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Review article

Robot-assisted dental implant surgery procedure: A literature review

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Abstract Robot-assisted dental surgery has gained significant attention in the field of dental implant therapy as an alternative to conventional free-hand surgery. It addresses challenges faced by human operators, such as limited visibility, operator fatigue, and lack of experience, which can lead to errors. Dental implant robots offer improved precision, efficiency, and stability, enhancing implant accuracy and reducing surgical risks. Accurate placement of dental implants is crucial to avoid complications during and after surgery. Robotic guidance in dental implant surgery provides several benefits. Firstly, the robotic arm offers haptic feedback, allowing physical guidance when placing the implant in the desired position. Secondly, a patient tracker integrated into the robotic system monitors patient movement and provides real-time feedback on a screen. This feature ensures that the surgeon is aware of any changes and can adjust accordingly. Lastly, the robotic system operates under human-robot collaboration, with the surgeon maintaining control and oversight throughout the procedure. Therefore, the objective of the current study is to review the dental implant robots, as well as accuracy

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and efficiency (e.g. operation and preparation time) of robot-assisted dental implant surgery procedures.

Introduction

Modern dentistry aims to restore patients' normal function, speech, health, and aesthetics, regardless of the deterioration, disease, or injury of the stomatognathic system. Dental implants have emerged as an ideal solution for patients who have lost teeth due to various reasons such as periodontal disease or injury.[1] With advancements in implant technology, dental implants have become the preferred choice for tooth restoration. However, precise implant placement is crucial for achieving successful outcomes.[2]

The long-term stability, survival, and success rate of an implant depend on the accuracy of its placement, including its position, angle, and depth within the jawbone.[3] Even a minor error or deviation can have an impact on the three-dimensional position of the implant, its long-term effectiveness (e.g. stability and success rate), and potentially lead to complications by damaging important anatomical structures.[4] Inaccurate insertion can result in intra-operative complications such as severe bleeding, nerve damage, and other accidents, as well as postoperative issues with prostheses.[5,6]

Surgical robots have transformed dental procedures by offering increased precision and decreased invasiveness, leading to better outcomes and decreased complications.[7,8] Dental implant robots comprise three primary parts: a robotic operating platform, a visual system, and a central control system. These elements carry out functions similar to those of a dentist's hands, eyes, and brain, respectively.[9] When performing surgery, the central control system employs the visual system to determine the current position of the area without teeth. It then guides the robotic arm to prepare the implant site and place the implant based on the pre-surgical plan.[10]

Dental implant robots offer great potential in terms of precise, efficient, and stable surgery compared to manual procedures. This potential leads to improved accuracy in implant placement and reduced risks during surgery.[7,9] Several advancements have been made to enhance the accuracy and safety of robot-assisted implant placement. Firstly, the robotic arm provides physical guidance through haptic feedback when positioning the implant. Secondly, a patient tracker is integrated into the robotic system to monitor patient movement and provide real-time feedback on a screen. Lastly, the robotic system is controlled and operated by a human operator, allowing for flexible modifications to the treatment plan and the ability to stop the drilling procedure if necessary.[10,11]

Recently, different types of dental implant robots have been introduced, such as active, passive, and semi-active systems, depending on the level of interaction between the dentist and the robot.[9,12,13] Furthermore, studies have evaluated the accuracy of robot-assisted implant placement.[5,10,11,13–18] Dental implant robots have gained significant attention for their ability to improve the efficiency, stability, and accuracy of implant placement while reducing surgical risks. However, there is currently no comprehensive review that evaluated the effects of dental implant robots on surgical efficiency (preparation and operation time) and the accuracy of implant placement across different robotic systems. Therefore, the objective of this study is to provide a comprehensive literature review on dental implant robots, as well as the accuracy and efficiency (e.g., operation and preparation time) of robot-assisted dental implant surgery procedures.

Robot-assisted implant surgery

Robotics has found applications in various fields, including machinery, electronics, aerospace, and medicine. Particularly in medicine, the use of robotics has gained significant attention. Robotic surgery has revolutionized medical interventions by providing numerous advantages that enhance surgical procedures.[7] These advantages include intra-operative communication, improved visibility of the operative field and critical structures, and enhanced surgical precision. Surgeons benefit from expanded hand-eye capabilities, allowing for better surgical control and reduced surgical damage.[9]

The application of robotics in jawbone reconstruction has been extensively studied for over two decades. Robot-assisted dental surgery has emerged as a prominent topic in dental implant therapy.[9] The development of robotic systems in dental surgery holds great promise for improving the precision and effectiveness of dental implant procedures, ultimately benefiting both patients and practitioners. Dental implant robots can be categorized into active, passive, and semi-active systems based on the level of human-robot interaction:[9,12,13]

1. *Active robots*: Examples include YekeBot (YekeBot Technology Co., Ltd, Beijing, China). These robots can independently enter and exit the mouth, prepare the implant site, and place the implant. The operator's role is primarily to replace the drill, provide instructions, and monitor the robot's operation.
2. *Passive robots*: Robots such as Yomi (Neosis Inc., Miami, United States) and DentRobot (Dcarer Medical Technology Co., Ltd, Suzhou, China) require the operator to guide their robotic arms during the procedure. The operator is responsible for the robot's entry and exit from the mouth, preparation of the implant site, and placement of the implant.

3. *Semi-active robots*: Semi-active implant robots, like the Remebot implant robot (Baihui Weikang Technology Co., Ltd, Beijing, China), can autonomously perform implant site preparation and implant insertion. However, these robots require the operator's assistance in maneuvering the robotic arm during mouth entry and exit.

Dental implant robots

Several dental implant robots have been introduced and utilized in previous studies (Table 1), including the following:

1. *YekeBot dental surgery robot*: YekeBot, developed by Yekebot Technology Co., Ltd (Beijing, China), is an advanced robotic system specifically designed to assist dental surgeons in the precise placement of dental implants. This robot features a robotic arm that is capable of autonomously entering and exiting the patient's mouth, as well as performing drilling and implants placement tasks.[13,19] During the procedure, the dental surgeon activates the robot using a foot controller. The robotic arm then moves to the designated area and automatically adjusts the position of the implant handpiece based on the pre-operative plan. The robot proceeds to prepare the implant site by drilling at a predetermined rate. Once the desired position is reached, the robotic arm returns the handpiece to its initial position. The surgeon then replaces the drill and repeats the process until the implant is successfully placed. Throughout the surgery, the YekeBot manages the movement of the robotic arm, the preparation of the implant site, and the placement of the implant, while the surgeon oversees the operation and provides instructions. This collaborative approach allows for enhanced precision and efficiency in dental implant procedures, potentially reducing the risk of human error and improving patient outcomes.[13,20]
2. *Autonomous robotic computer-assisted implant surgery (r-CAIS)*: r-CAIS is an advanced dental surgery robot that is based on the Remebot robot but with modifications to make it an active robot.[17] It is designed to perform implant osteotomy and placement during surgery with the surgeon's supervision. The technology behind r-CAIS can be divided into two systems: robot assistance and task autonomy.[5] In the robot assistance system, r-CAIS utilizes a semi-active robot, like the Remebot robot, which consists of an operational arm and a coordinate measurement machine arm. This system provides visual guidance and physical feedback (haptic feedback) to the surgeon during the implant osteotomy process.[5] However, the surgeon still maintains continuous control over the operational arm, which can introduce errors and be challenging to manage. On the other hand, the task-autonomy robotic system gives the surgeon discrete control over the r-CAIS system. In this system, the surgeon specifies the location for implant placement, and the robotic system autonomously carries out the implant osteotomy task. The surgeon's role is to monitor the procedure and intervene if necessary. Overall, r-CAIS is an active dental surgery robot that combines robot assistance and task autonomy to enhance the precision and efficiency of implant osteotomy and placement procedures.[17,21]
3. *Yomi dental surgery robot*: Yomi is a passive implant robot developed by Neocis in the United States. It is specifically designed for dental surgery and utilizes a coordinate measuring machine (CMM) arm to assist with the precise positioning of a dental implant. The Yomi system consists of an operational arm that is manually controlled by surgeons and a CMM arm that automatically positions the implant.[11,22] During implant surgery procedures such as drilling and implant placement, the surgeons use the operational arm to perform the drilling while the CMM arm ensures accurate positioning the dental implant. It's worth noting that the CMM arm is more expensive and occupies a narrow space in the patient's oral cavity.[13] Yomi obtained approval from the U.S. Food and Drug Administration (FDA) in 2017, indicating that it meets safety and effectiveness standards.[9]
4. *DentRobot dental surgery robot*: DentRobot, introduced by Dcarer Medical Technology Co., Ltd. in 2022, is a passive implant robot designed to assist in dental implant procedures.[9] The robot utilizes optical tracking technology and is controlled by the surgeon through a foot controller.[23] The surgeon manually guides the robotic arm into the patient's mouth to prepare the implant site and place the implant. During the drilling process, the robotic arm provides three-dimensional physical guidance to the surgeon. If the handpiece position is not optimal, the robot automatically adjusts and repositions it to the ideal position. Once the specified depth is reached, the surgeon removes the robotic arm from the implant site and mouth, replaces the drill, and repeats the process until the implant is placed. The surgeon's responsibilities include maneuvering the robotic arm in the mouth, preparing the implant site, changing the drill, and placing the implant. Additionally, the surgeon supervises the robot's functioning and gives instructions as necessary.[13]
5. *Remebot dental surgery robot*: In 2023, Baihui Weikang Technology Co., Ltd (Beijing, China) introduced Remebot, a semi-active implant robot.[17] Remebot is specifically designed to assist in the preparation and insertion of dental implants. While it can independently perform certain tasks, it still requires manual assistance from the operator during certain stages of the procedure. To operate Remebot, the surgeon uses a foot controller to guide and pull the robotic arm into the patient's mouth. Once inside, the robotic arm takes over and automatically adjusts the position of the implant handpiece, as well as prepares the implant site at a predetermined speed based on the pre-operative plan. The central control system ensures the accurate positioning of the drill. After the implant site is prepared, the robotic arm returns the handpiece to its initial position within the mouth. The process continues with the replacement of the drill, and this cycle is repeated until the implant is successfully placed. Throughout the procedure, the surgeon's primary responsibilities include guiding the robotic arm, replacing the drill, assembling the implant driver and implant, providing instructions, and

Table 1 Application of robots during dental implant surgery procedure.

Type of study	Robot			Comparison Group	Implant					Bone Densities	Accuracy			Time		Refs
	Name	Type	System		Sizes	Systems	Jaw	Positions	Total number of implants		Platform deviation	Apex deviation	Angulation	Preparation Time	Operation Time	
In vitro	HRCDIS	Semi-active	Drilling and placement	—	N/A	N/A	Mandible (phantom)	#35 #36 #45 #46 #47	15	N/A	1.04 ± 0.37 mm	1.56 ± 0.52 mm	3.74 ± 0.67°	N/A	N/A	14
Case series	Remebot	Semi-active	Drilling and placement	—	Diameter: 3.3, 3.4, 4.5, and 4.8 mm Length: 9, 10, 12, and 14 mm	Straumman Axiom Astra	Maxilla Mandible	Single tooth (Immediate and delay)	10	II, III, IV	0.74 ± 0.29 mm	0.73 ± 0.28 mm	1.11 ± 0.46°	N/A	N/A	17
Translational (*in vitro* to clinical application)	Langyue	Semi-active	Drilling and placement	Nothing for clinical study	Diameter: 3.5, 4.3, and 5 mm	Nobel Active or CC	Maxilla Mandible	19 Single tooth 9 Edentulous arches 8 Anterior 20 Posterior	12 (*in vitro*) 28 (clinical study)	N/A	0.53 ± 0.17 mm	0.56 ± 0.134 mm	0.79° ± 0.23°	Single tooth: 13 (12–16.3) min Edentulous: 16 min (4 implants) 23 min (5 implants) min	Single tooth: 9 (7.8–10) min Edentulous: 31 min (4 implants) 46 min (5 implants)	16
Single-blind RCT	Theta	Semi-active	Drilling and placement	Free-hand	Diameter: 3.3/4. and 1 mm Length: 8/10 mm	Straumann	Maxilla Mandible	Single tooth	20	N/A	Robot: 1.17 ± 0.36 mm; Free-hand: 1.88 ± 1.12 mm	Robot: 1.41 ± 0.62 mm; Free-hand: 2.89 ± 1.64 mm	Robot: 3.46° ± 3.11°; Free-hand: 8.23° ± 7.14°	N/A	N/A	18
In vitro	Remebot Yekebot DentRobot	Semi-active Active Passive	Drilling and placement	—	3.5 × 11.5 mm 4.3 × 10 mm	Nobel PMC	Mandible (Phantom)	#31, #36	60	N/A	Semi-active: 0.31 ± 0.10 mm Active: 0.23 ± 0.11 mm Passive: 0.40 ± 0.12 mm	Semi-active: 0.36 ± 0.12 mm Active: 0.24 ± 0.11 mm Passive: 0.49 ± 0.13 mm	Semi-active: 0.43 ± 0.14° Active: 0.54 ± 0.20° Passive: 0.96 ± 0.22°	Semi-active: 1.65 ± 0.19 min Passive: 2.14 ± 0.06 min Active: 3.85 ± 0.17 min	Semi-active: 4.59 ± 0.56 min Active: 4.89 ± 0.70 min Passive: 3.76 ± 0.59 min	13
In vitro	Theta	Semi-active	Drilling and placement	Yizhimei (Active infrared dynamic navigation system)	3.5 × 8 mm 4.3 × 11.5 mm 4.3 × 10 mm 5.0 × 10 mm	Nobel Parallel CC	Maxilla Mandible (Phantom)	#12 #14 #16 #21 #43 #45 #46	20 (10 in each group)	D2, D3	Theta: 0.58 ± 0.31 mm Yizhimei: 0.73 ± 0.20 mm	Theta: 0.69 ± 0.28 mm Yizhimei: 0.86 ± 0.33 mm	Theta: 1.08° ± 0.66° Yizhimei: 2.32° ± 0.71°	N/A	N/A	15
Single-arm clinical study	Yomi	Passive Robot	Drilling and implant placement	—	N/A	N/A	Maxilla Mandible	Complete-arch (Immediate and delay)	38	I-III	1.04 ± 0.70 mm	0.95 ± 0.73 mm	2.56 ± 1.48°	N/A	N/A	5

In vitro	HRS-DIS	Semi-active	Drilling and implant placement	Dynamic navigation (Beidou-SNS)	4.1 × 10 mm	Straumann	Maxilla Mandible (Phantom)	Multiple	480	N/A	Dynamic: 0.96 ± 0.57 mm Robotic: 0.83 ± 0.55 mm	Dynamic: 1.06 ± 0.59 mm Robotic: 0.91 ± 0.56 mm	Dynamic: 2.41 ± 1.42° Robotic: 1.00 ± 0.48°	N/A	N/A	10
In vitro	HRCDIS	Semi-active	Drilling	—	N/A	N/A	Mandible (Phantom)	#35 #36 #45 #46 #47	5	N/A	0.79 ± 0.17 mm	1.26 ± 0.27 mm	3.77 ± 1.57°	N/A		11

Abbreviations: CC, Conical connection; HRS-DIS, Hybrid robotic system for dental implant surgery; HRCDIS, Human-robot collaborative dental implant system; N/A, Not applicable; mm, Millimeter; min, Minute; PMC, Partially machined collar; SNS, Surgical navigation system; Refs, References.

supervising the overall operation of the robot. It's worth noting that Remebot represents advancement in dental implant technology by automating certain aspects of the procedure. However, it is still reliant on the expertise and oversight of a trained surgeon to ensure optimal results and patient safety.[13,24,25]

6. *Theta dental surgery robot*: The Theta robotic dental implant system, developed by Hangzhou Jianjia Robot Co. LTD in 2023, is a semi-active robot specifically designed for dental implant surgery.[9,15] It combines control buttons and an optical navigation system to enable precise positioning, drilling, and placement of dental implants. The system incorporates a UR-3e manipulator with fully rotating wrist joints and end joints capable of infinite rotation.[15,18] By utilizing force sensors, the manipulator can effectively collaborate with users in the same workspace through force position coupling control, ensuring accurate task execution. Theta is a comprehensive system that includes a mechanical arm, a binocular camera, an industrial control computer, an integrating platform, and an operation tool. The manipulator can be equipped with a handpiece to perform dental implant surgery. This system offers advanced capabilities to enhance the precision and efficiency of dental implant procedures, ultimately benefiting both dental professionals and patients.[15,18]
7. *Human—robot collaborative implant system (HRCDIS)*: HRCDIS is a semi-passive robot designed for human-machine collaboration. It incorporates a zero-force hand-guiding scheme and an operational task management system.[14] The robot utilizes a visual position tracking system comprising an optical camera and positioning marker, along with a modified UR5 Cobot from Universal Robots. With this setup, the HRCDIS accurately determines the positions of the robot arm, identifies the precise drilling location and direction, and carries out automatic drilling operations. The robot's semi-passive nature allows it to work in tandem with human operators, enhancing productivity and efficiency in tasks that involve drilling.[14]
8. *Langyue dental surgery robot*: The Langyue dental surgery robot, developed by Shecheng Co. Ltd., is a semi-active collaborative robot specifically designed to assist dental surgeons during procedures. It incorporates both autonomous and passive triggered actions to optimize the surgical process.[16] The robot is capable of autonomously executing tasks such as positioning the infrared tracking probe and robotic arm, maintaining drilling direction, and tracking patient motion. However, it requires human collaboration for the actual drilling procedure. The surgeon initiates the drilling process by applying slight pressure to the handpiece, and they have full control over the pressure and speed of the drill using a haptic controller.[16] The robotic system provides automatic angular control, allowing the surgeon to guide the drill forward or withdraw it. Once the drill reaches the desired depth, the robotic system halts the handpiece to prevent further drilling. The Langyue dental surgery robot comprises several components, including a main robotic arm, an auxiliary robotic arm equipped with a camera, a dental implant drilling system, and a controller. The robotic arms have an impressive

maximum reach of 500 mm and can handle payloads weighing up to 3 kg. The main arm is specifically equipped with a specialized handpiece for tasks such as osteotomy preparation and implant placement, further enhancing its versatility and effectiveness.[16]

9. *Hybrid robotic system for dental implant surgery (HRS-DIS)*: HRS-DIS is a semi-active robot developed in Shanghai, China. It consists of a 5-degree-of-freedom (DOF) serial manipulator and a 6-DOF Stewart manipulator.[10] The serial manipulator expands the robot's workspace, while the Stewart manipulator ensures precise positioning and stiffness. The robot uses a handpiece attached to the Stewart manipulator, allowing the surgeon to manually control its movements using a force transducer. This approach prevents any potential harm to the patient during the initialization procedure. The robot is equipped with a navigation system that tracks the target positions and exchanges data with the robot. The surgeon first adjusts the drill's alignment parallel to the target trajectory using the manipulator. Then, they manually position the handpiece end-effector close to the entry point of the implant trajectory. A second fine adjustment is made using the manipulator, and the drill is raised 2 mm above the entry point. The robot automatically performs the osteotomies and returns to the starting point after the drilling is complete. The handpiece is then removed from the mouth, and the next drill is manually changed. Finally, the robot places the dental implants.[10]

These dental implant robots offer different features and technologies to assist in dental implant procedures, providing improved accuracy and efficiency (e.g. operation and preparation time) in implant placement.

The efficiency of robot-assisted dental implant surgery

Various technologies have been introduced to improve the process of implant placement, including computer-assisted implant surgery. This technology has been well-documented for its ability to significantly enhance the accuracy of implant placement.[26] The goal of computer-assisted implant surgery is to achieve better clinical outcomes by reducing failures, complications, and adverse effects, such as damage to adjacent anatomical tissue and surgical complications;[9,26] computer-assisted implant surgery includes two main technological approaches: static and dynamic computer-assisted implant surgery. In static computer-assisted implant surgery, a surgical guide is used to guide the osteotomy and implant placement. Conversely, the computer-assisted implant surgery system, also known as real-time navigation, assists surgeons in real-time by using optical tracking devices to provide live imaging during the procedure. Both systems are widely used and extensively studied, showing their capability to help surgeons achieve higher accuracy in implant placement compared to free-hand surgery.[9,26] While computer-assisted technologies have improved preoperative planning, surgical templates, and video navigation, they still have some limitations.[26,27] One challenge is ensuring real-time accuracy and stability during drilling and cutting procedures. Additionally, guided dental implant placements are typically performed manually by dentists, which can be affected by human factors and the instability of hands.

To address these concerns, robotic systems have been introduced in dental implant surgery. Recent reports have shown that implants placed by robotic systems are more accurate than those placed by computer-assisted implant surgery systems. Studies and applications of robotic dental implant placement have demonstrated improved intraoperative performance, with enhanced accuracy and safety. In summary, computer-assisted implant surgery has been a significant advancement in improving implant placement, but it still has limitations.[26,27] The introduction of robotic systems in dental implant surgery offers potential improvements in accuracy and safety, and recent studies have shown promising results in this regard.[9,10]

Accuracy

In all studies, the accuracy of implant positioning was assessed using the methodology described by Talmazov et al.[28] Postoperative cone beam computed tomography (CBCT) was employed to measure the extent of deviation in three aspects of the actual implant placement: coronal (platform) deviation, apex deviation, and angular deviation (see Fig. 1). Coronal (platform) deviation refers to the linear displacement, measured in millimeters (mm), between the center of the neck platform of the placed implant and the planned implant. Apex deviation refers to the linear displacement, also measured in millimeters (mm), between the center of the apical part of the placed implant and the planned implant. Axial deviation represents the angle in degrees (°) between the hypothetical central axis of the placed implant and the planned implant.

The standard coronal (platform) deviation, apex deviation, and angular deviation of the first robot that has FDA approval are reported to be 1.04 mm, 0.95 mm, and 2.56°, respectively.[5,16] Overall, the studied robots demonstrated a deviation that was equal to or lower than the global value,

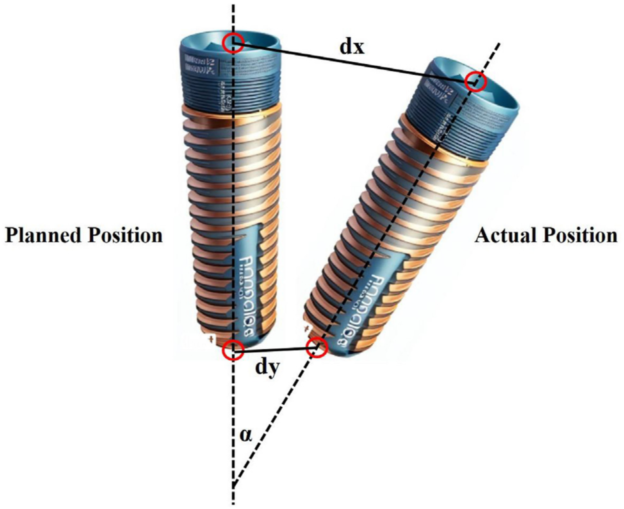

Figure 1 The schematic diagram of measurement accuracy (dx, Coronal [platform] deviation; dy, Apex deviation; α, angular deviation).

indicating an acceptable level of accuracy.[5,10,11,14,16,17] This accuracy can be attributed to the control of angular deviation and axial errors during the procedure.[10,16,17] When compared to free-hand placement, robot-assisted implant placement exhibited significantly greater positional accuracy.[18] The platform deviation, apex deviation, and angular deviation for free-hand placement were reported to be 1.88 ± 1.12 mm, 2.89 ± 1.64 mm, and 8.23° ± 7.14°, respectively. In contrast, robot-assisted placement resulted in a platform deviation of 1.17 ± 0.36 mm, an apex deviation of 1.41 ± 0.62 mm, and an angular deviation of 3.46° ± 3.11°.[18] This improvement in accuracy could be attributed to the reduction of human error and the robot's visual control loop, which compensates for patient movements.[18,29]

Tao et al.[10] and Chen et al.[15] conducted studies comparing the accuracy of robot-assisted placement and computer-assisted dynamic navigation techniques.[10,15] Chen et al.[15] found that the robot-assisted placement system (Theta) had smaller angular deviations compared to the computer-assisted dynamic navigation system (Yizhimei).[15] The deviation values for implant platform, apex, and angulation were 0.58 ± 0.31 mm, 0.69 ± 0.28 mm, and 1.08 ± 0.66°, respectively, for Theta, while they were 0.73 ± 0.20 mm, 0.86 ± 0.33 mm, and 2.32 ± 0.71° for Yizhimei.[15] Although the differences in platform and apex deviation between Theta and Yizhimei were not significant, the angulation deviation in Theta was significantly smaller.[15] In another study by Tao et al.,[10] the robotic system called HRS-DIS was compared to the dynamic navigation system called the Beidou-Surgical navigation system (SNS).[10] The results demonstrated that the robotic system had superior implant positioning accuracy compared to the dynamic navigation system. The mean entry deviation was 0.96 ± 0.57 mm for Beidou-SNS and 0.83 ± 0.55 mm for HRS-DIS, with a significant difference ($p = 0.04$). Similarly, the mean exit deviation was 1.06 ± 0.59 mm for Beidou-SNS and 0.91 ± 0.56 mm for HRS-DIS, also with a significant difference. The mean angle deviation was 2.41 ± 1.42° for Beidou-SNS and 1 ± 0.48° for HRS-DIS, again with a significant difference.[10] These results indicate that the robotic system offers greater accuracy in implant positioning compared to the dynamic navigation system, suggesting its potential as a valuable tool for dental implant surgery. The improved accuracy of the robotic system could be attributed to its ability to stabilize the location and axis of the drills, eliminating human tremors. On the other hand, computer-assisted dynamic navigation heavily relies on the surgeon's skill and experience, which may introduce variability in the accuracy of implant placement.[9,10,15,30,31]

In a study conducted by Xu et al.,[13] they investigated and compared different types of dental implant robots, including active robot (Yekebot), semi-active robot (Remebot), and passive robot (DentRobot).[13] The researchers discovered that the accuracy of implant placement was enhanced when utilizing robots that involved varying degrees of human-robot interaction during the surgical procedure. The active and the semi-active robots demonstrated similar levels of implant accuracy. Conversely, the passive robot exhibited greater deviations in implant placement.[13] This disparity can be attributed to the fact that robotic arms offer a more stable and precise grip on the implant handpiece during surgery, effectively minimizing potential hand tremors that may be present when a dentist performs the procedure manually.[10] Additionally, the dental implant surgery navigation system automatically calibrates and registers the robotic arm, patient, and optical tracker. This eliminates the need for manual calibration and reduces the influence of human factors compared to calibration and registration performed solely by visual observation.[32]

Surgery time

To fully understand the impact of robots on surgical procedures, it is necessary to conduct clinical studies with larger sample sizes and control groups. In general, although there was limited clinical data, *in vitro* studies indicated reasonably fast preparation times. Studies have shown that the duration of surgery using robots is comparable to free-hand surgeries.[13,16] However, a study conducted by Qiao et al.[16] provided some insights into the effect of robots on surgery time. They found that for single-tooth implant placement, the surgical procedures took around 20–25 min, while for two edentulous arches, the procedures took 47 and 70 min. They utilized the Langyue (as a semi-active robot) dental surgery robot, which eliminated the need for manual registration and calibration, making it a more efficient option for full edentulism cases.[16] Furthermore, the operation time varied depending on the type of robot used. The active robot had the longest operation time, while the passive robot had the shortest operation time. This was because the dentist directly guided the robotic arm during the implant bed preparation in the case of the passive robot, resulting in a quicker procedure.[5,13] Also, it is important to note that the use of dental implant robots may increase the pre-operative preparation time. Xu et al.[13] demonstrated that the active robot had the longest preparation time due to the need to transfer the drill's spatial position, conduct calibration and registration, and plan the movement of the robotic arm in and out of the mouth.[13,19] The passive robot required manual manipulation for calibration and registration, while the semi-active robot's central control system automatically recognized the registration. Therefore, the semi-active robot had the shortest pre-operative preparation time.[33]

Safety, advantages, and limitations

Safety concerns during dental implant surgery include the potential for bleeding complications, altered nerve sensation, and the risk of aspirating foreign objects. Fortunately, no complications were reported in the clinical studies.[5,16–18] The key finding across all was that the robotic systems, regardless of type, demonstrated higher accuracy and precision in implant positioning compared to human practitioners. This indicates that robotic systems can surpass the accuracy achieved even by expert clinicians, and would have even greater accuracy gains compared to average dental practitioners.[5,10,11,13–18]

A key advantage of robotic systems is the lack of fatigue or variability inherent in human operators. Factors like exhaustion, stress, or distractions do not affect the precision of robots like they would a human surgeon. The robotic arm can also avoid natural hand tremors that could lead to inadvertent deviations.[34–37] However, all of the robotic systems still require some level of human supervision or collaboration. Most utilized a "semi-active" approach where the robot performs drilling and implant placement but the surgeon monitors progress and can intervene if necessary.[10,11,13–18] Regarding preparation and operation times, while clinical data were limited, the *in vitro* studies showed reasonably quick preparation times. Surgery duration was comparable to human-performed surgeries.[13,16]

Incorporating artificial intelligence (AI) into these systems could push them into an entirely new paradigm.[7] AI algorithms can analyze anatomical CBCT scans, design optimal implant treatment plans, compare pre and post-operative scans, and even control robotic movements more intelligently.[38] During surgery, real-time AI assessment of bone density, proximity to vital structures, and other variables could enable safer and more dynamic surgical guidance.[39] Rather than just following a pre-determined plan, AI-empowered robots could respond to unexpected developments and improve decision-making.[40] They could also accumulate procedural experience and data across surgeries, using that collective knowledge to refine techniques. As computing power and AI capabilities grow, integrating smart learning systems into dental robots could make them autonomous surgeons, executing procedures with far greater precision. The promising accuracy results of current prototypes likely represent just the beginning if AI transforms dental implant robotics.[39]

While robotic systems demonstrate clear advantages for implant placement, it is important to note their limitations in performing advanced reconstructive procedures. The main limitation noted across the reviewed studies was the lack of high-quality clinical research. Many findings were derived from phantom models. More extensive clinical studies on robot-assisted implant placement will be critical to demonstrate long-term safety and efficacy before these systems gain wider adoption. However, initial results demonstrate significantly improved accuracy and precision in implant positioning to make a strong case for robotic dental surgery. The dental implant robots discussed in these studies demonstrate impressive accuracy and precision, but there is room for even more advancement. Also, robot-assisted surgery is costly. Robotic arms are not well-suited for cases involving limited mouth opening and are difficult to use in the second molar area.

The reviewed studies focused primarily on osteotomy and insertion, but dental implants often require auxiliary surgeries such as guided bone regeneration (GBR), sinus lift, or the use of graft materials to ensure sufficient bone volume.[41,42] Humans still significantly outperform robots in handling soft, unpredictable biological tissues, accurate suturing, and decision-making in complex anatomical scenarios. All studies utilized a flapless approach, avoiding the need for soft tissue elevation. Robotic systems currently lack the capability to reflect flaps, handle variable tissue anatomy, or close flaps with sutures. They also cannot perform extraction of failing dentition or subsequent socket preservation. Techniques like GBR utilize barrier membranes and bone grafts secured with pins to encourage site regeneration after implant placement.[43] Delicate handling of friable graft particles and stabilizing tissue layers is extremely difficult to automate. Sinus lift procedures elevate the sinus membrane and often involve intricate membrane repairs if perforated. Free gingival grafts or connective tissue grafts are common for addressing deficient keratinized tissue or isolated recession around implants.[44] The harvesting and suturing of autogenous soft tissue grafts remains completely outside the scope of current dental robots. Though implant positioning itself can be highly optimized with robotics, executing more advanced supplemental surgeries still requires human surgical judgment, tactile feedback, planning flexibility, microsuturing capability, and experience managing intraoperative complications. Robotics-assisted dental surgery currently cannot replicate these higher-level biological capabilities.

In conclusion, dental implant robots have limitations including cost, difficulty in accessing hard-to-reach areas (e.g. second molars), and the inability to manage complex cases (e.g. compromised sinus/nerves, esthetic zone, and insufficient bone quality and quantity) and perform advanced reconstructive procedures. These tasks still require human expertise. However, dental implant robots have demonstrated good accuracy in implant positioning. To ensure long-term safety and efficacy, further high-quality clinical studies are needed. Moreover, since existing studies are limited to laboratory settings or simple cases, no specific recommendations have been made regarding the suitability of dental implant robots for specific conditions. Conducting more studies and exploring different cases would be beneficial. Additionally, there is a need for new robots with more options and functionality compared to current dental implant robots. These new robots should have a smaller size, be able to assist dentists during auxiliary surgeries such as GBR and sinus lift procedures and incorporate AI. The integration of AI into dental implant robots has the potential to revolutionize the field by providing real-time guidance, dynamic decision-making, and autonomous surgical capabilities.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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