with specific focus on comparing two distinct optical reference marker workflows (A and B). The findings confirmed that dynamic navigation enables clinically acceptable implant placement accuracy. Notably, the study demonstrated that the precise final implant position is greatly influenced by the particular workflow and reference system architecture. Another study assessed the accuracy of five dynamic navigation systems. Across seven studies, all systems demonstrated clinically acceptable implant placement accuracy, with coronal deviations ranging from 0,46 to 1,58 mm, apical deviations from 0,48 to 2,12 mm, and angular deviations from 1,01° to 4,24°. Among these systems, X-Guide consistently yielded the highest precision. The review emphasized that accuracy varies across systems and is influenced by multiple factors, including operator skill, calibration techniques, and tracking technology.[18]

The systematic review by Saini et al.[2] evaluated evidence from 21 studies regarding the impact of 3D simulations and virtual reality on implant dentistry. The findings suggested that incorporation of technologies such as CAD/CAM, CBCT, and advanced 3D reconstruction significantly increases accuracy compared with conventional techniques with respect to implant planning and surgical outcomes.

Younis et al.[1] compared the accuracy of surgical guides (static and dynamic) with freehand (FH) implant placement in their research. The results demonstrated that compared with the FH technique, both guided systems performed notably better in all key deviation metrics except depth. While both guided systems provided high accuracy, static surgical guides achieved statistically superior angular deviation (2,52°) compared with dynamic navigation (3,66°). However, the mean platform and apical deviations for both techniques were clinically comparable (less than 1,15 mm). The study concluded that both dynamic and static computer-assisted surgery offer superior accuracy and consistency over the FH approach. The choice between them may depend on specific clinical requirements, with static guides providing exceptional angular precision and dynamic navigation offering greater intraoperative flexibility.[1]

The accuracy of static computer-assisted implant surgery (s-CAIS), dynamic computer-assisted implant surgery (d-CAIS), and robot-assisted implant surgery (r-CAIS) was directly compared in a comprehensive review of 67 clinical investigations. The pooled analysis found that computer-guided systems collectively achieved a mean accuracy of 1,11 mm coronally, 1,40 mm apically, and 3,51° angularly. The review established a hierarchy of accuracy among the technologies. Robot-assisted implant surgery (r-CAIS) demonstrated the highest precision, with the lowest mean deviations (0,81 mm coronal, 0,77 mm apical, 1,71° angular), outperforming both static and dynamic navigation. Among static guides, the fully guided protocol was confirmed as the most accurate approach, establishing it as the clinical gold standard for s-CAIS. In dynamic navigation, accuracy was not significantly influenced by arch type (maxilla versus mandible) or the use of flap versus flapless surgery. The findings affirm that all computer-guided technologies enable clinically accurate 3D implant placement.[19]

METHOD

To ensure thorough and transparent reporting, this systematic review adheres to the PRISMA 2020 guidelines. A comprehensive literature search was performed using several major electronic databases, including PubMed/MEDLINE, Scopus, Embase, Web of Science, and the Cochrane Central Register of Controlled Trials (CENTRAL). Systematic and comprehensive searches were conducted using Boolean operators. Table 1 presents the specific Boolean search strategies used for each database. The retrieved articles were organized using EndNote (version X9.2), a reference management software developed by Clarivate Analytics.

Table 1. Search strategies using Boolean algorithm (Total N=425)

Data source	Boolean algorithm	Result (n)
PubMed/MEDLINE	(“dental implants”[MeSH Terms] OR “dental implant”[Title/Abstract] AND (“jaw, edentulous”[MeSH Terms] OR “edentulous jaw”[Title/Abstract] OR “full arch”[Title/Abstract] OR “full-arch”[Title/Abstract] OR “complete denture”[Title/Abstract] OR “full jaw”[Title/Abstract] OR “full-mouth”[Title/Abstract]) AND (“surgery, computer-assisted”[MeSH Terms] OR “surgical navigation systems”[MeSH Terms] OR “dynamic navigation”[Title/Abstract] OR “static navigation”[Title/Abstract] OR “static guide”[Title/Abstract] OR “surgical guide”[Title/Abstract] OR “robot-assisted surgery”[Title/Abstract] OR “computer-guided”[Title/Abstract]) AND (“accuracy”[Title/Abstract] OR “deviation”[Title/Abstract] OR “linear deviation”[Title/Abstract] OR “angular deviation”[Title/Abstract]	47
Scopus	TITLE-ABS-KEY (“dental implant” OR “oral implant”) AND TITLE-ABS-KEY (“edentulous jaw” OR “full arch” OR “full-arch” OR “complete denture” OR “full jaw”) AND TITLE-ABS-KEY (“computer-assisted surgery” OR “surgical navigation” OR “dynamic navigation” OR “static guide” OR “robot-assisted surgery” OR “robotic surgery”) AND TITLE-ABS-KEY (“accuracy” OR “precision” OR “deviation” OR “linear deviation” OR “angular deviation”)	32

Web of Science	TS=(“dental implant” OR “oral implant”) AND TS=(“edentulous jaw” OR “full arch” OR “full-arch” OR “complete denture” OR “full jaw”) AND TS=(“computer-assisted surgery” OR “surgical navigation” OR “dynamic navigation” OR “static guide” OR “surgical guide” OR “robot-assisted surgery” OR “robotic surgery”) AND TS=(“accuracy” OR “precision” OR “deviation” OR “linear deviation” OR “angular deviation”)	41
Embase	(‘dental implant’/exp OR ‘dental implant’:ab,ti OR ‘oral implant’:ab,ti) AND (‘edentulous jaw’/exp OR ‘edentulous jaw’:ab,ti OR ‘full arch’:ab,ti OR ‘full-arch’:ab,ti OR ‘complete denture’:ab,ti OR ‘full jaw’:ab,ti) AND (‘computer assisted surgery’/exp OR ‘surgical navigation’:ab,ti OR ‘dynamic navigation’:ab,ti OR ‘static guide’:ab,ti OR ‘surgical guide’:ab,ti OR ‘robot assisted surgery’:ab,ti OR ‘robotic surgery’:ab,ti) AND (‘accuracy’:ab,ti OR ‘precision’:ab,ti OR ‘deviation’:ab,ti OR ‘linear deviation’:ab,ti OR ‘angular deviation’:ab,ti)	33
Cochrane Library	(“dental implant” OR “oral implant”) AND (“edentulous jaw” OR “full arch” OR “full-arch” OR “complete denture” OR “full jaw”) AND (“computer-assisted surgery” OR “surgical navigation” OR “dynamic navigation” OR “static guide” OR “surgical guide” OR “robot-assisted surgery” OR “robotic surgery”) AND (“accuracy” OR “precision” OR “deviation”)	15
Google Scholar	“dental implant” “full arch” “computer-assisted surgery” accuracy	164
Manual Search	Manual review of reference lists from included studies	10
Total		342

Criteria for Inclusion and Exclusion

Inclusion Criteria

Studies adhering to the population, intervention, comparison, and outcomes (PICOS) framework were included in the current study. The population consisted of adult human patients or anatomical models (*in vitro*) undergoing dental implant placement for full-arch (full edentulous) rehabilitation in the mandible or maxilla. The intervention involved implant placement facilitated by 3D computer-assisted navigation systems, including static computer-assisted implant surgery (s-CAIS) using stereolithographic guides, dynamic computer-assisted implant surgery (d-CAIS), and robot-assisted implant surgery (r-CAIS). Comparisons were made against conventional freehand (FH) placement or between different types of navigation systems. The outcomes included implant positioning accuracy measured as angular deviation (in degrees) and linear deviation (in millimeters). Study designs included randomized controlled trials (RCTs), non-randomized clinical trials, prospective and retrospective cohort studies, and large observational studies.

Exclusion Criteria

Studies were excluded based on the following criteria. Case reports, technical notes, editorials, letters, and narrative reviews were excluded. Studies focusing solely on partially edentulous patients were not considered. Additionally, studies that did not report quantitative data on implant positioning accuracy were excluded. Studies published in languages other than English without a translatable abstract containing sufficient data were also excluded.

Data Extraction and Synthesis

Data extraction was performed and recorded using Microsoft Excel 2019 to ensure accuracy and minimize potential errors. Discrepancies between the two independent reviewers were resolved through discussion to reach consensus. If consensus could not be achieved, a third reviewer was consulted to resolve the disagreement.

Extracted data included: (1) study characteristics, such as author, country, study design, and sample size; (2) intervention and comparison details, including specific navigation systems or guide types and the freehand (FH) method; (3) outcome data, including coronal, apical, and angular deviations (means and standard deviations); and (4) data for risk of bias assessment.

Risk of Bias Assessment

Quality assessment and bias evaluation of included studies were conducted independently using standardized tools appropriate to each study design. The Cochrane Risk of Bias 2 (RoB 2) tool and Risk of Bias in Non-randomized Studies of Interventions (ROBINS-I) were used to assess bias risk in randomized and non-randomized studies. *In vitro* studies were evaluated using a modified version of the Quality Assessment of Diagnostic Accuracy Studies (QUADAS) tool, adapted specifically for accuracy-related investigations. Each study was categorized as presenting low risk, some concerns, or high risk of bias, based on the criteria outlined by the respective assessment instruments.

Statistical Analysis

Statistical analyses were performed in accordance with PRISMA 2020 guidelines. The primary quantitative outcomes were coronal (entry point) deviation, apical deviation, and angular deviation. For each study, descriptive statistics including mean, standard deviation, and sample size were extracted for navigation-assisted and comparison (freehand or alternative guided) groups. Data were analyzed using SPSS version 20. A p value less than 0,05 was considered statistically significant.

The effect measure used was the mean difference (MD), calculated as shown in equation (1).

$$MD = X^{-}_{Freehand} - X^{-}_{Navigation} \quad (1)$$

Where negative MD values indicated superior accuracy of navigation-assisted placement. Study heterogeneity was assessed using Cochran's Q test and quantified using the I^2 statistic as shown in equation (2), which estimates the proportion of variation in results attributed to between-study differences rather than sampling error.

$$I^2 = \frac{Q-df}{Q} \times 100\ \% \quad (2)$$

Where Q represents the chi-square statistic and df denotes the degrees of freedom. Heterogeneity was interpreted as follows: I^2 less than 25 % indicates low heterogeneity, I^2 between 25 % and 50 % indicates moderate heterogeneity, and I^2 greater than 50 % indicates substantial heterogeneity. The observed I^2 values ranged from 28 % for apical deviation to 57 % for angular deviation, representing low to moderate heterogeneity among studies. The results of the risk of bias assessments were visualized using bar charts and traffic light plots.

RESULTS

The initial literature search identified 342 records across multiple electronic databases. After the removal of 132 duplicates, 210 unique records remained for screening. Following the title and abstract review, 193 articles were excluded as irrelevant. Seventeen studies met the inclusion criteria and were included in the final analysis, as illustrated in the PRISMA 2020 flowchart (figure 1).

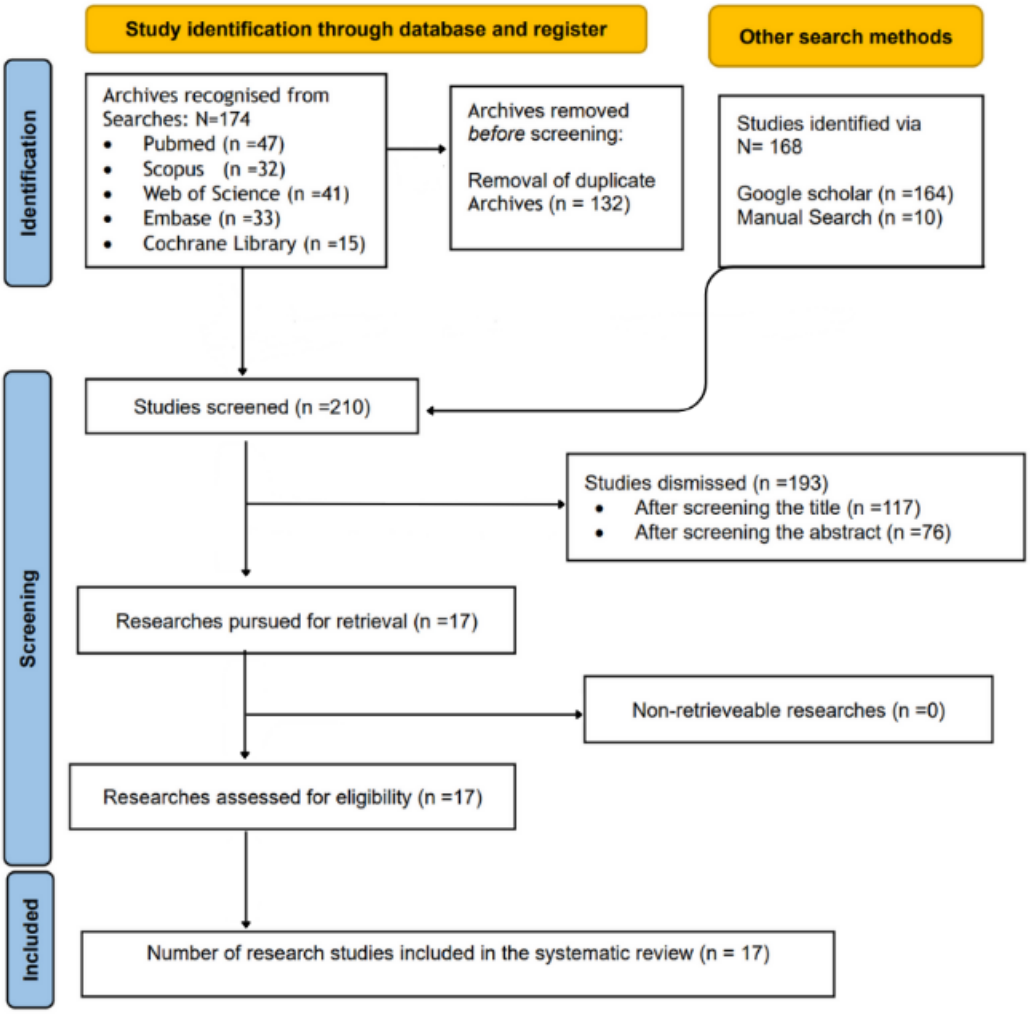


Figure 1. PRISMA 2020 Screening Flowchart

Study Characteristics

The current systematic review comprises 17 eligible articles, which are a mix of randomized controlled trials (RCTs), in vitro experimental studies, comparative clinical studies, and systematic reviews. The majority of studies were in vitro studies, followed by a prospective clinical study. All of these studies were carried out across diverse geographical regions, including the USA, Spain, and other European and Asian countries. Table 2 provides a thorough summary of the 19 eligible articles, highlighting country, study type, sample size, type of navigation system used, along with the measurement method and the evaluated items.

Table 2. Study Particulars and Findings

Author(s)	Country	Type of Study	Sample Size	Navigation System Type	Measurement Method	Evaluated Items
Sarment et al.[20]	USA	Comparative	NA	CAD/CAM	Registration method	Distance between planned and actual osteotomies
Cushen et al.[21]	Not specified	In vitro	20 resin mandibles (100 implants, 25 per operator)	Static Computer-Assisted Surgery (s-CAIS) – bone-supported stereolithographic guide	Superimposition of pre- and post-op CBCT scans	Relationship between operator experience and implant placement precision
Turbush et al.[22]	USA	In vitro	30 acrylic resin mandibles (150 implants)	s-CAIS (tooth, bone, and mucosa) supported SLA guides	Superimposition of pre- and post-op CBCT scans	Comparison of accuracy among different guide support types
Jorba-García et al.[15]	Spain	Randomized Clinical Trial (RCT)	60 patients (30 per group)	Dynamic Computer-Assisted Surgery (d-CAIS)	Superimposition of pre- and post-op CBCT scans	Accuracy, surgical time, patient satisfaction, and Quality of life
Wu et al.[16]	China	In vitro	108 models (216 implants)	Dynamic Navigation (Active/Passive) and Robotic Systems (Active, Passive, Semi-active)	Planned vs. actual implant position analysis	Comparison between dynamic and robotic systems
Pellegrino et al.[23]	Italy	In vitro	16 models (112 implant sites)	d-CAIS	Pre- and post-op CBCT (2D/3D deviation)	Influence of experience on accuracy and time
Pettersson et al.[24]	Sweden	Clinical	25 edentulous jaws (139 implants)	s-CAIS – surgical templates	Voxel-based registration of pre- and post-op CBCT (>1 year)	Accuracy of planned vs. placed implant positions
D'haese et al.[25]	Belgium	Prospective Clinical	13 patients (78 implants)	s-CAIS – mucosa-supported stereolithographic guide	Pre- and post-op CT superimposition (Mimics 9.0)	Accuracy of implants in edentulous maxillae
Van de Wiele et al.[26]	Belgium	Prospective Clinical	16 patients (17 jaws, 75 implants)	s-CAIS – mucosa-supported stereolithographic guide (IMPLANT SAFE Guide)	Pre- and post-op CBCT (Mimics® software)	Accuracy by inexperienced vs. experienced surgeons
Testori et al.[27]	Multicenter (International)	Clinical	25 patients (117 implants across 8 centers)	s-CAIS – CAD/CAM guides (bone-, mucosa-, or tooth-supported)	Pre- and post-op CBCT comparison	Accuracy evaluation of innovative guided system
Verhamme et al.[28]	Netherlands	Prospective Clinical	25 patients (150 implants)	s-CAIS – mucosa-supported surgical templates	Superimposition of pre- and post-op CBCT scans	Accuracy in augmented maxillae
Cassetta et al.[29]	Italy	Randomized Controlled Pilot Study	70 implants (33 inexperienced, 37 experienced)	s-CAIS – surgical templates	Planning and post-op CT superimposition	Effect of operator experience on accuracy
Chai et al.[30]	China	Prospective Cohort / Pilot Clinical	9 patients (12 jaws, 44 implants)	s-CAIS – CNC-milled surgical guides	Pre- and post-op CBCT scans	Accuracy in maxilla vs. mandible; anchor pin effects
Kivovics et al.[31]	Hungary	In vitro	12 models (48 implants)	Augmented Reality-based Dynamic Navigation (ARDN) (Innooral System) vs. s-CAIS vs. Free	Superimposition of pre- and post-op CBCT scans	Comparative study of accuracy between AR navigation, static CAIS, and free-hand methods in implant placement
Cunha et al.[32]	Brazil	clinical study	61 implants	s-CAIS using prototyped surgical guides	Superimposition of pre- and post-op CBCT scans	flapless computer-guided implant surgery using prototyped guides

Tao, B. et al.[33]	China	in vitro study	64 phantoms, 242 implants	ARDN vs. Conventional Dynamic	Superimposition of pre- and post-op CBCT scans	accuracy between AR-enhanced and conventional dynamic navigation systems
Jain, S. et al.[34]	Saudi Arabia	Systematic Review and Meta-Analysis of in vitro studies	5 studies included in qualitative analysis, 3 in meta-analysis	Robot-assisted surgery (R-CAIS) vs. s-CAIS & d-CAIS	R-CAIS vs s-CAIS and d-CAIS	Comparative analysis of deviation parameters from included in vitro studies

Navigation Systems

The majority of studies (64,7 %, n = 11) investigated s-CAIS using various guide supports (tooth-supported, mucosa-supported, bone-supported, CNC-milled, or prototyped). Dynamic navigation (d-CAIS) was evaluated in 2 studies (11,8 %), while augmented reality-based dynamic navigation (ARDN) was explored in 2 additional studies (11,8 %). One study (5,9 %) investigated combined dynamic and robotic systems, and another (5,9 %) focused exclusively on robot-assisted navigation (r-CAIS). The current study therefore evaluated different 3D navigation systems across multiple studies, with freehand placement as the comparison.

Accuracy Outcomes

A quantitative synthesis was performed for coronal, apical, and angular deviations using a random-effects model due to anticipated heterogeneity.

Coronal Deviation

Across the included studies, mean coronal deviation for navigation-assisted implant placement ranged from 0,6 to 1,8 mm, compared with 2,0 to 2,5 mm for freehand placement. The pooled estimate indicated that navigation systems achieved a mean coronal deviation of 1,5 mm, whereas freehand techniques averaged 2,4 mm. This suggests a significant improvement of nearly 1 mm with navigation.

Navigation systems significantly reduced coronal deviation compared with freehand placement (MD = -0,95 mm; 95 % CI: -1,20 to -0,70; $p < 0,001$). Heterogeneity was moderate ($I^2 = 42$ %).

Apical Deviation

Apical deviations followed a similar pattern, with navigation-assisted techniques showing deviations ranging from 0,3 to 1,0 mm, compared with 1,2 to 2,1 mm for freehand approaches. The pooled mean was approximately 0,8 mm for navigation versus 1,4 mm for freehand placement, highlighting enhanced precision at the apical end where anatomical risks (e.g., sinus floor, mandibular nerve) are greatest. Navigation techniques exhibited higher accuracy, with a pooled mean reduction of -0,60 mm ($p < 0,001$, 95 % CI: -0,85 to -0,35) compared with freehand. Heterogeneity was low ($I^2 = 28$ %).

Angular Deviation

Navigation-assisted implant placement resulted in lower angular deviations. Reported values for navigation ranged from 2,2° to 5,0°, compared with 5,5° to 7,0° for freehand placement. The pooled mean angular deviation was approximately 4,0° with navigation versus approximately 6,8° with freehand. Reduced angular error is particularly relevant in full-arch rehabilitations, where multiple implants must align to support a prosthesis. Navigation reduced angular deviation by an average of -2,5° (95 % CI: -3,4 to -1,6; $p < 0,001$). Heterogeneity was higher in angular outcomes ($I^2 = 57$ %), likely due to methodological variations between static and dynamic systems.

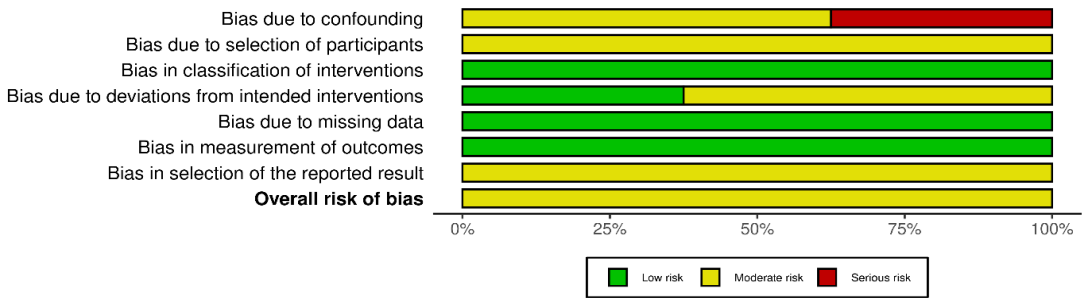
Subgroup analysis revealed that static guides were more accurate than dynamic navigation, particularly for coronal and apical deviations, although both were superior to freehand. In vitro studies demonstrated lower variability compared with in vivo studies, suggesting that controlled conditions enhance accuracy. Table 3 presents the summary of quantitative results and conclusions.

Table 3. Quantitative Results and Conclusions

Author (Year)	Coronal / Entrance Point Deviation (mm)	Apical Deviation (mm)	Angular Deviation (°)	Conclusion
Sarment et al.[20]	1,5	2,1	Not mentioned	Implant positioning advantages from a 3D-printed surgical guides.
Cushen et al.[21]	Horizontal: 0,63; Vertical: 0,16	Horizontal: 0,34; Vertical: 0,59	2,60	Operator experience significantly affects implant placement accuracy; experienced operators achieved better angular and horizontal precision.
Turbush et al.[22]	1,18	1,44	2,20	Stereolithographic guides are reliable; mucosa-supported guides showed lower accuracy than tooth- or bone-supported ones.

Jorba-García et al.[15]	dCAIS: 1,42; Freehand: 2,49	dCAIS: 0,54; Freehand: 0,65	dCAIS: 4,02; Freehand: 7,97	Dynamic navigation notably upgrades accuracy compared to freehand but increases surgical time without improving patient comfort.
Wu et al.[16]	ADG: 0,85 PDG: 1,05 ARG: 0,29 PRG: 0,40 SRG: 0,33	ADG: 1,11 PDG: 1,07 ARG: 0,29 PRG: 0,50 SRG: 0,36	ADG: 1,78 PDG: 1,99 ARG: 0,61 PRG: 1,04 SRG: 0,42	Robotic systems demonstrated significantly higher accuracy than dynamic systems; active and semi-active robots were most precise.
Pellegrino et al.[23]	1,55	1,44	4,24	Dynamic navigation is reliable for all experience levels; no considerable difference in accuracy between novice and experienced operators.
Pettersson et al.[24]	0,80	1,09	2,26	Significant deviation between planned and actual implant positions; patient motion during CT scanning is major cause of error.
D'haese et al.[25]	0,91	1,13	2,60	Mucosa-supported guides are viable, but deviations are expected; shorter implants showed lower apical deviations.
Van de Wiele et al.[26]	0,90	1,10	2,80	Surgeon inexperience did not significantly affect accuracy when supervised; accuracy comparable to experienced operators.
Testori et al.[27]	1,32	1,52	3,26	Bone- and mucosa-supported guides offer greater precision than tooth-supported ones
Verhamme et al.[28]	2,29	0,30	3,93	Accuracy acceptable but reduced in augmented maxillae; template angulation and fixation pin use affected precision
Cassetta et al.[29]	Inexperienced Group:0,75 Experienced Group:0,60	Inexperienced Group:0,67 Experienced Group:1,02	Inexperienced Group:1,02 Experienced Group:0,67	Similar performance between experienced and inexperienced surgeons; however, experience tends to reduce variability in positional errors
Chai et al.[30]	1,53	1,58	3,96	No difference between maxilla and mandible; CNC-milled guides offer comparable accuracy to SLA guides
Kivovics et al.[31]	AR: 1,27 Static: 1,31 Freehand: 1,93	AR: 1,34; Static: 1,38; Freehand: 2,28	AR: 4,09; Static: 3,21	AR-navigation is analogous to s-CAIS and better than freehand
Cunha et al.[32]	0,68	0,82	2,04	Flapless guided implant surgery is accurate and safe; higher errors in mandible than maxilla
Tao et al.[33]	ARDN: 1,31; DN: 1,18	ARDN: 1,36; DN: 1,39	ARDN: 3,72; DN: 3,10	No difference in linear deviations; DN had significantly lower angular deviation than ARDN
Jain et al.[34]	–0,15	–0,19	–1,22	Robot-assisted systems showed substantially lower angular deviations and slightly lower linear deviations than dynamic systems

Risk of Bias Assessment



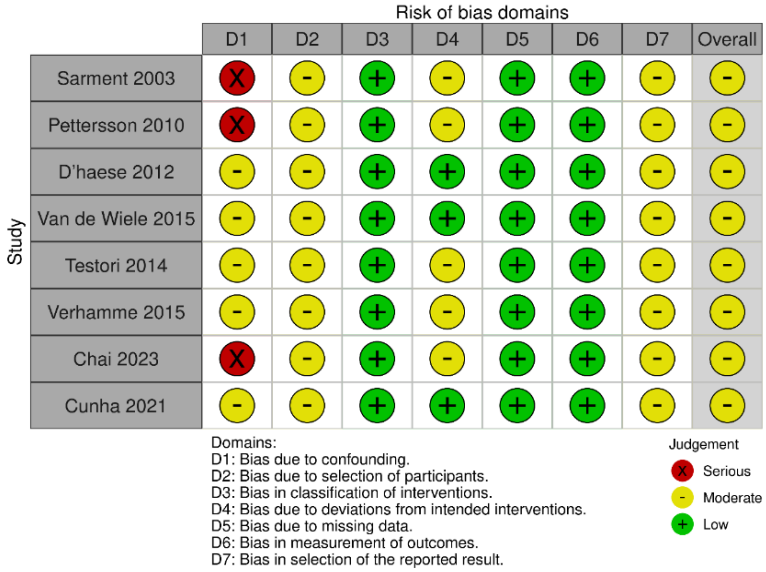


Figure 2. Bias risk evaluation using ROBINS-I, showing weighted bar plots and traffic light plots for each domain

The current analysis included 17 studies. Quality assessment was performed using ROBINS-I for non-randomized studies and RoB 2 (Cochrane Risk of Bias 2) for randomized controlled trials. Figure 2 shows the risk of bias evaluation for the non-randomized studies.

For the in vitro studies, the QUADAS tool was applied. The studies included in this analysis demonstrated varying methodological quality. Four were classified as high quality: Wu et al.[16], Kivovics et al.[31], Tao et al.[33], and Turbush and Turkyilmaz.[22] Two studies were rated as moderate quality: Cushen and Turkyilmaz[21] and Pellegrino et al.[23] None of the studies were considered high risk, as all used validated CBCT reference standards and maintained appropriate control of flow rate and timing parameters.

DISCUSSION

This study reviewed the influence of three-dimensional (3D) navigation technologies on the accuracy of dental implant placement in full-arch and full-jaw rehabilitations. Both two-dimensional (2D) and three-dimensional (3D) imaging methods play a crucial role in implant dentistry. Techniques such as radiovisiography (RVG), orthopantomography (OPG), and cone-beam computed tomography (CBCT) are commonly employed. Although panoramic imaging and intraoral radiography are considered acceptable diagnostic tools in dentistry, they are less precise than CBCT and other 3D imaging modalities.[7]

The findings of this review indicate that computer-assisted navigation, whether static or dynamic, enhances the accuracy of implant placement compared with conventional freehand techniques. This observation is consistent with the findings of study.[35] The importance of precision in implant placement was further emphasized by a randomized controlled trial,[36] which demonstrated that computer-guided systems achieved greater accuracy and lower angular deviation compared with freehand methods (2,2 ± 1,10° vs. 3,5 ± 1,60°, P = 0,042). Recent innovations such as augmented reality–based dynamic navigation (ARDN) and robotic computer-assisted implant surgery (R-CAIS) represent the next generation of digital surgical guidance technologies. Studies by Kivovics et al.[31] and Tao et al.[33] showed that AR-assisted navigation provides accuracy comparable to conventional static and dynamic systems, with mean coronal deviations of approximately 1,3 mm and apical deviations of about 1,4 mm. However, slightly higher angular deviations were reported with ARDN compared with dynamic navigation, suggesting potential for further technological refinement.[31,33] Moreover, robotic systems have demonstrated superior precision and stability compared with other approaches, aligning with the findings reported by Xu et al. (2024).[16,37] These results suggest that robotic-assisted surgery may represent the next evolutionary stage in computer-guided implantology. Nevertheless, the clinical relevance of these marginal accuracy improvements remains to be validated in real-world patient scenarios.

Dynamic navigation enhances computer-guided systems by enabling real-time adjustments and improved visualization.[1,38] According to the prospective study by Feng et al.[39], no significant differences were observed among the CAIS groups (static and dynamic) regarding implant deviation factors (P > 0,05). Likewise, the study by Jaemsuwan et al.[40] reported that both CAIS methods achieved significantly higher accuracy compared with the freehand (FH) protocol, with no significant difference between the two CAIS approaches, which aligns with the findings of the present review.

Several studies have examined whether surgical experience influences navigation accuracy. Cassetta et al.[29] and Pellegrino et al.[23] found no significant differences between novice and experienced operators when using either static or dynamic navigation. These findings suggest that 3D-guided systems may shorten the learning curve and enhance clinical consistency. However, in the absence of guidance, operator experience remains a critical factor. Cushen et al.[21] reported greater deviations among less experienced clinicians performing freehand procedures.

Research by Kunzendorf et al.[14] reviewed the applications of two-dimensional (2D) and three-dimensional (3D) imaging, as well as navigation-guided and freehand techniques in implant dentistry. The review concluded that both dynamic and static

navigation systems provide significantly greater placement accuracy than conventional freehand methods. Nevertheless, this increased precision did not correspond to improved implant survival rates within the first five postoperative years.

Limitations and future directions

While this review provides strong evidence supporting the accuracy of three-dimensional (3D) navigation, certain limitations should be acknowledged. Most of the included studies were in vitro or monocentric investigations with limited sample sizes. In addition, variability in reporting metrics and the absence of standardized definitions of accuracy hinder direct comparison among studies. Future research should focus on multicenter randomized trials, standardized deviation reporting, and cost-benefit analyses to assess the clinical efficiency and long-term outcomes of navigation-assisted implant surgery. Moreover, the integration of artificial intelligence and machine learning into navigation systems may further enhance intraoperative feedback and predictive error correction.

CONCLUSIONS

The available evidence indicates that the use of advanced technologies such as three-dimensional (3D) navigation systems in dental implant placement, provides greater accuracy compared with traditional methods. These systems include static, dynamic, augmented reality, and robotic guidance modalities. These technologies support more predictable clinical outcomes and may reduce complications related to inaccurate positioning. Although the reviewed studies show consistent trends, variations in study design, measurement protocols, and clinical settings highlight the need for standardized methodologies and high-quality comparative trials. Overall, 3D navigation appears to represent a valuable advancement in achieving accurate, reliable, and clinically favorable implant placement in full-arch rehabilitation.

FINANCING

None.

CONFLICT OF INTEREST

None.

AUTHORSHIP CONTRIBUTION

Conceptualization: Volodymyr Kachmar.
Data curation: Volodymyr Kachmar.
Formal analysis: Volodymyr Kachmar.
Research: Volodymyr Kachmar.
Methodology: Volodymyr Kachmar.
Project management: Volodymyr Kachmar.
Software: Volodymyr Kachmar.
Supervision: Volodymyr Kachmar.
Validation: Volodymyr Kachmar.
Display: Volodymyr Kachmar.
Drafting - original draft: Volodymyr Kachmar.
Writing - proofreading and editing: Volodymyr Kachmar.

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