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Accuracy of Dental Implant Placement using Robotics. A Systematic Review of *in vitro* Studies

Keywords

Dental Implants
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ABSTRACT

Purpose/Aim: Robotic-assisted techniques have the potential to revolutionize dental implantology by offering enhanced precision, accuracy, and clinical outcomes compared to computer-assisted implant placement techniques. This study aimed to evaluate the accuracy of dental implant placement using robot-assisted implant surgery in vitro settings. Methods: An unrestricted search of indexed databases along with a manual search was performed up to March 2024. In vitro, studies comparing the positioning accuracy of robotic systems in dental implant placement of planned pre-operative coordinates and postoperative outcomes in phantom and simulated models were included. QUIN Tool was used to assess the quality of the included studies. Result: A total of 13 in vitro studies were included. All studies except one used entry, exit, or angle deviation as parameters to assess the accuracy of implants placed on phantom models or simulated virtual implant placement. Overall, pooled entry deviations were 0.72 ± 0.68 mm, exit deviations were 0.86 ± 0.92 mm, and angular deviations were 1.47 ± 1.610 favoring robot-assisted implant surgery. Conclusion: Based on the current evidence, robotic-placed implants have the potential to revolutionize dental implantology by offering enhanced precision, accuracy, and clinical outcomes compared to dynamic and static computer-assisted implant surgery techniques.

INTRODUCTION

Robotic systems have emerged as a promising tool in dental implantology, aiming to enhance the accuracy, safety, and predictability of implant placement. Robotic systems enable the integration of advanced imaging technologies, such as cone-beam computed tomography (CBCT) and intraoral scanners, for comprehensive patient anatomy assessment. This facilitates precise three-dimensional (3D) virtual planning, allowing the clinician to simulate the implant placement procedure and assess anatomical limitations, optimizing the positioning of implants and reducing potential complications.[1]

One of the main challenges of dental implant surgery is to achieve optimal implant placement, which depends on many factors such as bone quality and quantity, anatomical structures, prosthetic design, and patient preferences. Traditionally, implant surgery is performed by manual drilling based on preoperative planning and intraoperative guidance. However, manual drilling has limitations such as human error, operator fatigue, limited visibility, and lack of real-time feedback. These limitations can lead to complications such as implant mispositioning, nerve injury, sinus perforation, infection, implant failure, and aesthetic problems.[1] To overcome these limitations, robotic systems have been developed and can be classified into two types: static-guided surgery and dynamic-guided surgery. Static-guided surgery uses a prefabricated surgical template that is attached to the patient's jaw and guides the drilling trajectory. Dynamic guided surgery uses a computerized navigation system that tracks the position and orientation of the drill and the patient's jaw in real time and displays them on a monitor. Both types of robotic systems have advantages and disadvantages in terms of accuracy, flexibility, cost, and workflow.[2]

The first robotic dental surgery system that was cleared by the Food and Drug Administration (FDA) for dental implant procedures in the United States combines haptic guidance and visual guidance to assist the surgeon in implant placement.[3] In haptic guidance the robot provides physical feedback to the surgeon through the drill handpiece, such as resistance or vibration, to indicate the optimal drilling direction and depth. In visual guidance, the robot displays the planned implant position and orientation on a monitor along with the real-time drill position and orientation. The surgeon can also adjust the plan intraoperatively if needed.[4]

Robotic systems use optical or electromagnetic tracking devices to provide continuous feedback on the position and orientation of the implant drill and the patient's anatomy. The surgical guidance facilitates precise osteotomy preparation, implant insertion, and angulation control, thereby reducing the risk of damage to vital structures and enhancing accuracy. Robotic systems offer high levels of precision and accuracy in implant placement, surpassing the limitations of manual techniques. The robotic arm's steadiness and tremor-free operation, combined with real-time navigation, enable the execution of the preoperative plan with sub-millimeter accuracy. This precision contributes to optimal implant positioning, improved osseointegration, and predictable aesthetic outcomes.[5] However, robot-assisted implant surgery also faces some challenges and limitations. The robotic system is expensive to purchase and maintain, which may limit its accessibility and affordability for many dental clinics and patients. These systems require a steep learning curve and extensive training for the surgeon and the staff, as well as a reliable calibration and registration process for the navigation system. The robotic system raises some ethical and legal questions regarding the responsibility and liability of the surgeon and the manufacturer in case of complications or malfunctions.[6] Limited studies have compared the accuracy of robotic implant systems with a static guide and dynamic navigation, and *in vitro* studies published in the literature have shown acceptable outcomes with lower deviations of dental implants placed by robotic systems in both partially and completely edentulous jaws.[2,7,8] Currently, immediate implant placement has become popular attributed to its potential advantages of shorter treatment time and minimally invasive surgery. However, it becomes challenging to place an immediate implant in limited bone and an uneven bone density as it results in an uneven force thereby causing an implant to lean towards the labial side.[9] Wang *et al* reported that robot-assisted immediate implant placement provides real-time calibration through continuous measurements and the automated robotic arm minimizes the deviations caused by a slight movement of the operator's arm.[9] In addition, an increase in precision and positional accuracy of an immediate implant under robotic guidance has been observed irrespective of implant shape and length. To our best knowledge, by our literature search, no systematic review has evaluated the accuracy of implant placement by automated or hybrid robots *in vitro* settings, hence pointing to the need for more evidence-based clinical studies in this domain.

MATERIALS AND METHODS

PROTOCOL REGISTRATION

The present study adhered to the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist. Since the present study focused on *in vitro* studies, it was not eligible for registration on the International Prospective Register of Systematic Reviews (PROSPERO).[10]

SEARCH STRATEGY

To identify relevant literature, an electronic search was conducted up to May 30, 2023, using PubMed, EMBASE, Web of Science, and the Cochrane Library. The search strategy involved using the following keywords: "Dental Implants," "Robotics," "Accuracy," "Registration," and "Stewart manipulator." Boolean operators (OR, AND) were employed to combine these keywords and expand the search results. The search was limited to publications in English. Two authors (VR and RN) independently screened the titles and abstracts of the identified studies based on the aforementioned search protocol. Full texts of relevant studies were read independently. To identify any additional relevant literature, a manual search was conducted by reviewing the reference lists of the included studies as well as relevant original studies and review articles. Any disagreements between the two authors were resolved through discussion and consultation with a third researcher (JM). The search strategy aimed to comprehensively gather scientific literature on the topic of robotic-placed implants compared to surgical guide dental implants, specifically focusing on accuracy.

PATIENTS, INTERVENTIONS, CONTROL, OUTCOME, (PICO):

Patient, (P): Implants placed using robots, (I): Placement of implants or simulation of implant placement, (C): Pre-operative planned CBCT or computed tomography (CT) data, (O): Accuracy of Post-operative implant position, (S): *In vitro* studies. Any other type of study was excluded.

ELIGIBILITY CRITERIA

The present systematic review included *in vitro* studies analyzing the entry deviation, exit deviation, and angle deviation

INCLUSION CRITERIA

Inclusion of studies that assessed (a) implants placed by automated robots, (b) implant simulations by automated robots, (c) implants placed on phantom models, dry maxilla and mandible and simulations, (d) preoperative and postoperative CBCT data, (e) assesses exit, entry or angle deviation.

EXCLUSION CRITERIA

Studies were excluded if (a) implants placed other than robots (surgical guide, freehand placement, or robot-assisted), (b) other parameters for measurement of accuracy.

RESULTS

STUDY SELECTION AND DATA COLLECTION

The included articles underwent a rigorous review process conducted by two investigators (VR, RN). The review process involved screening the titles and abstracts of 241 identified studies through an electronic search of databases and registers to select relevant articles for further analysis. Studies that were deemed irrelevant, duplicates, or did not address the focused question were excluded. Disagreements between the reviewers were resolved through mutual discussion, and in cases where a consensus could not be reached, a third reviewer (JM) and a fourth reviewer (JK) were consulted *(Figure 1*). The gathered information from the 13 included *in vitro* studies[2,3,7-9,11-18] was synthesized by tabulating the data according to various aspects, including study design, characteristics of the robots used, relevance of the study to implants being placed or simulated, drilling sequence, and study outcomes related to accuracy measurements such as entry, exit, or angle deviation

GENERAL CHARACTERISTICS OF INCLUDED STUDIES

All the studies included in this systematic review were *in-vitro*, had an intervention group as implants placed using a robotic system, and a control group as implants placed with Dynamic Computer Assisted Implant Surgery (CAIS) protocol,[2] with 3D printed surgical stent,[11] and manual placement of zygomatic implants.[7] In a study by Fortin *et al.*,[15] titanium tubing 10 mm long and of 2 mm internal diameter, and 9 *in-vitro* studies[3,4,8,9,13,14,16-18] preoperative CBCT scan data was the control group. Studies in this systematic review showed differences in the type and dimensions of dental implants and several implants placed or simulations varied from 5 to 480 in the included studies. Most of the studies used sequential drilling techniques to place the implants, however, two studies by Jin *et al.*[11] and Cheng *et al* used conventional sequential drilling technique,[12] and Feng *et al* in their study used a single drilling protocol with 3.5 mm drill and sequential drilling protocol with 2.2, 2.8-, and 3.5-mm drill.[13] Entry deviation, exit deviation, and angular deviation were the errors measured to determine the accuracy of the implant robotic system in the studies *(Table 1*).

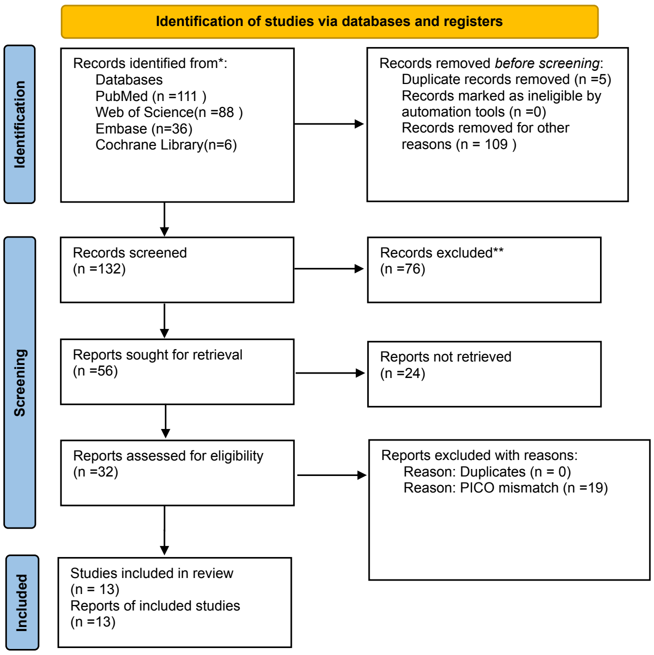

Figure 1: Flow chart of included studies.

CHARACTERISTICS OF IMPLANT PLACEMENT

In vitro studies in this systematic review showed variations in several models used (3D phantom models, reconstructed or simulated cast models), model material (resin, polyurethane, plaster, rapid prototyping using fused deposition modeling technique), and robot characteristics. Two *in-vitro* studies by Tao *et al.*,[2,14] and studies by Jin *et al.*[11] Cheng *et al.*,[12] Xu *et al.*,[16] Chen Jinyan *et al.*[8] and Wang *et al.*[9] used 3D printer, and three studies mentioned printer characteristics as 0.1 mm tolerance, and 0.9 mm positioning error.[2,12,14] Manual change of drill type was done in all included studies, and tracking accuracy was evaluated by CMA-ES algorithm,[13] Polaris optical tracking system,[7] computer-aided design (CAD) implant,[15] 3D slicer,[3] and Rhinoceros 7.0[17] software in studies. Repeatability after 20 different positions was specified in two studies by Jin *et al.*,[11] and Feng *et al.*,[13] and a target position accuracy of 0.03 mm was achieved in one study by Cheng *et al.*[12] Various methods of calibration for implant placement tip-tip,[2] planned drilling trajectory,[13] tool center point (TCP) calibration matrix,[7] U tube,[3] calibration probe,[16] and array plate[8] were used. Image data fusion was performed in most of the studies except studies by Fortin *et al.*,[15] Zhao *et al*,[17] Zhou *et al.*,[18] and Wang *et al.*[9] had not mentioned image fusion. For proper positioning of implants, two studies used spherical markers,[2,11] nine studies used positional marking tools with accuracy measuring gauge,[12] titanium mini-screws and optical markers,[13] mini-screws as fiducial points,[14] six fiducial markers,[17] Polaris

Table 1. General Characteristics of studies included.

Author	Year	Region	Study Design	Implants Placed or Simulations	Drilling Technique used	Control	Type of implant used	Dimensions of implants used	Errors Measured
Tao et al[2]	2022	Shanghai, China	IN VITRO	480	Sequential drilling technique	Implants placed with the Dynamic CAIS group	Strauman AG,	4.1 x 10 mm	Entry deviation, Exit deviation & Angle deviation
Jin et al[11]	2022	Seoul, S. Korea	IN VITRO	14	Conventional Sequential drilling technique	The implant was placed with a 3D-printed surgical stent	Internal connection implant (TS III, Osstem implats)	4.5 x 10 mm	Angular deviation, Linear deviation, and Depth deviation
Cheng et al[12]	2021	Hangzhou, China	IN VITRO	5	Conventional Sequential drilling technique with diameters 2.0 mm, 2.8 mm, 3.25 mm, and 3.75 mm	Preoperative CT scan data using postoperative measuring gauges	No implants placed	No implants placed	Central deviation at hex and apex, Horizontal deviation at the hex and the apex, Vertical deviation at the hex and the apex and Angular deviation
Feng et al[13]	2021	Shanghai, China	IN VITRO	20	Single drilling protocol with 3.5 mm drill and sequential drilling protocol with diameters 2.2 mm, 2.8 mm, and 3.5 mm	Preoperative CT scan data	No implants placed	No implants placed	Entry deviation, Exit deviation & Angle deviation
Tao et al[14]	2022	Shanghai, China	IN VITRO	160	Sequential drilling protocol using twist drills d diameter 2.2 mm, 2.8 mm, and 3.5 mm.	Preoperative CBCT scan data	Strauman AG,	4.1 x 10 mm	Entry deviation, Exit deviation & Angle deviation
Cao et al[7]	2018	Shanghai, China	IN VITRO	12	Not mentioned	Manual placement of zygomatic implants	Zygomatic implants	5 times the size of a normal implant?	Entry deviation, Exit deviation & Angle deviation
Fortin et al[15]	2002	Grenoble, France	IN VITRO	16	1.8 mm drill	Titanium tubing of 2 mm internal diameter and 10 mm long	No implants placed	No implants placed	Accuracy based on Contact with titanium tubing using CT images
Chen et al[3]	2023	Hangzhou, China	IN VITRO	20	Sequential drilling technique	Preoperative CBCT scan data	Nobel Parallel CC	Different dimensions as 3.5 x 8 mm, 4.3 x10 mm, 4.3 x 11.5 mm, and 5.0 x10 mm	Platform, apex, and angular deviation

Table 1 continued overleaf

Table 1. General Characteristics of studies included continued...

Xu et al[16]	2023	Fuzhou, China	IN VITRO	60	Sequential drilling technique	Preoperative CBCT scan data	Nobel	3.5 x 11.5 mm	Coronal, apical, and axial deviation
Chen et al[8]	2023	Shanghai, China	IN VITRO	80	Sequential drilling technique	Preoperative CBCT scan data using postoperative CBCT data with markers	Strauman AG	4.1 x 10 mm	Coronal Deviation, Lateral coronal deviation, Coronal Depth deviation, Apical depth deviation, Lateral apical deviation, Angular deviation
Zhao et al[17]	2023	Wuhan, China	IN VITRO	96	Sequential drill	Preoperative CBCT scan data using postoperative CBCT data with fiducial markers	Strauman AG	4.1 x 10 mm	Platform deviation, apex deviation, angular deviation
Zhou et al[18]	2023	Jiamusi, China	IN VITRO	Not mentioned	Not mentioned	Preoperative CBCT scan data using postoperative CBCT DICOM data with OT – Marker coordinate system	Not mentioned	Not mentioned	Entry level deviation, entry depth deviation, entry deviation, apical level deviation, apical depth deviation, apical deviation, angle deviation.
Wang et al[9]	2024	Wuhan, China	EN VIRO	18	Sequential repeated drilling	Preoperative CBCT scan data using postoperative CBCT data with markers	Strauman AG	4.1 x 8 mm 4.1 x 10 mm 4.1 x 12 mm	Cornoal deviation, apical deviation, angular deviation

CBCT, Cone beam computed tomography; 3D, three dimensional; CAIS, Computer assisted implant surgery; OT-Marker- Optical tracing – Marker; DICOM, Digital Imaging and Communications in Medicine

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optical tracking system,[7] optical tracker coordinate system,[18] radiological markers,[16] silver nitride markers,[8] fixed markers on adjacent teeth[9] and remaining two studies by Fortin *et al.*[15] and Chen Jainping *et al.*[3] have not reported the use of markers or fiducial screws. The duration of the study was not mentioned in all selected studies, and the impact of study duration on outcome measurements to evaluate implant placement accuracy should be taken into account in future studies *(Table 2*).

CHARACTERISTICS OF ROBOTIC SYSTEM

Robotic systems and software for preoperative planning and accuracy measurement varied across the studies, but the control group preoperative image data (computed tomography (CT) or CBCT) was similar. *In vitro* studies in this systematic review were performed by a surgeon except for two studies which were performed by a dentist Xu *et al.*,[16] by both a surgeon and an engineer Fortin *et al.*[15] and one study by Jin *et al.*[11] has not mentioned about this aspect. Studies reported placement of dental implants by automated robots in partially edentulous (Jin *et al.*,[11] Cheng *et al.*,[12] Chin Jinyan *et al.*,[8] Wang *et al.*[9]), edentulous (Cao *et al.*,[7] Fortin *et al.*,[15] Chen Jianping *et al.*,[3] Xu *et al.*,[16] Zhao *et al.*[17]), both edentulous and partially edentulous (Tao *et al.*,[2] Feng *et al.*,[13] Tao *et al.*[14]) and one study by Zhou *et al.*[18] did not report. Implants were placed in both the maxilla and mandible in the studies except in four studies by Feng *et al.*,[13] Cao *et al.*,[7] Chen Jinyan *et al.*,[8] and Wang *et al.*[9] implant placement was done in the maxilla, in two studies by Xu *et al.*[16] and Zhao *et al.*[17] in mandible, and one study by Zhou *et al.*[18] did not report. In addition, only one study by Fortin *et al.*[15] has specified the type of drill motion (pitch) to place the dental implants *(Table 3*).

CHARACTERISTICS OF OUTCOME VARIABLES

Overall, the data was reported as means and standard deviation. Sample size calculation was done in all studies except seven studies by Tao *et al.*,[2] Jin *et al.*,[11] Cheng *et al.*,[12] Cao *et al.*,[7] Fortin *et al.*,[15] Xu *et al.*,[16] and Zhou *et al.*[18] did not report about sample size. Statistically significant differences were obtained for errors measured in the included studies but two studies by Jin *et al.*[11] and Tao *et al.*[14] did not show any significant difference for entry, exit, and angular deviations. No significant difference was observed in angular deviation in a study by Feng *et al.*,[13] for entry and exit deviations (Chen Jianping *et al.*[3]) and entry and angular deviations (Chen Jinyan *et al.*[8]). Four studies (Cheng *et al.*,[12] Cao *et al.*,[7] Zhao *et al.*,[17] and Wang *et al.*[9]) did not report p values *(Table 4*).

QUALITY ASSESSMENT WITHIN STUDIES

The quality assessment of included studies was assessed by using the Quality Assessment Tool For *In Vitro* Studies (QUIN Tool) comprising a list of twelve different criteria as clearly stated aims/objectives, a detailed explanation of sample size calculation, a detailed explanation of sampling technique, details of comparison group, detailed explanation of methodology, operator details, randomization, method of measurement of outcome, outcome assessor details, blinding, statistical analysis, and presentation of results.[19] Each criterion was scored as adequately specified (2 points), inadequately specified (1 point), not specified (0 points), and not applicable (exclude criteria from the calculation). Thereafter, twelve scores were added to obtain a total score for each included invitro study. Thus, the scores obtained were used to grade every single study as high, medium, or low risk (> 70 % as low risk of bias, 50% to 70% as medium risk of bias, and < 50 % as high risk of bias) by using the following formula as Final score = (Total score X 100)/ (2 X number of criteria applicable). Four studies by Tao *et al.*,[14] Chen Jinyan *et al.*,[8] Chen Jianping *et al.*,[3] and Wang *et al.*[9] showed low-risk bias. Seven studies by Tao *et al.*,[2] Jin *et al.*,[11] Feng *et al.*,[13] Cao *et al.*,[7] Xu *et al.*,[16] Zhao *et al.*,[17] and Zhou *et al.*[18] presented medium risk bias, and remaining two studies by Cheng *et al.*[12] and Fortin *et al.*[15] presented high-risk bias *(Table 5*).

DISCUSSION

Dental implants have become a popular treatment of choice for the replacement of missing teeth, to restore function and achieve better esthetics. Our analysis of selected studies suggests that implant robotic systems have the potential to assist dentists with accurate implant surgeries, with short operation and preparation time, and surgeons can perform implant surgeries based on real-time feedback, and can also monitor the performance of robots during surgery. Wang *et al.*[9] have reported that recently immediate implant placement is increasing in demand due to shorter treatment times with comparable outcomes to conventional treatment. In addition, minimally invasive computer-assisted implant surgeries using static guides dynamic navigation systems, and robotic systems have emerged to improve implant accuracy, achieve long-term stability of the implants, and reduce surgical risks.[9] Studies showed a significantly smaller coronal, apical, and angular deviation of the implants in the robotic system group than in the dynamic navigation group.[8] Xu *et al.*[16] compared the accuracy of different dental implant robots classified as active, passive, and semi-active and found that active and passive robots showed comparable accuracy, however implants placed by passive robots depicted significantly higher coronal, apical, and axial deviations in anterior and posterior regions. In their study, the active robot showed the longest preparation time as they had to complete the path planning for the movement of the robotic arm in and out of the mouth, whereas the semi-active robot had the shortest preparation time as the central control system automatically recognized registration.

Studies have reported that robotic systems require correct patient-to-image registration and optimal alignment of fiducial markers can improve the registration accuracy.[17] Zhao *et al.*[17] in their study explored the effect of the number and distribution of fiducial markers by digitally planning and placing four

Table 2. Characteristics of implant placement.

Author	Number of Models	3D printer used	Model materials	Robot characteristics	Duration of the study	3D printer characteristics	Change of drill tips	Tracking Accuracy	Calibration of implant placement	Implant Placement Protocol Control	CBCT image fusion	Fiducial Screws and spherical markers
Tao et al[2]	80 Phantom Models	3D printer, (Zhixi Biomedical Technology, China)	Resin: Somos Evolve 128	The robot has 11 DOF 5-DOF serial manipulator 6-DOF Stewart manipulator	Not Mentioned	0.1 mm tolerance	Manual	Not mentioned	Tip-tip calibration 2 mm	Dynamic CAIS protocol	Semi-automatic surface-based fusion method	Yes and 3 spherical markers were used
Jin et al[11]	1 3D printed phantom head and jaw	3D printer (Form 3, Fromlabs, USA)	Resin	6 DOF Robotic arm with position repeatability of ±0.1 mm 5 kg load capacity and working range of 850 mm	Not Mentioned	Not Mentioned	Manual	Repeatability after 20 different positions	No calibration done	Conventional implant drilling protocol	Best Fit Algorithm	4 spherical markers
Cheng et al[12]	1 3D reconstructed cast model	3D printer (FunMatHT, China)	Resin using fused deposition modeling using polylactic acid	UR 5 robot, Universal robots, Denmark. 5 kg load capacity and working range of 850 mm.	Not Mentioned	0.09 mm positioning error tolerance	Manual	Target position accuracy of 0.03 mm	No calibration done	Not mentioned	Image fusion	Positional marking tool with Accuracy measuring gauges
Feng et al[13]	1 Simulated head model	Not mentioned	Not mentioned	Serial manipulator of hybrid robot: 3-DOF for assisting parallel manipulator position adjustment 2-DOF for assisting parallel manipulator orientation adjustment. 6-DOF for Stewart platform	Not Mentioned	Not mentioned	Manual	CMA- ES algorithm Repeatability after 20 different positions	Planned drilling trajectory using the navigation system	Not mentioned	Image overlap	Titanium mini screw markers and optical markers
Tao et al[14]	32 Simulated Phantom Models	3D printer, (Zhixi Biomedical Technology, China)	Resin: Somos Evolve 128	The robot has 11 -DOF 5-DOF serial manipulator 6-DOF Stewart manipulator	Not mentioned	0.1 mm tolerance	Manual	Not mentioned	Not mentioned	Not mentioned	Semi-automatic surface-based fusion method	Mini screws as fiducial points

Table 2 continued overleaf

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Table 2. Characteristics of implant placement continued...

Cao et al[7]	3 Phantom models	Not mentioned	Not mentioned	The robot has 6 -DOF 6-DOF Stewart manipulator	Not mentioned	Not mentioned	Manual	Polaris optical tracking system	TCP calibration matrix	Manual placement	Image fusion	Polaris optical tracking system
Fortin et al[15]	3 models. Dry maxilla, Plaster cast, and Dry mandible	Not mentioned	Dry Maxilla and mandible and plaster model	Specific 6-axis robot with Laser-guided alignment, mechanical guide alignment, and templates	Not mentioned	Not mentioned	Manual	CAD implant software	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Chen Jianping et al[3]	10 models	Not mentioned	Not mentioned	UR-3e manipulator robotic arm 360^0	Not mentioned	Not mentioned	Manual	3D slicer software	U-tube (Digital Health Care Ltd)	Not mentioned	Image data fusion	Not mentioned
Xu et al[16]	30 mandibular phantoms	3D printer (Wanxiang Technology, China)	Photosensitive resin	Robotic arm with 6^0 freedom (UR 5 robot, Universal robots, Denmark)	Not mentioned	Not mentioned	Manual	Not mentioned	calibration probe was placed at six registration holes	Not mentioned	Image data fusion	Radiological markers
Chen Jinyan et al[8]	40 Upper models	3D Printer (UnionTech Co., Ltd)	photosensitive resin	Not mentioned	Not mentioned	Not Mentioned	Manual	Not mentioned	Array plate used for calibration	Virtual / Dynamic CAIS Protocol	Image fusion	Silver nitride Markers
Zhao et al[17]	24 Phantoms	Not mentioned	Rapid prototype using the fused deposition modeling technique	Not mentioned	Not mentioned	Not mentioned	Manual	Rhinoceros 7.0 software	Not mentioned	Not mentioned	Not mentioned	6 Fiducial Markers
Zhou et al[18]	2 Cubic models	Not mentioned	polyurethane model	Not mentioned	Not mentioned	Not mentioned	Manual	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Optical tracker-marker coordinate system
Wang et al[9]	18 models	3D Printer (UnionTech D600)	Somos EvoLVe 128 resin	Not mentioned	Not mentioned	Not mentioned	Manual	using the marker file, CBCT, and optical tracking locator	Not mentioned	Not mentioned	Fusion	Fixed marker used on adjacent teeth

DOF, Degree of Freedom; CAIS, Computer-assisted implant surgery; TCP, Tool Center Point; CBCT, cone beam computed tomography

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Table 3. Characteristics of the Robotic System.

Author	Robotic system used	Preoperative planning	Control Group	Study performed by	State of Edentulism	Jaw	Type of drill motion Roll or Pitch motion	Accuracy assessment software used
Tao et al[2]	Hybrid Robotic System for Dental Implant Surgery (HRS-DIS; Shanghai, China)	Geomagic Studios, 2013, South Carolina, USA	Preoperative CBCT image data	Surgeon with experience in dCAIS	Edentulous and partially edentulous	Maxilla and Mandible	Not mentioned	BrainLAB AG, Munich, Germany)
Jin et al[11]	Robot arm (Puloon, Korea), Robot operating software (MI2RL, Korea)	MI2RL software for the robotics group	Preoperative CBCT image data, DICOM data	Not Mentioned	Partially Edentulous	Maxilla and Mandible	Not mentioned	3D metrology software- (Geomagic control X), Intraoral scanner (i500, MEDIT Corp.), and Scan body (Geodent Suro) And compared using Best best-fit algorithm
Cheng et al[12]	UR5 Robot arm Universal Robots, Denmark HRCDIS based on Robot Operation System (ROS) and MoveIt	RVIZ robot visualization tool	Preoperative CT image data	Surgeon	Partially Edentulous	Maxilla and Mandible	Not mentioned	Not mentioned
Feng et al[13]	Optical tracking device (NDI), Hybrid robot manipulator	CAPPOIS for preoperative planning	Preoperative CBCT image data	Surgeon	Partially Edentulous and Edentulous	Maxilla	Not mentioned	Not mentioned
Tao et al[14]	HRS-DIS with a Preoperative planning system (Dental-Helper planning software), Navigation system, and a robotic system	BEUDOU – SNS NAVIGATION SOFTWARE	Preoperative CBCT image data	Surgeon	Partially Edentulous and Edentulous	Maxilla and Mandible	Not mentioned	BrainLAB AG, Munich, Germany)
Cao et al[7]	UR robotic system Odense, Denmark	In-house software of CAPPOIS for preoperative planning	Preoperative CT image data	Surgeon	Edentulous – Zygomatic implant	Maxilla	Not mentioned	CAPPOIS
Fortin et al[15]	Specific 6-axis robot with Laser-guided alignment, mechanical guide alignment, and templates	RCS and CAD implant software	Preoperative CBCT image data	Surgeon and Engineer	Edentulous	Maxilla and Mandible	Pitch	Newton plus CAD implant software

Table 3 continued overleaf

Table 3. Characteristics of the Robotic System continued...

Chen Jianping et al[3]	Not mentioned	THETA and Yizhimei	Preoperative and postoperative CBCT image data	Surgeon	Edentulous	Maxilla and Mandible	Not mentioned	Not mentioned
Xu et al[16]	Yomi and DentRobot	UR5, Universal Robots Inc.	Preoperative CBCT DICOM image data	Dentist	Edentulous	Mandible	Not mentioned	Not mentioned
Chen Jinyan et al[8]	Task autonomous robotic system (Remebot Tech); Dynamic navigation system (Yizhime Dcarer)	Robotic/Dynamic navigation software	Preoperative / Postoperative CBCT image data	Surgeon	Partially edentulous	Maxilla	Not mentioned	Not mentioned
Zhao et al[17]	DentRobot, Dcarer	Preoperative surgical planning software	Preoperative CBCT image data	Surgeon	Edentulous	Mandible	Not mentioned	Yizhimei V3.0 software
Zhou et al[18]	Optic-based robotic system (Remebot)	CMM software	Preoperative CBCT image data	Surgeon	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Wang et al[9]	Remember, Ruiyibo Technology	DICOM format using NNT Viewer software	Preoperative CBCT image data, DICOM data	Surgeons	Partially Edentulous	Maxilla	Not mentioned	RemebotDent software

CT, Computed Tomography; CAPPOIS, Computer Assisted Preoperative Planning for Oral Implant Surgery; CAD, Computer Aided Design; CMM, Coordinate Measuring machine; CBCT, Cone Beam Computed tomography

Table 4. Outcome variables of included studies.

Author	Sample size calculation	Entry deviation Mean & SD	Exit Deviation Mean & SD	Angle deviation Mean & SD	Study model	Statistical Analysis and Normality	P value Entry deviation	P value Exit deviation	P value Angle deviation
Tao et al[2]	Not mentioned	0.83 ± 0.55 mm	0.91 ± 0.56 mm	1 ± 0.480	Linear mixed model with random intercept	Normality: Shapiro Wilk test	0.04	0.04	0.00
Jin et al[11]	Not mentioned	0.49(0.39) mm	0.17(0.12) mm	2.38(0.62)	Not mentioned	Homogeneity of Variances: Levene's test Normality: Shapiro Wilk test and Mann-Whitney U test	>0.05	>0.05	>0.05
Cheng et al[12]	Not mentioned	hh/mm 0.61 (0.19) hda/mm 0.91 (0.55)	vdh/mm 0.38 (0.17 via/mm 0.37 (0.20)	3.77 (1.57)	Not mentioned	Mean and standard deviation	Not mentioned	Not mentioned	Not mentioned
Feng et al[13]	Calculated using the CMA-ES algorithm	1.22 mm(0.38)	1.44 mm(0.42)	1.18(0.27)	Not mentioned	Mean and standard deviation	0.0345	<0.001	0.2602
Tao et al[14]	The statistical power of 95% minimum sample size 64 and 114 respectively	1.22 mm(0.38)	1.44 mm(0.42)	1.18(0.27)	Mixed effect model with random intercepts	Mean and standard deviation	0.79	0.88	0.85
Cao et al[7]	Not mentioned	0.8mm(0.54)	0.87mm(0.54)	1.01(0.44)	Not mentioned	Mean and standard deviation	Not mentioned	Not mentioned	Not mentioned
Fortin et al[15]	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Mean	Linear accuracy less than 0.2 mm and rotation less than 1.1°		
Chen Jianping et al[3]	Calculated from results of previous studies	THETA-0.58 mm (0.31) Yizhimei-0.73 mm (0.20)	THETA-0.69 mm (0.28) Yizhimei-0.86 mm (0.33)	THETA-1.08 (0.66) Yizhimei-2.32(0.71)	Not mentioned	Normality: Shapiro Wilk test	>0.05	>0.05	<0.001
Xu et al[16]	Not mentioned	0.31 mm (0.13)	0.37 mm (0.15)	0.64 0 (0.29)	Not mentioned	Normality: Shapiro Wilk test	0.009	<0.001	<0.001
Chen Jinyan et al[8]	Sample size 40	0.46 mm(0.29)	0.56 mm(0.30)	1.360 (0.54)	Simple randomization	Student's two-sample t-tests Kolmogorov-Smirnov test	0.14	.002	.011
Zhao et al[17]	The sample size increased to 96	0.53 mm (0.19)	0.59 mm (0.2)	1.42 0 (0.73)	Not mentioned	Shapiro-Wilk test	Not mentioned	Not mentioned	Not mentioned
Zhou et al[18]	Not mentioned	0.33 mm (0.10)	0.41 mm(0.11)	0.33 0 (0.13)	Not mentioned	Kolmogorov-Smirnov test	<0.001	<0.001	<0.001
Wang et al[9]	Sample size 18 with mean d=0.211	0.87 ± 0.35 mm	0.81 ± 0.34 mm	2.40 ± 1.33°	Simple randomization	GraphPad Prism and Shapiro-wilk test	Not mentioned	Not mentioned	Not mentioned

hda, horizontal deviation at apex; hdh, horizontal deviation at hex; vdh, vertical deviation at apex; vda, vertical deviation at apex; CMA-ES, Covariance Matrix Adaptation Evolution Strategy

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Table 5. Risk of Bias and Quality Assessment using QUIN Tool.

Author	Clearly stated aims/ objectives	Detailed explanation of sample size calculation	Detailed explanation of the sampling technique	Details of the comparison group	A detailed explanation of the methodology	Operator details	Randomization	Method of measurement of outcome	Outcome assessor details	Blinding	Statistical analysis	Presentation of results	Score	Bias Evaluation
Tao et al[2]	2	0	1	2	2	1	0	2	1	1	2	2	16	66.6% (medium risk)
Jin et al[11]	2	0	1	2	2	1	0	2	1	0	2	1	14	58.3% (medium risk)
Cheng et al[12]	2	0	1	1	2	1	0	2	0	0	1	2	12	50.0% (high risk)
Feng et al[13]	2	1	1	1	2	1	0	2	1	0	1	2	14	58.3% (medium risk)
Tao et al[14]	2	2	2	1	2	1	0	2	1	0	2	2	17	70.8% (low risk)
Cao et al[7]	2	0	1	2	2	1	0	2	1	0	2	2	13	54.1% (medium risk)
Fortin et al[15]	2	0	1	1	2	1	0	2	1	0	0	2	12	50.0% (high risk)
Chen Jianping et al[3]	2	1	1	2	2	1	1	2	1	0	2	2	17	70.8% (low risk)
Xu et al[16]	2	0	1	2	2	1	0	2	1	1	2	2	16	66.6% (medium risk)
Chen Jinyan et al[8]	2	1	1	2	2	1	1	2	1	0	2	2	18	75.0% (low risk)
Zhao et al[17]	2	2	1	1	1	1	0	2	0	0	2	2	14	58.3% (medium risk)
Zhou et al[18]	2	0	1	1	2	0	0	2	0	0	2	2	12	50.0% (medium risk)
Wang et al[9]	2	1	1	2	2	1	1	2	1	0	2	2	17	70.8% (low risk)

Score: adequately specified: 2 points; inadequately specified: 1 point; not specified: 0 points; not applicable: NA. Bias: low risk > 70%; medium risk between 70% and 50%; and a high risk < 50%.

implants in edentulous mandibular phantoms under robotic guidance. It was observed that the insertion of six fiducial markers achieved optimal position accuracy at the platform and apex deviations. Additionally, an inverse relationship was demonstrated between implant deviation and the number of fiducial markers at the apex and platform, and this finding signifies that on decreasing the number of fiducial markers there is an increase in target registration error

A dental implant robotic system has been found to achieve stable guidance and provide real-time alignment similar to dynamic navigation, and the robotic arm enables more quicker and accurate adjustments by comparing real-time data. Wang *et al.*[9] suggested that implant shape and length have a significant influence on immediate implant placement accuracy, and they compared the accuracy of tapered and cylindrical implants of three different lengths (8, 10, and 12 mm) in immediate implant placement using robotic systems. Limited bone and uneven bone density have been reported to affect the implant accuracy in immediate implant placement under static or dynamic navigation systems however, in their study, with an implant robotic system implant accuracy was acceptable with reduced deviations that may result from variations in operator experience.[2,9] In addition, high-quality preoperative digital images are required to achieve accurate placement of implants placed by robot-assisted implant surgery.[2,9]

In included studies, robots have been effectively found to increase the accuracy of dental implant surgery compared with manual operation. Feng *et al.*[13] documented that most of the robotic-assisted implant systems are serial robots, with low stiffness and non-unique inverse kinematic solution. To overcome this, they designed a hybrid robot system with higher stiffness and higher precision than serial robots, and the angle, entry, and exit deviation of the hybrid robot was found to be superior to both serial robots and manual operation. This indicates that the hybrid robot system is more stable thereby minimizing surgical risks. In their study, phantom experiments validated the satisfactory performance of the proposed hybrid robot system and could be used in implant surgery in the future.[13] Another study by Cao *et al.*,[7] stated that surgical robots for traditional implant dentistry are not suitable for placement of implants in the zygomatic region due to variable anatomy, limited surgical view, and it becomes more difficult to place implants in severe atrophic maxilla. To reduce complications, they designed and developed a novel surgical robot system and evaluated its accuracy for zygomatic implant placement through phantom experiments. Improved accuracy of the robot operation, with angle, entry point, and exit point deviation was found in comparison to manual operation.

By systematically searching and reviewing all relevant *in vitro* studies on automated implant placement with robots, this systematic review provided a comprehensive evaluation of the current evidence. It allowed for a synthesis of findings across multiple studies, providing a more robust and reliable assessment of the technology's performance in controlled laboratory settings. This systematic review identified gaps in the existing literature and emphasized areas where further research is needed. This could guide future research directions for the designing and development of *in vivo* and clinical studies. This systematic review provided an objective assessment of the available evidence. By adhering to a predetermined set of criteria and using standardized methods for data extraction and analysis, subjectivity, and bias in the interpretation of results were minimized.

Included studies demonstrated heterogeneity which made it challenging to directly compare and combine data across studies, potentially affecting the synthesis and interpretation of results. To establish the efficacy and safety of automated implant placement, extensive clinical studies and trials are required. These studies should compare outcomes of robot-assisted procedures with traditional manual techniques, assessing factors such as implant survival rates, osseointegration, soft tissue healing, and patient satisfaction. Long-term studies are necessary to evaluate the stability and longevity of implants placed by robots. Assessing the success rates and complications over an extended period will provide valuable insights into the durability of robot-assisted implant placements. Further research is needed to enhance the ability of robots to adapt to variations in patient anatomy and clinical situations. This involves developing algorithms and technologies that can handle anatomical complexities, bone quality, and other factors that influence implant placement. A thorough investigation into potential risks associated with robot-assisted implant placement is necessary. Identifying and mitigating possible complications, such as accidental damage to vital structures, infections, or implant mispositioning, should be a priority to ensure patient safety. By addressing these research areas, the field of automated implant placement with robots can progress, ensuring evidence-based implementation and optimizing patient outcomes. Collaboration between dental professionals, engineers, and researchers is crucial for the advancement and validation of this technology.

In conclusion, robotic-placed implants have the potential to revolutionize dental implantology by offering enhanced precision, accuracy, and clinical outcomes compared to traditional surgical guide techniques. The integration of robotics in dental implant procedures holds promise for improving implant survival rates, reducing complications, and ensuring patient satisfaction. Further advancements and widespread adoption of robotic systems in dental implantology are expected as research and development efforts continue to overcome existing challenges. Limited accumulating evidence is available to support the clinical application of robotic implant systems and needs to be explored further by more *in vivo* and clinical studies.

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