Concise Review

Current Status and Future Perspectives of Robot-Assisted Dental Implant Surgery

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ARTICLE INFO

Article history:
Received 2 January 2025
Received in revised form
15 February 2025
Accepted 24 February 2025
Available online xxx

Key words:
Robot
Dental implant surgery
Immediately implantation
Dentition defect
Edentulism

ABSTRACT

Dental implant surgery is now a well versed approach for tooth replacement, addressing various limitations of fixed bridges and removable dentures, thereby reinstating both the form and function of missing teeth. However, it is technically sensitive and highly dependent on the clinical experience and the expertise of the dentist. With breakthrough progress in robot-assisted surgery for a variety of systemic diseases, robot-assisted dental implant surgery has emerged as a new way to potentially enhance the efficacy of dental implant procedures. Widely researched by dental researchers, it is progressively revealing advantages in the treatment of dentition defects or edentulism. This article summarizes the current research status of robot-assisted dental implant surgery and provides a perspective grounded in the ongoing research landscape.

Introduction

According to statistics from the World Health Organization, the estimated global average prevalence of complete tooth loss is almost 7% among people aged 20 years or older. For people aged 60 years or older, a much higher global prevalence of 23% has been estimated. Losing teeth can be psychologically traumatic, socially damaging and functionally limiting.[1] Tooth loss can impair dental function, affecting individuals' eating, speech, aesthetic appearance, psychological well-being, even overall health.[2,3] Dental implant surgery involves the implantation of artificial tooth implants into the jawbone to restore the form and function of missing teeth. Compared to fixed bridges and removable dentures, implant dentures offer advantages such as aesthetics, comfort, good restoration of chewing function, non-damage to adjacent teeth, and long lifespan, gradually becoming an important means of restoring missing teeth.[4] However, traditional dental implant surgery is technically sensitive and can be influenced by the clinical experience or precision of operation of the dentist, and even the dentist's physical condition, leading to potential surgical complications.[5] Therefore, there is an urgent need to explore new methods that can enhance the accuracy of dental implant surgery.

In recent years, robotic surgery has flourished in various medical fields, gradually leading to the refinement and minimally invasive nature of surgical procedures. Some studies have shown that robotic surgery can significantly improve the outcomes of surgeries such as distal gastrectomy, pancreatic resection, knee arthroplasty, hip arthroplasty, and pulmonary lobectomy.[6-11] With the approval of robots for dental implant surgery by the Food and Drug Administration (FDA) in 2017, robot-assisted implant surgery (RAIS) has also attracted the attention of dental scholars and is beginning to be widely researched.[12] However, they are in the early stages of those clinical research, with unconsolidated directions and unclear consensus application procedures and accuracy. Our study summarizes the publications of RAIS and explores its potential applications.

The relevant overview of RAIS

Definition, components, and classification of dental implant robots

Dental implant robots refer to the surgical robots for implanting dental implants. And the "drills" are posited accurately and the computers' motion are controlled by the robots to achieve precise implantation.

Robot-assisted dental implant systems mainly consist of three main components: the robotic arm ("hand"), optical tracking system ("eye"), and surgical navigation software ("brain"), responsible for surgical operations, tracking

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https://doi.org/10.1016/j.identj.2025.02.020

positioning, and overall control. Additionally, dental implant robots include various hardware components such as system integration carts, calibration templates, control pedals, force feedback sensors, and more.

The classification of dental implant robots is similar to the classification of other medical robots. Dupont et al categorized medical robots based on their autonomy level into six categories: non-autonomous (Level 0), robot-assisted (Level 1), robot-controlled (Level 2), conditionally autonomous (Level 3), highly autonomous (Level 4), and fully autonomous (Level 5), with higher levels indicating greater autonomy.[13] Troccaz et al classified medical robots based on their operating modes as passive, teleoperated, semi-autonomous, co-manipulative, and autonomous.[14] Building on these classifications, Lin et al advocate for categorizing dental implant robots as passive robots, semi-autonomous robots, manipulative robots, and autonomous robots.[15] Various commercial dental implant robotic systems that have been published include YOMI, DentRobot, Remebot, Yekebot, Dencore, etc.[16-18]

Clinical process of RAIS

The process of RAIS can be divided into: patient assessment, data collection, implant design and accessory preparation, robot-assisted surgery, and postoperative phase.

When patients arrived, attention should first be given to the patient's systemic diseases, chief complaints, treatment expectations, mouth opening capacity, vertical distance, adjacent teeth, and the condition of surrounding soft and hard tissues. Subsequently, a comprehensive digital intraoral model of the patient is collected, and a registration device (such as a U-shaped tube) is placed at the site of the missing tooth for a parallel cone-beam computed tomography (CBCT) examination. The digital model and CBCT data are imported into the software for robotic design to plan the steps of implant surgery, and 3D printing is used to prepare surgical guides, visual marking connection accessories, auxiliary mouth opening and saliva suction devices, etc. If immediate implant restoration is needed, temporary restorations also need to be designed and fabricated. Registration and calibration need to be completed during the intraoperative phase. Subsequently, the actuator is installed on the robotic arm, and the spatial position is recorded using a tracker; the calibration plate with markers is mounted on the implant site for drilling calibration; the registration probe needs to be sequentially inserted into the registration holes of the clamp positioning plate for spatial registration. The flap elevation is made or not based on the situation. For full-mouth implant surgery, personalized guides are used for invasive or non-invasive fixation. The surgeon monitors the robot operation at all times and issues instructions to stop the surgery if necessary to address emergencies. Postoperatively, a CBCT is required to check the implant status, along with accuracy measurements.[5,19]

The pre-clinical studies of RAIS

Currently published preclinical studies mainly focus on the following aspects (Table 1):[1] Exploring whether RAIS is superior to static computer-assisted implant surgery (sCAIS) or traditional dynamic computer-assisted implant surgery (dCAIS) in accuracy,[2] Investigating the impact of different types of robots, robotic arms, and handpiece on surgical accuracy,[3] Examining the influence of different types of implants, distribution, and quantity of markers on surgical accuracy,[4] Exploring novel implantation patterns of implant robots.

There is controversy regarding whether RAIS is more accurate than sCAIS or dCAIS

sCAIS refers to the application of static computer systems to aid in dental implant surgery, like surgical guides. And traditional dCAIS involves dynamic computer navigation systems to support dental implant procedures, including implant navigation systems. Human directly interact with the surgical site during sCAIS or traditional dCAIS, serving as the primary operators of the surgery. These methodologies are prevalent in clinical practice. Nonetheless, the question of whether RAIS outperforms sCAIS or dCAIS in accuracy remains a topic of debate.

Jain et al[20] and Yang et al[21] conducted systematic reviews and meta-analyses comparing RAIS to static or dynamic CAIS in vitro. They found that in models, the coronal deviation, apical deviation, and angular deviation of RAIS were 0.7 ± 0.1 mm, 0.8 ± 0.2 mm, and 1.8 ± 0.6°, respectively, showing reductions of 0.15 ± 0.09 mm, 0.19 ± 0.08 mm, and 1.22 ± 0.16°, leading to more precise implants.

Mozer et al[22] compared the accuracy of passive robot-assisted dental implant surgery (p-RAIS) (YOMI, Haptic tracking) (n = 51, NobelActive, NobelBiocare Kloten, Switzerland) and CAIS (n = 51, NobelActive, NobelBiocare Kloten, Switzerland) in an in vitro setting. The implants are placed in 15, 16 and 17. All procedures are performed by the same experienced surgeon. They found coronal deviation of 1.51 ± 0.53 mm and 0.79 ± 0.28 mm, apical deviations of 1.97 ± 0.79 mm and 0.82 ± 0.26 mm, and angular deviations of 2.66 ± 1.83° and 0.68 ± 0.38°, respectively. The study indicated that RAIS is less accurate than static CAIS, and contrary to many articles.

He et al[23] compared the accuracy of autonomous robot-assisted dental implant surgery (a-RAIS) (YakeRobot) (n = 40, Straumann, Institute Straumann AG, Basel, Switzerland) with sCAIS (n = 40, Straumann, Institute Straumann AG, Basel, Switzerland) in vitro maxillary models of missing 11. All operators possess over one year of experience in implant surgery and have undergone identical training programs. The coronal deviations were 0.58 ± 0.60 mm and 1.50 ± 1.46 mm, apical deviations were 0.58 ± 0.60 mm and 1.78 ± 1.35 mm, and angular deviations were 1.01 ± 0.87° and 2.93 ± 1.59°, respectively. The results indicated that the apical deviation and angular deviation of a-RAIS were significantly lower than those of static CAIS, with no significant difference in platform deviation.

Guo et al[24] placed 110 implants (Brånemark System ® Zygoma, Nobel Biocare, Balsberg, Switzerland) in 56 vitro models to compare the accuracy of semi- autonomous robot-assisted dental implant surgery (s-RAIS) (Remebot, Passive optical tracking system) and dCAIS of zygomatic implants. All procedures are performed by the same experienced surgeon. The study showed that the coronal deviation (2.39 ± 1.24

Table 1 – The pre-clinical trials of robot-assisted dental implant surgery.

No.	Author	Study Design	Year	Calculated Implants	Robotic systems	Clinical situations	Platform deviation (mean ± SD), mm	Apical deviation (mean ± SD), mm	Angular deviation (mean ± SD), degree	Preparation times (mean ± SD), min	Operation time (mean ± SD), min
1	Jain et al.	Meta-Analysis	2023	610 RAIS: 306 CAIS: 304	NA	NA	−0.15 ± 0.08	−0.19 ± 0.08	−1.22 ± 0.17	NA	NA
2	Yang et al.	Meta-Analysis	2024	809	NA	NA	0.7 ± 0.1	0.8 ± 0.1	1.8 ± 0.6	NA	NA
3	Mozer et al.	Comparative vitro Study	2024	102 RAIS: 51 CAIS: 51	PR (YOMI)	Modified typodont	RAIS: 0.79 ± 0.28 CAIS: 1.51 ± 0.53	RAIS: 0.82 ± 0.26 CAIS: 1.97 ± 0.79	RAIS: 0.68 ± 0.38 CAIS: 2.66 ± 1.83	NA	NA
4	He et al.	Comparative vitro Study	2024	80 RAIS: 40 CAIS: 40	AR (YakeRobot)	Maxillary models	RAIS: 0.58 ± 0.60 CAIS: 1.50 ± 1.46	RAIS: 0.58 ± 0.60 CAIS: 1.78 ± 1.35	RAIS: 1.01 ± 0.87 CAIS: 2.93 ± 1.59	NA	NA
5	Guo et al.	Comparative vitro Study	2024	110 RAIS: 55 CAIS: 55	SR (Remebot)	Zygomatic model	RAIS: 2.39 ± 1.24 CAIS: 1.82 ± 1.25	RAIS: 2.39 ± 1.24 CAIS: 1.83 ± 1.25	RAIS: 1.55 ± 0.82 CAIS: 1.50 ± 0.83	NA	NA
6	Bai et al.	Animal Study	2021	18 RAIS: 9 CAIS: 9	AR (ADIR)	Bilateral mandibular premolars loss in dogs	RAIS: 0.27 ± 0.15 CAIS: 0.91 ± 0.87	RAIS: 0.254 ± 0.218 CAIS: 1.179 ± 0.176	RAIS: 0.99 ± 0.52 CAIS: 4.21 ± 5.21	NA	NA
7	Xu et al.	Comparative vitro Study	2023	60 AR: 20 SR: 20 PR: 20	AR (Yekebot) SR (Remebot) PR (DentRobot)	16 and 36 missed in phantoms	AR: 0.23 ± 0.11 SR: 0.31 ± 0.10 PR: 0.40 ± 0.12	AR: 0.24 ± 0.11 SR: 0.36 ± 0.12 PR: 0.49 ± 0.13	AR: 0.54 ± 0.20 SR: 0.43 ± 0.14 PR: 0.96 ± 0.22	AR: 3.85 ± 0.17 SR: 1.65 ± 0.19 PR: 2.14 ± 0.06	AR: 4.89 ± 0.70 SR: 4.59 ± 0.56 PR: 3.76 ± 0.59
8	Xu et al.	Comparative vitro Study	2024	216 AR: 24 SR: 24 PR: 24 AD: 72 PD: 72	AR (Yekebot) SR (Remebot) PR (DentRobot)	31 and 36 lost in models	AR: 0.29 ± 0.15 SR: 0.33 ± 0.14 PR: 0.40 ± 0.16 AD: 0.85 ± 0.17 PD: 1.05 ± 0.42	AR: 0.29 ± 0.15 SR: 0.36 ± 0.16 PR: 0.50 ± 0.19 AD: 1.11 ± 0.23 PD: 1.07 ± 0.38	AR: 0.61 ± 0.25 SR: 0.42 ± 0.18 PR: 1.04 ± 0.37 AD: 1.78 ± 0.73 PD: 1.99 ± 1.20	NA	NA
9	Qiao et al.	Comparative translational study	2024	36 (a): 12 (b): 12 (c): 12	Co-operating robots with (a), (b) or (c)	Future Industry	(a): 0.50 ± 0.20 (b): 0.39 ± 0.10 (c): 0.37 ± 0.14	(a): 0.52 ± 0.21 (b): 0.41 ± 0.09 (c): 0.44 ± 0.17	(a): 0.72 ± 0.19 (b): 0.73 ± 0.13 (c): 0.75 ± 0.29	NA	NA
10	Wang et al.	Comparative vitro Study	2024	18 CI 8: 3 CI 10: 3 CI 12: 3 TI 8: 3 TI 10: 3 TI 12: 3	SR (Remebot)	Models	CI 8: 0.79 ± 0.18 CI 10: 0.64 ± 0.21 CI 12: 0.64 ± 0.37 TI 8: 0.68 ± 0.26 TI 10: 0.70 ± 0.12 TI 12: 0.71 ± 0.15	CI 8: 0.77 ± 0.33 CI 10: 0.55 ± 0.17 CI 12: 0.65 ± 0.34 TI 8: 0.71 ± 0.20 TI 10: 0.66 ± 0.23 TI 12: 0.77 ± 0.29	CI 8: 1.32 ± 0.19 CI 10: 1.03 ± 0.56 CI 12: 1.31 ± 0.38 TI 8: 1.27 ± 0.64 TI 10: 1.10 ± 0.43 TI 12: 1.05 ± 0.45	NA	NA

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Table 1. (*Continued*)

No.	Author	Study Design	Year	Calculated Implants	Robotic systems	Clinical situations	Platform deviation (mean ± SD), mm	Apical deviation (mean ± SD), mm	Angular deviation (mean ± SD), degree	Preparation times (mean ± SD), min	Operation time (mean ± SD), min
11	Linn et al.	Comparative vitro Study	2023	NA	AR (experimental robotic surgical system)	Partially edentulous models	0.58 ± 0.36	0.99 ± 0.56	3.78 ± 1.97	NA	NA
12	Zhao et al.	Comparative vitro Study	2023	96 (1): 12 (2): 12 (3): 12 (4): 12 (5): 12 (6): 12 (7): 12 (8): 12	PR (DentRbot)	Edentulous mandibular phantoms	(1): 0.73 ± 0.38 (2): 0.73 ± 0.38 (3): 0.56 ± 0.29 (4): 0.53 ± 0.19 (5): 0.61 ± 0.25 (6): 0.60 ± 0.29 (7): 0.71 ± 0.39 (8): 0.64 ± 0.38	(1): 0.80 ± 0.37 (2): 0.79 ± 0.38 (3): 0.64 ± 0.30 (4): 0.59 ± 0.20 (5): 0.69 ± 0.26 (6): 0.68 ± 0.31 (7): 0.74 ± 0.37 (8): 0.70 ± 0.38	(1): 1.49 ± 0.85 (2): 1.40 ± 0.80 (3): 1.52 ± 0.92 (4): 1.42 ± 0.73 (5): 1.48 ± 0.73 (6): 1.51 ± 0.55 (7): 1.66 ± 1.15 (8): 1.18 ± 0.67	NA	NA
13	Li et al.	Animal Study	2020	8	Universal Robots	Phantoms of pigs	1.44 ± 1.0	1.68 ± 0.76	1.01 ± 1.06	NA	NA
14	Sin et al.	Vitro Study	2023	NA	Robots with 6-DOF Motion-Tracking System	NA	NA	NA	NA	NA	NA
15	Tao et al.	Single arm vitro Study	2022	160	HRS-DIS	Phantoms	0.8 ± 0.54	0.87 ± 0.54	1.01 ± 0.44	NA	NA

No., Number; RAIS, robot-assisted implant surgery; CAIS, computer-assisted surgeries; NA, not applicable; AR, autonomous robotic system; SR, semi-active robot system; PR, passive robot system; AD, active dynamic navigation system; PD, passive dynamic navigation system. (a), robotic arm and registration handpiece without lock-on structure. (b), robotic arm and registration handpiece with lock-on structure. (c), robotic arm and sterilized handpiece with lock-on structure. CI, cylindrical implants. TI, tapered implants. (1), three fiducial markers dispersed. (2), three fiducial markers localized. (3), four fiducial markers dispersed. (4), four fiducial markers localized. (5), five fiducial markers dispersed. (6), five fiducial markers localized. (7), six fiducial markers dispersed. (8), six fiducial markers localized. HRS-DIS, dental implant placement by a novel image-guided hybrid robotic system for dental implant surgery.

mm) and apical deviation (2.10 ± 1.12 mm) in the robot group were significantly higher than those in the dynamic navigation group (1.82 ± 1.25 mm, 1.28 ± 0.81 mm); the depth deviation of the robot system (-0.20 ± 1.25 mm) was significantly lower than that of the dynamic navigation group (0.44 ± 1.56 mm), but there was no statistical difference in apical and entry deviations between the two groups. This study indicated that robot-assisted zygomatic implant surgery can effectively prevent implants from being placed too deep, although with slightly lower accuracy.

Bai et al[25] extracted bilateral maxillary premolars from 9 Chinese rural dogs to prepare mandibular dental arch defect models, and used RAIS (ADIR) and CAIS. They found that the coronal deviation, apical deviation, and angular deviation of RAIS (0.269 ± 0.152 mm, 0.254 ± 0.218 mm, and 0.989° ± 0.517°) were significantly lower than those of CAIS (0.910 ± 0.872 mm, 1.179 ± 1.176 mm, and 4.209 ± 5.208°), with no significant difference in initial stability between the two groups. This study suggested that in animal experiments, RAIS offers higher precision compared to CAIS.

Autonomous or semi-autonomous RAIS may offer better accuracy than passive robots

Publications primarily compares the surgical time and accuracy of a-RAIS, s-RAIS, and p-RAIS with these studies supporting the higher accuracy of autonomous robot (AR) or semi-autonomous robot (SR). The accuracy of AR is not inferior to that of SR.

Xu et al[26] used AR (Yekebot, n = 20), SR (Remebot, n = 20), and passive robot (PR) (DentRobot, n = 20) for dental implant surgery in vitro model with missing teeth.[31,36] The preparation times were 3.85 ± 0.17 minutes, 1.65 ± 0.19 minutes, and 2.14 ± 0.06 minutes, while the operation times were 4.89 ± 0.70 minutes, 4.59 ± 0.56 minutes, and 3.76 ± 0.59 minutes, respectively. The coronal deviations were 0.23 ± 0.11 mm, 0.31 ± 0.10 mm, and 0.40 ± 0.12 mm, the apical deviations were 0.24 ± 0.11 mm, 0.36 ± 0.12 mm, and 0.49 ± 0.13 mm, and the angular deviations were 0.54 ± 0.20°, 0.43 ± 0.14°, and 0.96 ± 0.22°. This study indicated that p-RAIS had shorter average surgical times and larger deviations, with no significant difference between a-RAIS and s-RAIS of the accuracy.

Xu et al[16] compared the accuracy of a-RAIS (Yekebot) (n = 12, 24 implants), p-RAIS (DentRobot) (n = 12, 24 implants), s-RAIS (Remebot) (n = 12, 24 implants), and active dynamic computer-assisted dental implant surgery (AD-RAIS) (n = 36, 72 implants), passive dynamic computer-assisted implant surgery (PD-RAIS) (n = 36, 72 implants) in vitro model. Surgeons implanted implants at positions 31 and 36 on each model, repeating the process 12 times. The coronal deviations of the implants were 0.85 ± 0.17 mm, 1.05 ± 0.42 mm, 0.29 ± 0.15 mm, 0.40 ± 0.16 mm, and 0.33 ± 0.14 mm; the apical deviations were 1.11 ± 0.23 mm, 1.07 ± 0.38 mm, 0.29 ± 0.15 mm, 0.50 ± 0.19 mm, and 0.36 ± 0.16 mm; and the angular deviations were 1.78 ± 0.73°, 1.99 ± 1.20°, 0.61 ± 0.25°, 1.04 ± 0.37°, and 0.42 ± 0.18°. The study found that the apical deviation of a-RAIS was significantly lower than that of PD-CAIS, and the angular deviations of a-RAIS and s-RAIS were significantly lower than those of p-RAIS.

The different combinations of robotic arms and handpiece may not be related to the accuracy of implants

Qiao et al[27] conducted oral implant surgery using a non-locking structure robotic arm with a standard handpiece, a locked structure robotic arm with a standard handpiece, and a locked structure robotic arm with a sterilized handpiece on a resin dental arch model that they designed. They found that the accuracy was within 0.3 mm, with coronal deviations of 0.50 ± 0.20 mm, 0.39 ± 0.10 mm, 0.37 ± 0.14 mm, apical deviations of 0.52 ± 0.21 mm, 0.41 ± 0.09 mm, 0.44 ± 0.17 mm, and angular deviations of 0.72 ± 0.19°, 0.73 ± 0.13°, 0.75 ± 0.29°, with no significant differences between the three methods.

The accuracy of RAIS is not related to shape and length but is related to the diameter of the implants

Wang et al[28] used RAIS (Remebot) to implant different shapes (Straumann) of implants in vitro models. They found that for implants of different shapes and lengths (8 mm cylindrical, 10 mm cylindrical, 12 mm cylindrical, 8 mm tapered, 10 mm tapered, 12 mm tapered), the platform deviations were 0.79 ± 0.18 mm, 0.64 ± 0.21 mm, 0.64 ± 0.37 mm, 0.68 ± 0.26 mm, 0.70 ± 0.12 mm, 0.71 ± 0.15 mm, apical deviations were 0.77 ± 0.33 mm, 0.55 ± 0.17 mm, 0.65 ± 0.34 mm, 0.71 ± 0.20 mm, 0.66 ± 0.23 mm, 0.77 ± 0.29 mm, and angular deviations were 1.32 ± 0.19°, 1.03 ± 0.56°, 1.31 ± 0.38°, 1.27 ± 0.64°, 1.10 ± 0.43°, 1.05 ± 0.45°. This study indicated that the shape and length of the implant do not affect the accuracy of RAIS.

Linn et al[29] compared the accuracy of robot-assisted (experimental robotic surgical system) and freehand implantation of three different diameter implants (Ø = 3.5 × 10 mm, 4.0 × 10 mm, 5.0 × 10 mm) (n = 76) in vitro models. The study showed that the platform deviation of RAIS was 0.58 ± 0.36 mm, apical deviation was 0.99 ± 0.56 mm, and angular deviation was 3.78 ± 1.97°. The study found that the largest deviation occurred when using robot-assisted implantation of a 5 mm diameter implant, suggesting that robot assistance is more accurate for the placement of smaller diameter implants.

Increasing the number of reference points may reduce the deviation of implantation

Zhao et al[30] explored the impact of the number and distribution of reference points on the accuracy of RAIS (DentRbot) in edentulous mandible patients. They used different numbers of reference points (3,4, or 5) and different distributions (localized or dispersed) for marking on the models. The results showed that using 6 points significantly reduced the platform deviation (0.53 ± 0.19 mm) and apical deviation (0.59 ± 0.2 mm), but there was no significant change in angular deviation, and the concentration or dispersion of reference points had no significant impact on accuracy.

New calibration and tracking methods of robots are expected to further improve surgical accuracy

Li et al[31] proposed a new optical navigation method for robot automatic calibration in dental implant surgery and validated its application in implant surgery on the maxilla of pigs. The study found that the platform deviation of RAIS using this new calibration method was 1.44 ± 1.0 mm, apical deviation was 1.68 ± 0.76 mm, and angular deviation was 1.01 ± 1.06°, which is lower than the reported deviations of template-guided or optical navigation-assisted dental implant surgery.

Sin et al[32] suggested optical tracking systems of RAIS often used for positioning, but optical tracking may have limitations such as fixed markers, insufficient light sources, or line-of-sight obstacles. They proposed a new 6-degree-of-freedom motion tracking system composed of an end effector clamp fixed inside the patient's alveolar, a 3-degree-of-freedom translational motion tracking structure, and a 3-degree-of-freedom rotational motion tracking structure, with the introduction of a passive gravity compensation mechanism to enhance reverse driving performance. This system is expected to provide real-time measurements and high reverse driving performance, with higher reliability and usability.

Tao et al[33] developed a novel image tracking hybrid system for dental implant surgery, which combines a 5-degree-of-freedom serial mechanical arm and a 6-degree-of-freedom Stewart platform. They implanted 160 implants in 32 models to verify the accuracy, and the results showed that the platform deviation, apical deviation, and angular deviation of RAIS using this hybrid system were 0.8 ± 0.54 mm, 0.87 ± 0.54 mm, and 1.01 ± 0.44°, respectively. This vitro study suggested that precise implantation can be performed by this hybrid system for dental implant surgery.

We analyzed of data extracted from the aforementioned pre-clinical studies, revealing that in RAIS, the coronal deviation was 0.76 ± 0.75 mm (AR: 0.45 ± 0.42 mm; SR: 1.35 ± 1.31 mm; PR: 0.62 ± 0.31 mm), apex deviations were 0.83 ± 0.75 mm (AR: 0.57 ± 0.54 mm; SR: 1.36 ± 1.30 mm; PR: 0.69 ± 0.30 mm), and angular deviations were 1.18 ± 1.02°(AR: 1.67 ± 1.80°; SR: 1.07 ± 0.79°; PR: 1.15 ± 0.70°). While inconsistencies exist in the utilization of implant robotic systems, static or dynamic navigation assistance systems, implant diameters, and brands across preclinical investigations, the majority of studies suggest that RAIS demonstrates superiority or at least non-inferiority to sCAIS or dCAIS. Furthermore, the study indicated that AR may exhibit better control over coronal and apex deviations, while SR could potentially offer advantages in managing angular deviations; however, statistical significance has not been established. Enhancements in accuracy for RAIS may be achievable through the implementation of smaller diameter implants, increased markers, and novel configurations.

Clinical trials of RAIS

Current published clinical trial mainly focuses on the following aspects (Table 2)[1]: exploring whether RAIS can effectively control implant deviations,[2] the impact of different surgical sites, flapless procedures, implant lengths, and different surgeons on surgical accuracy,[3] the clinical application of RAIS in patients with edentulous,[4] the clinical application of robot-assisted immediate implantation in patients with missing anterior teeth,[5] the clinical application of RAIS in patients with jaw bone defects.

RAIS can effectively control implant deviations

Yang et al[21] and Khaohoen et al[34] conducted systematic reviews and meta-analyses on clinical studies comparing RAIS and CAIS. They found that the coronal deviations of RAIS were 0.6 ± 0.1 mm and 0.81 ± 0.44 mm, apical deviations were 0.7 ± 0.2 mm and 0.77 ± 0.34 mm, and angular deviations were 1.6 ± 0.5° and 1.71 ± 1.67°, respectively. The results indicate that RAIS is likely to improve the accuracy of CAIS and become a new clinical recommendation. However, the number of studies on CAIS included in this research is limited, and further studies are needed.

In recent years, several scholars have conducted retrospective clinical studies on the accuracy of RAIS and CAIS, finding that the accuracy of RAIS is significantly better than that of CAIS. He et al[23] collected data from RAIS (YakeRobot, n = 32, 52 implants) and CAIS (n = 28, 55 implants) conducted between 2019 and 2023. They found that the coronal deviation (0.45 ± 0.28 mm), apical deviation (0.47 ± 0.28 mm), and angular deviation (0.95 ± 0.50°) of RAIS were significantly lower than those of CAIS (1.45 ± 1.27 mm, 1.77 ± 1.14 mm, 4.31 ± 2.60°). Zhang et al[35] compared the accuracy and pain levels of dCAIS (n = 38 patients, 62 implants) and s-RAIS (n = 39 patients, 62 implants), finding that the coronal deviation (0.68 ± 0.36 mm), apical deviation (0.69 ± 0.36 mm), and angular error (1.37 ± 0.92°) of a-RAIS were significantly lower than those of dynamic navigation-assisted oral implant surgery (1.25 ± 0.54 mm, 1.39 ± 0.52 mm, 4.09 ± 1.79°); there was no significant difference in patient pain scores. Jia et al[36] compared a-RAIS (ADIR, n = 20, 30 implants) with sCAIS (n = 19, 30 implants) for oral implantation and found no complications. The coronal deviation, apical deviation, and angular deviation in the autonomous robot group were significantly lower than in the static navigation group (coronal deviation: 0.43 ± 0.18 mm vs 1.31 ± 0.62 mm; apical deviation: 0.56 ± 0.18 mm vs 1.47 ± 0.65 mm; angular deviation: 1.4 ± 0.59° vs 2.4 ± 1.55°).

Several single-arm studies have also found that RAIS can effectively control implant deviations. Yang et al[37] used Remebot to conduct a case series study on 10 patients with a single implant, with no adverse events or postoperative complications reported. The average coronal deviation was 0.74 ± 0.20 mm, apical deviation was 0.73 ± 0.20 mm, and angular deviation was 1.11 ± 0.33°. Chen et al[38] performed RAIS (Dencore) on 28 patients (31 implants), with coronal deviation, apical deviation, and angular deviation of 0.53 ± 0.23 mm, 0.53 ± 0.24 mm, and 2.81 ± 1.13°, respectively. Klass et al[39] conducted a-RAIS or s-RAIS on patients with missing teeth (n = 7, 10 implants). The study found that 8 implants were buccally inclined compared to the planned design. The coronal deviation, apical deviation, and angular deviation of implants in a-RAIS were 1.31 ± 0.46 mm, 1.58 ± 0.61 mm, and 2.34 ± 1.71°, respectively. For s-RAIS, the coronal deviation, apical deviation, and angular deviation of implants were 1.31 ± 0.49 mm, 1.45 ± 0.3 mm, and 3.75 ± 2.53°. Compared to reported accuracy of CAIS, RAIS demonstrated higher precision.

Since 2024, several researchers have conducted prospective studies on RAIS, and the results also support the efficacy of deviations by RAIS. Yang et al[40] conducted a four-center, randomized controlled trial to compare the accuracy of s-RAIS (THETA, n = 70) with conventional freehand dental

Table 2 – The clinical trials of robotic system-assisted dental implant surgery.

No.	Author	Study Design	Year	Calculated Implants	Robotic systems	Clinical situations	Platform deviation (mean ± SD), mm	Apical deviation (mean ± SD), mm	Angular deviation (mean ± SD), degree	Preparation times (mean ± SD), min	Operation time (mean ± SD), min
1	Yang et al.	Meta-Analysis	2024	257	NA	NA	0.6 ± 0.1	0.7 ± 0.2	1.6 ± 0.5	NA	NA
2	Khaohoen et al.	Meta-Analysis	2024	5673 RAIS: 44 CAIS: 5629	NA	NA	RAIS: 0.81 ± 0.44 CAIS: 1.11 ± 0.08	RAIS: 0.77 ± 0.34 CAIS: 1.40 ± 0.09	RAIS: 1.71 ± 1.67 CAIS: 3.51 ± 0.26	NA	NA
3	He et al.	Retrospective Comparative	2024	113 RAIS: 58 CAIS: 55	AR (YakeRobot)	NA	RAIS: 0.45 ± 0.28 CAIS: 1.45 ± 1.27	RAIS: 0.47 ± 0.28 CAIS: 1.77 ± 1.14	RAIS: 0.95 ± 0.50 CAIS: 4.31 ± 2.60	NA	NA
4	Zhang et al.	Retrospective Comparative	2024	124 RAIS: 62 CAIS: 62	AR	Partially edentulous	RAIS: 0.68 ± 0.36 CAIS: 1.25 ± 0.54	RAIS: 0.69 ± 0.36 CAIS: 1.39 ± 0.52	RAIS: 1.37 ± 0.92 CAIS: 4.09 ± 1.79	NA	NA
5	Jia et al.	Retrospective Comparative	2023	60 RAIS: 30 CAIS: 30	AR (ADIR)	Partially edentulous	RAIS: 0.43 ± 0.18 CAIS: 1.31 ± 0.62	RAIS: 0.56 ± 0.18 CAIS: 1.47 ± 0.65	RAIS: 1.48 ± 0.59 CAIS: 2.42 ± 1.55	NA	NA
6	Yang et al.	Case series	2023	10	~~A~~SR (Remebot)	A single missing tooth	0.74 ± 0.20	0.73 ± 0.20	1.11 ± 0.33	NA	NA
7	Chen et al.	Prospective single-arm	2023	31	PR (Dencore)	Partially edentulous	0.53 ± 0.23	0.53 ± 0.24	2.81 ± 1.13	NA	NA
8	Klass et al.	Single-arm	2024	10 AR: 7 SR: 3	NA	Partially edentulous	AR: 1.31 ± 0.46 SR: 1.31 ± 0.49	AR: 1.58 ± 0.61 SR: 1.45 ± 0.3	AR: 2.34 ± 1.71 SR: 3.75 ± 2.53	NA	NA
9	Yang et al.	Muti-center randomized clinical trial	2024	140 RAIS: 70 FHIS: 70	SR (THETA)	A single missing tooth	RAIS: 0.76 ± 0.36 FHIS: 1.48 ± 0.93	RAIS: 0.85 ± 0.48 FHIS: 2.14 ± 1.25	RAIS: 2.05 ± 1.33 FHIS: 7.36 ± 4.67	NA	NA
10	Wang et al.	Prospective single-arm	2024	20	AR	Partially edentulous	0.65 ± 0.32	0.66 ± 0.34	1.52 ± 1.01	NA	NA
11	Wu et al.	Prospective single-arm	2024	86	AR	Partially edentulous	0.61 ± 0.20	0.79 ± 0.32	2.56 ± 1.10	NA	NA
12	Neugarten	Prospective single-arm	2024	273	PR(YOMI)	Partially edentulous	1.10 ± 0.69	1.12 ± 0.69	1.42 ± 1.53	NA	NA
13	Yang et al.	Case report	2022	6	SR (Remebot)	Fully edentulous	0.59 ± 0.24	0.61 ± 0.23	0.89 ± 0.38	NA	NA
14	Li et al.	Retrospective case series	2023	59	AR	Fully edentulous	0.67 ± 0.37	0.69 ± 0.37	1.27 ± 0.59	NA	NA
15	Shu et al.	Retrospective case series	2024	28	AR	Fully edentulous	0.91 ± 0.43	1.01 ± 0.45	1.21 ± 1.24	NA	NA
16	Xie et al.	Prospective single-arm	2024	102	AR (YakeRobot)	Fully edentulous	0.53 ± 0.19	0.58 ± 0.17	1.83 ± 0.82	NA	NA
17	Bolding et al.	Prospective single-arm	2022	38	PR (YOMI)	Fully edentulous	1.04 ± 0.70	0.95 ± 0.73	2.56 ± 1.48	NA	NA
18	Wang et al.	Prospective Comparative	2024	84 RAIS: 36 CAIS: 48	PR (Yakebot)	Fully edentulous	RAIS: 0.65 ± 0.25 CAIS: 1.37 ± 0.72	RAIS: 0.65 ± 0.22 CAIS: 1.28 ± 0.68	RAIS: 1.43 ± 1.18 CAIS: 3.47 ± 2.02	NA	NA

(continued on next page)

Table 2. (*Continued*)

No.	Author	Study Design	Year	Calculated Implants	Robotic systems	Clinical situations	Platform deviation (mean ± SD), mm	Apical deviation (mean ± SD), mm	Angular deviation (mean ± SD), degree	Preparation times (mean ± SD), min	Operation time (mean ± SD), min
19	Liu et al.	Case report	2024	1	AR	22 missed	NA	NA	NA	10	20
20	Jia et al.	Case report	2024	1	AR	11 missed	0.86	0.72	0.85	NA	NA
21	Zhao et al.	Retrospective case series	2024	20	SR	Maxillary anterior teeth missed	0.75 ± 0.20	0.70 ± 0.27	1.17 ± 0.73	NA	NA
22	Li et al.	Retrospective Comparative	2024	106 RAIS: 33 CAIS: 33 FHIS: 40	SR (Remebot)	Maxillary anterior teeth missed	RAIS: 0.62 ± 0.28 CAIS: 1.01 ± 0.41 FHIS: 1.29 ± 0.52	RAIS: 0.65 ± 0.27 CAIS: 1.24 ± 0.52 FHIS: 1.78 ± 0.59	RAIS: 1.46 ± 0.57 CAIS: 2.94 ± 1.71 FHIS: 6.46 ± 2.21	NA	NA
23	Li et al.	Case report	2023	2	SR (Remebot)	1626 missed severe atrophy in the maxilla	16: 0.98 26: 0.68	16: 1.02 26: 1.17	16: 1.21 26: 1.70	NA	NA
24	Deng et al.	Single-arm	2023	8	SR (Remebot)	Severe atrophy in the maxilla	0.97 ± 0.42	1.27 ± 0.56	1.48 ± 0.52	NA	NA
25	Deng et al.	A new technique	2023	NA	AR	Severe atrophy in the maxilla	NA	NA	NA	NA	NA
26	Su et al.	Case report	2024	1	AR	Severe atrophy in maxilla	0.56	0.59	0.94	NA	NA
27	Li et al.	Case report	2024	1	AR	Severe atrophy in Mandible	0.50	0.51	1.29	NA	NA

No., Number; NA, not applicable; RAIS, robot-assisted implant surgery; CAIS, computer-assisted surgeries; AR, autonomous robotic system; SR, semi-active robot system; FHIS, free-hand implant surgery.

implant surgery (n = 70) in patients with single missing teeth. The results showed that the coronal deviation, apical deviation, and angular deviation in the s-RAIS group were significantly lower than in the freehand group (s-RAIS: 0.76 ± 0.36 mm, 0.85 ± 0.48 mm, and 2.05 ± 1.33°; freehand: 1.48 ± 0.93 mm, 2.14 ± 1.25 mm, and 7.36 ± 4.67°). Wang et al[41] performed RAIS to 13 patients (20 implants) and found that the coronal deviation, apical deviation, and angular deviation were 0.65 ± 0.32 mm, 0.66 ± 0.34 mm and 1.52 ± 1.01°, respectively. Wu et al[42] used AR for RAIS (n = 74, 86 implants) without any adverse events during the procedure. The coronal deviation, apical deviation, and angular deviation of the implants were 0.61 ± 0.20 mm, 0.79 ± 0.32 mm, and 2.56 ± 1.10°, respectively. Neugarten[43] conducted a study on 108 patients (273 implants) of RAIS (YOMI) and found that the coronal deviation, apical deviation, and angular deviation of the implants were 1.10 ± 0.69 mm, 1.12 ± 0.69 mm, and 1.42 ± 1.53°, demonstrating higher accuracy compared to freehand implantation and static or dynamic computer-assisted oral implant surgery.

The clinical application of RAIS in edentulous patients with edentulous

Full-mouth dental implant surgery requires balancing the orientation and position of all implants, and patients are often elderly with systemic diseases, which demand higher technical requirements for oral surgeons. Clinical research on RAIS for patients with edentulous has gradually been carried out.

Yang et al[44] used SR (Remebot) to implant 6 implants in a 58-year-old female patient with maxillary dentition missing and performed immediate restoration. The coronal deviation, apical deviation, and angular deviation were 0.59 ± 0.24 mm, 0.61 ± 0.23 mm, and 0.89 ± 0.38°, respectively. This demonstrated the feasibility of a-RAIS for immediate implant restoration in the edentulous. Li et al[45] and Shu et al[46] conducted retrospective studies on 10 edentulous patients (59 implants) and 3 edentulous patients (immediately, 28 implants) using RAIS. No adverse events were reported, and the coronal deviations were 0.67 ± 0.37 mm, 0.91 ± 0.43 mm while the apical deviations were 0.69 ± 0.37 mm, 1.01 ± 0.45 mm, and the angular deviations were 1.27° ± 0.59°,1.21 ± 1.24°, respectively. Both studies indicated that RAIS provided higher accuracy in the restoration of edentulous patients compared to traditional implant surgery, warranting clinical promotion.

In the past three years, several articles have prospectively studied the application of RAIS in edentulous patients. Xie et al[47] and Bolding et al[48] performed RAIS on 12 edentulous patients (YakeRobot, 102 implants) and 5 edentulous patients (YOMI, 38 implants) respectively, finding coronal deviations of 0.53 ± 0.19 mm, 1.04 ± 0.70 mm, apical deviations of 0.58 ± 0.17 mm, 0.95 ± 0.73 mm, and angular deviations of 1.83 ± 0.82°, 2.56 ± 1.48°. Rui Xie et al found that the periodontal indices, buccal bone thickness, and alveolar bone remained stable during the one-year follow-up. Wang et al[49] compared Yakebot RAIS (n = 3, 36 implants) with CAIS (n = 5, 48 implants) in edentulous patients and found significant differences in coronal deviation, apeical deviation, and angular deviation between the two groups (robot group: 0.65 ± 0.25 mm, 0.65 ± 0.22 mm and 1.43 ± 1.18°; computer group: 1.37 ± 0.72 mm, 1.28 ± 0.68 mm and 3.47 ± 2.02°). This suggests that RAIS is more precise than CAIS and is a promising treatment modality.

Robot-assisted immediate implant restoration in the anterior maxillary region

Anterior maxillary tooth loss significantly affects patients' aesthetics and speech. To minimize the impact of missing teeth, immediate implant restoration is often performed after tooth extraction. Liu et al[50] and Jia et al[51] each reported a case of a-RAIS in the anterior maxillary region, achieving good aesthetic results and comfort. Zhao et al[52] also used a robot for immediate implant surgery in the anterior maxillary region (n = 15, 20 implants) and found coronal deviations, apical deviations, and angular deviations of the implants to be 0.75 ± 0.20 mm,0.70 ± 0.27 mm and 1.17 ± 0.73°, respectively. They also observed that RAIS positioned the implants more towards the lip side and apex than planned. These case reports preliminarily confirm the feasibility and accuracy of robots in immediate restoration of anterior maxillary tooth loss.

Retrospective clinical studies also indicate the meaningful use of robots in immediate implant restoration for anterior tooth loss. Li et al[53] conducted immediate implant surgery in the anterior maxillary region using robots (Remebot, n = 21, 33 implants), static computers (n = 18, 33 implants), and freehand (n = 30, 40 implants), studying the accuracy of implant placement. The results showed coronal deviations of 0.62 ± 0.28 mm, 1.01 ± 0.41 mm and 1.29 ± 0.52 mm; apical deviations of 0.65 ± 0.27 mm, 1.24 ± 0.52 mm and 1.78 ± 0.59 mm; and angular deviations of 1.46 ± 0.57°, 2.94 ± 1.71°and 6.46 ± 2.21°, respectively. This study indicated that the coronal, apical and angular deviation in the robot group were significantly lower than in the computer and freehand groups. The apical and angular deviation in the computer group were significantly lower than in the freehand group, but there was no significant difference in coronal deviation between the computer and freehand groups. This study demonstrated that the accuracy of RAIS is significantly superior to CAIS or freehand.

RAIS in patients with maxillary bone defects

Transzygomatic implant surgery is an effective method for treating severe maxillary bone defects with tooth loss. Scholars have reported the steps of transzygomatic implant surgery using AR: using regular drills to create holes in the alveolar ridge, then switching to zygomatic drills to gradually expand the holes and insert the implants. This new approach expands the use of robots and is expected to overcome the limitations of traditional zygomatic implant surgery in cases of severe maxillary bone defects with restricted mouth opening.[54] Li et al[55] conducted transzygomatic implant surgery on a 45-year-old male patient using SR (Remebot) after performing the surgery on 30 models ex-vivo. Immediate restoration was completed, with coronal deviations, apical deviations, and angular deviations of 0.98 mm, 1.02 mm, and 1.21° for 16 teeth, and 0.68 mm, 1.17 mm, and 1.70° for 26 teeth. Deng et al[56] also used SR (Remebot) for transzygomatic implant surgery (n = 6, 8 implants) without any adverse events. The coronal deviation of the implants was 0.97 ± 0.42 mm, apical deviation was 1.27 ± 0.56 mm, and angular deviation was 1.48 ± 0.52°.

In addition, AR has been used for maxillary sinus floor elevation in edentulous patients with maxillary bone defects. Su et al[57] reported this procedure without any adverse events during the perioperative period, no maxillary sinus perforation, a 2 mm elevation of the sinus floor, a coronal deviation of 0.56 mm, apical deviation of 0.59 mm, and angular deviation of 0.94°. Trephine drilling is another method for repairing maxillary bone defects. Li et al[58] reported one case that used trephine drilling in RAIS, where they successfully extracted autologous bone using the robot and implanted the implants. No adverse events occurred during the study, with a coronal deviation of 0.50 mm, apical deviation of 0.51 mm, and angular deviation of 1.29°. This study confirms the feasibility of using trephine drilling in RAIS.

The accuracy of RAIS is independent of the surgical site, whether flap elevation is performed, implant length, and the operating surgeon

Multiple studies have investigated factors such as the location of implants (maxilla or mandible, left or right side, anterior or posterior teeth),[36,41, 42, 47] the use of flap elevation,[41] different implant lengths,[42,47] and variations in surgical operators.[42] The results indicate that these factors do not have a significant impact on the accuracy of implants by the robot.

In summary, the clinical studies revealed that the coronal deviation in RAIS was 0.78 ± 0.52 mm (AR: 0.60 ± 0.31 mm, SR: 0.71 ± 0.34 mm, PR:1.04 ± 0.68 mm), apex deviations was 0.82 ± 0.53 mm, (AR: 0.68 ± .34 mm, SR: 0.75 ± 0.39 mm, PR:1.05 ± 0.68 mm), and angular deviation was 1.66 ± 1.26° (AR: 1.67 ± 1.04°, SR: 1.61 ± 1.10°, PR: 1.67 ± 1.56°). These findings suggest advantages of RAIS in specific clinical scenarios, such as edentulous dentition, anterior tooth loss, and jaw defects. The study indicated that AR or SR demonstrate greater potential in controlling both coronal and apex deviations. Additionally, SR showed more promise in managing angular deviation. However, it is important to note that the statistical significance of these differences has not yet been established.

Discussion

Although a few review and meta-analysis articles have published that summarized the history and the structure of implant robots, as well as the surgical precision of RAIS, there remains a lack of systematic description in this field. From the perspective of clinical investigators and surgeons, this study not only provides a briefly introduction to these topics, but also summarizes and analyzes the latest published research on RAIS. This article reports the mean deviations of implants placed using RAIS to quantify the accuracy of the procedures. The findings indicate that RAIS demonstrates significant advantages in complex cases, such as edentulous dentition, immediate implant restoration for upper anterior tooth loss, zygomatic implantation, and management of jaw defects. Additionally, the study explores the factors influencing the accuracy of RAIS, providing valuable references for both clinical practice and research.

Current preclinical and clinical application published studies have confirmed the feasibility and safety of RAIS. While the conclusion on whether RAIS is superior to CAIS in preclinical studies is not consistent, most studies indicate that RAIS is not inferior to CAIS. It can effectively control coronal deviations, apical deviations, and angular deviations with no significant adverse reactions. This conclusion has been supported by numerous published clinical application studies. Therefore, RAIS holds great potential as a restoration solution for tooth loss and is expected to become a frontline recommended treatment for tooth loss in the future. However, further validation through multicenter, randomized controlled clinical trials is still needed.

Precise implant accuracy in cases of edentulism, anterior tooth loss, and associated maxillary bone defects remains a challenge. Several clinical studies have demonstrated the success of robots in edentulous patients, immediate implant restoration in cases of anterior tooth loss, transzygomatic implantation, maxillary sinus floor elevation, and trephine drilling. While many of these studies are case reports, case series, or retrospective studies with small sample sizes, they provide valuable insights for using RAIS in challenging implant cases in clinics and offer theoretical support for future prospective clinical randomized controlled trials.

The implant accuracy of RAIS is influenced by multiple factors such as the robots, the surgeon, the patients, and the implants. In-depth studies have been conducted on these factors in published studies. Current research has shown that AR or SR are superior to PR, increasing the number of reference points, and using larger diameter implants can help reduce implant deviations. However, coronal deviations, apical deviations, and angular deviations during implantation are not related to different surgeons, different robotic arms and implant combinations, implant morphology, implant length, or different surgical areas. This suggests that when using robots for oral implant surgery, it is important to select the appropriate type of robot and implant diameter, perform accurate and stable marking, in order to achieve relatively stable outcomes.

Future directions of robot-assisted dental implant

Current research indicates that RAIS has significant advantages in clinical applications and warrants further in-depth investigation. Although there are several published clinical trial results on RAIS, further researches about following issues are still required.

The accuracy and safety of RAIS need to be studied in multicenter, large-sample randomized controlled trials. Published studies comparing RAIS with CAIS and freehand are mostly small-sample retrospective analyses (3-39 participants), with only one multicenter randomized controlled trial involving 70 participants reported. Studies on RAIS for edentulism, anterior tooth loss, and maxillary bone defects mainly consist of case reports and single-arm studies without control groups. Only a few small-sample controlled trials have investigated the application of robots in edentulous patients (n = 3) and patients with anterior tooth loss in the maxilla (n = 21). Therefore, well-designed, multicenter, large-sample clinical trials are essential for further promoting the clinical application of RAIS.

Further exploration is needed to determine if RAIS can effectively reduce the surgical duration of dental implant procedures. Current clinical studies do not compare the surgical duration of RAIS, CAIS, or freehand dental implant surgeries. Only Xu et al[26] have compared the surgical durations of dental implant procedures among different types of robots, but this does not conclusively prove whether RAIS is more time-saving or time-consuming compared to traditional methods. It is well-known that meticulous preoperative data collection and planning are required before using robots for implant surgery, which incurs additional costs. Whether these extra efforts are beneficial in reducing the surgical duration of implant remains uncertain. Therefore, the clinical trials that surgeons are proficient in the surgical techniques, practice extensively before surgery, and focus on surgical duration in RAIS will help determine the feasibility of widespread adoption of robots in dental implant procedures.

Whether RAIS can reduce postoperative complications in patients is worth further exploration. Current research has shown that robots can significantly reduce postoperative complications in spinal surgery,[59] plastic and reconstructive surgery,[60] laparoscopic colorectal resection surgery.[61] In clinical application of RAIS, only Zhang et al[35] have studied the degree of postoperative pain in patients, with no detailed reports on postoperative adverse reactions such as swelling, numbness of the lower lip, peri-implant inflammation, implant loosening, implant failure, etc. This research gap prevents us from objectively assessing the short-term and long-term efficacy of RAIS. Therefore, systematically documenting postoperative complications of RAIS may be a promising research direction.

New robot operating modes are worth further in-depth research. A small number of studies have achieved good results in vitro by changing the calibration and tracking methods of robots to study the accuracy of implant placement, but they have not yet progressed to in vivo studies. Furthermore, some studies have indicated that implants placed with robot assistance may be more buccal (cheek) or apical than planned.[39,52] Therefore, developing new robot operating modes may better control the direction and angle of implants, which would be beneficial for the application of robots in complex dental implant surgeries.

Conflicts of interest

The authors declare that they have no conflicts of interest.

CRediT authorship contribution statement

Shuang Huang: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft. **Zhongli Wang:** Methodology, Investigation. **Miaomiao Li:** Validation, Visualization. **Yingli Song:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Yuezhi Li:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Data availability

All original datasets presented can be found in the article. Further inquiries can be directed to the corresponding authors.

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