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CLINICAL RESEARCH

Accuracy of an autonomous dental implant robotic system in dental implant surgery

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ABSTRACT

Statement of problem. Autonomous dental implant robot systems (ADIRSs) have been marketed for dental implant surgery; however, research on their accuracy is limited.

Purpose. The purpose of this clinical study was to examine the accuracy of an ADIRS.

Material and methods. Seventy-four participants with partial edentulism underwent implant surgery by using the ADIRS. Before surgery, a cone beam computed tomography (CBCT) scan was conducted, and its image data were fed into the ADIRS navigation and positioning system for iterative reconstruction and surgical path planning. After local anesthesia administration, area disinfection, and patient registration, the robot prepared the osteotomy and placed the implant under guidance of the navigation system. A postoperative CBCT scan was made to assess deviations between the planned and actual implant positions. The global coronal, apical, and angular deviations were measured and analyzed. A generalized linear mixed model (GLMM) was used to compare the differences in major outcome variables (α=.05).

Results. All implant procedures were successfully carried out without any complications during surgery. A total of 86 implants were placed in 74 participants. The mean ±standard deviation global coronal deviation, global apical deviation, and angular deviation was 0.61 ±0.20 mm (95% CI: 0.23 to 1.0 mm), 0.79 ±0.32 mm (95% CI: 0.17 to 1.41 mm), and 2.56 ±1.10 degrees (95% CI: 0.42 to 4.70 degrees), respectively. The findings from the GLMM revealed that the implant region (premolar, molar; maxilla, mandible; left, right), implant length, and surgeon did not significantly impact accuracy (*P*>.05).

Conclusions. ADIRS showed high accuracy for implant placement because of the control of angular deviation and axial errors. The implant region, implant length, and surgeon had no significant influence on the accuracy of implant placement. Nevertheless, more clinical studies are required to support evidence-based clinical outcomes. (J Prosthet Dent 2025;133:764-770)

Implant-supported prostheses have become a popular approach in China for treating patients with partial or complete edentulism. However, precise implant placement is essential for ensuring satisfactory long-term outcomes.[1–4]

In traditional freehand implant placement, the accuracy of implant positioning primarily hinges on the clinical proficiency of the surgeon. Even slight errors or deviations during the procedure can impact functional and esthetic results and may harm vital anatomic structures. Consequently, the accuracy of implant placement depends considerably on the surgeon's expertise. Nevertheless, even experienced surgeons have reported instances of implant failure attributed to positional deviations, with estimates reaching as high as 10%.[5]

Before the introduction of autonomous dental implant robot systems (ADIRSs), static computer-assisted implant surgery (sCAIS) and dynamic computer-assisted implant surgery (dCAIS) were used to enhance implant placement accuracy and minimize associated complications. Both techniques have been reported to enhance the accuracy of implant placement compared with freehand placement.[6–9] The mean ±standard deviation platform, apex, and angular deviations of sCAIS and dCAIS have been reported to be significantly lower than those of freehand placement (1.16 ±0.52 mm or 0.98 ±0.60 mm versus 1.86 ±0.77 mm, 1.32 ±0.61 mm or

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Clinical Implications

Successful outcomes of dental implant restorations are mainly determined by precise prosthetically driven implant placement. ADIRSs can perform surgical procedures autonomously according to preprogrammed procedures without intervention by the surgeon. They can provide excellent accuracy and are minimally invasive, making them a potential option in dental implant surgery.

1.19 ±0.69 mm versus 2.40 ±1.00 mm, and 2.84 ±1.60 degrees or 3.68 ±2.32 degrees versus 6.68 ±4.06 degrees, respectively).[10] Furthermore, research has demonstrated that dCAIS offers significantly higher accuracy than sCAIS.[11]

Although both sCAIS and dCAIS can enhance implant placement accuracy compared with freehand placement, they have limitations. sCAIS is hampered by a prolonged preoperative guide production cycle, an inability to adjust designs during surgery, and the potential for guide plates to impede surgical cooling and obstruct the surgeon's view during procedures. Additionally, the surgeon's experience influences the accuracy of template-guided dental implant surgery.[12–14] dCAIS also has drawbacks, such as requiring continuous screen focus instead of direct observation and the lack of physical guidance, leading to potential plan deviation.[15–17] Furthermore, compared with traditional freehand placement, heavier and bulkier surgical tools may require greater stability and endurance, resulting in a steeper learning curve for surgeons.[18]

ADIRSs utilize real-time navigation for the robotic arm through visual navigation and image registration technology, automating implant osteotomy and placement with image-guided, robot-assisted techniques to enhance accuracy.[19,20] ADIRSs assist surgeons in achieving precise and consistent implant surgery, reducing complexity and trauma and enabling minimally invasive dental implant placement.[21] A previous in vitro study using a robotic system placed 240 implants, reporting a mean ±standard deviation platform deviation, apex deviation, and angular deviation of 0.83 ±0.55 mm, 0.91 ±0.56 mm, and 1.00 ±0.48 degrees, respectively.[22] In vivo study revealed a mean ±standard deviation overall coronal deviation of 0.74 ±0.29 mm, a mean overall apical deviation of 0.73 ±0.28 mm, and an angular deviation of 1.11 ±0.46 degrees for an ADIRS.[23] Another study reported a coronal deviation of 0.43 ±0.18 mm, apical deviation of 0.56 ±0.18 mm, and angular deviation of 1.48 ±0.59 degrees.[20] A clinical trial was conducted in our hospital in 2020, which revealed a total coronal deviation of 0.63 ±0.23 mm, total apical deviation of 0.64 ±0.26 mm, and angular deviation of 2.27 ±0.98 degrees.[24]

While there have been literature reports on the accuracy of ADIRSs, the sample sizes in these articles were small. The present ADIRS trial with a larger sample size was conducted in 2022. The purpose of this clinical study was to evaluate the accuracy of implant placement in partial edentulism treatments by using this ADIRS.

MATERIAL AND METHODS

The study was approved by the Medical Science Research Ethics Committee of Peking University Third Hospital [Approval No: (2022) Yao Lun Shen No. (016–02)] and was registered in The Chinese Clinical Trial Registry (ChiCTR2300075735). Seventy-four participants (28 men, 46 women; average age=45 years, range 23 to 65) with partial edentulism accepted ADIRS implant technology for the restoration of missing teeth from May to June 2022. A total of 86 implants were inserted with 1 to 5 implants in each participant. The implant surgeries were performed with the ADIRS by 2 surgeons (Y.W., S.Q.Z.).

The inclusion criteria were adults with partial edentulism who voluntarily accepted implant restoration and signed informed consent after a comprehensive treatment protocol description, remaining teeth (≥3) on the contralateral side of the same jaw, and sufficient bone in the edentulous area. Additionally, participants had good general health and oral hygiene. The exclusion criteria were the presence of local or systemic contraindications for dental implant restoration, limited mouth opening (<35 mm), and severe alveolar bone deficiency.

The participants received comprehensive information regarding the possible treatment plan, associated costs, risks, principles, and indications of ADRIS. All participants were informed about and consented to the use of ADRIS during surgery. Before the procedure, various tests, including electrocardiogram, blood and urine tests, coagulation function assessments, biochemical analyses, and immune tests, were performed to exclude contraindications to surgery.

Implant surgeries were performed by an autonomous dental implant robotic system (FZ-DISAS-I; Sichuan Fengzhun Robot Technology Co, Ltd) alongside the dental implant machine (Kavacol Dental Medical Devices Co, Ltd). The ADIRS included an operating system, a robotic arm, an optical tracker, a software control system, and positioning markers (Fig. 1). The positioning marker comprised 4 optical pellets and can be tracked in real-time by an optical tracker.

The complete process of the clinical trial was as follows: prior to the surgical procedure, a positioning

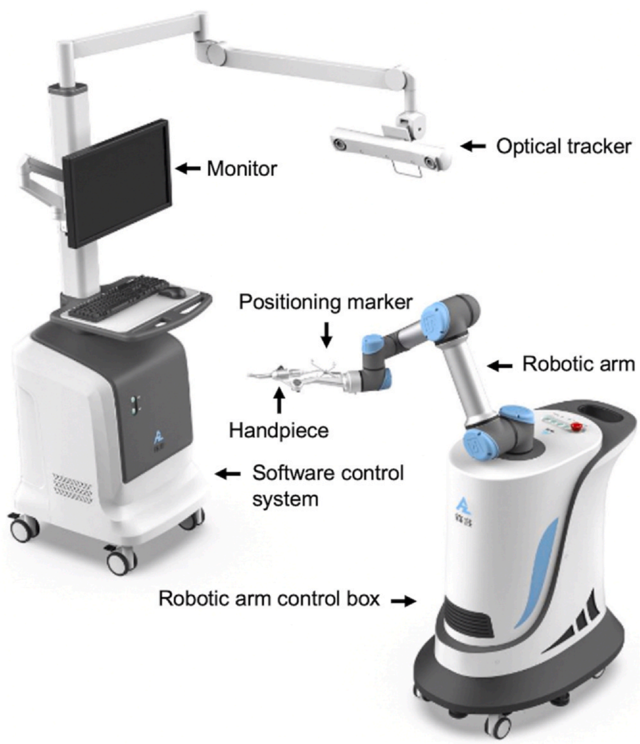

Figure 1. Autonomous dental implant robotic system.

marker was fixed to the contralateral tooth of the same jaw at the patient's implant site using an interim crown material (Luxatemp; DMG). Then, after the stability of the marker had been verified, a preoperative cone beam computed tomography (CBCT) scan (3DeXam; KaVo) was made. The preoperative CBCT data were subsequently imported into the software control system of the ADIRS to facilitate the planning of the 3-dimensional position of the implant before the surgery. Moreover, the implant type, drilling sequence, and processing conditions were set up.

Similarly, the end of the robotic arm incorporated the same positioning marker. The spatial coordinate system of the optical positioning instrument enabled the establishment of a coordinate correlation between the drill needle tip, which was attached to the end of the robotic arm, and the alveolar bone in the missing tooth region. The optical positioning instrument provided real-time visualization of the precise location of the drill needle tip within the alveolar bone, displayed in real time on the screen. According to the preprogrammed procedures, the robotic arm accomplished surgical procedures autonomously. The surgeon monitored the ADIRS and made necessary changes to the drill needle throughout the surgery.

After intraoral and extraoral disinfection, local anesthesia was administered by using 4% articaine (Primacaine Adrenaline; ACTEON Group) in the edentulous area. A full-thickness soft tissue flap was lifted to expose the alveolar bone, or a flapless approach was used. Then, the ADIRS autonomously performed osteotomies step-by-step and implant (ITI; Straumann Medical Device Trading Co., Ltd) insertion according to the predetermined scheme. The drills were changed by the surgeon (Y.W. or S.Q.Z.) outside the mouth. The corresponding healing abutment was installed by the surgeon. Throughout the procedure, the surgeon observed the surgical parameters from all angles and could have halted the robot's movements using the pedal. The software program could have triggered an automatic alarm in the event of any positional deviation, prompting the robot to cease movement and sound an alarm upon reaching the planned position. During surgery, the surgeon could have suspended the operation at any time according to the specific conditions of the operation, replan, adjust the 3-dimensional position of the implant in the system, and perform the operation according to the new design. After the implant had been placed, the gingival tissues were trimmed, and the wound was closed. The participants then underwent a postoperative CBCT scan, after which the positioning marker was removed. Oral antibiotics, painkillers, and mouthwash solutions were prescribed after surgery (Fig. 2).

Postoperative CBCT data were imported into the ADIRS, where the software program automatically superimposed the 4 optical pellets from the preoperative and postoperative images. The deviations between the actual and planned position of the implant could be observed and calculated in the software program. The global coronal deviation represented the distance between the neck center point of the planned and actual implant positions, the global apical deviation represented the distance between the apical center point of the planned and actual implant positions, and the angular deviation represented the angle between the central axis of the planned and the placed implants (Fig. 3).

A statistical software program (IBM SPSS Statistics, v25; IBM Corp) was used for statistical analysis. Descriptive statistical parameters for both experimental groups are presented as the mean ±standard deviation, median, 95% confidence interval, and maximum and minimum values. A GLMM was established to analyze the factors contributing to the deviation (α=.05).

RESULTS

A total of 86 implants were placed in 74 participants. Thirty implants were placed in the premolar and 56 in the molar; 30 implants were placed in the maxilla and 56 in the mandible; 43 implants were placed on the left side and 42 on the right side; the length of 5 implants was 8 mm, 34 implants were 10 mm, and 47 implants were 12 mm; 44 implants were placed by 1 surgeon (Y.W.)

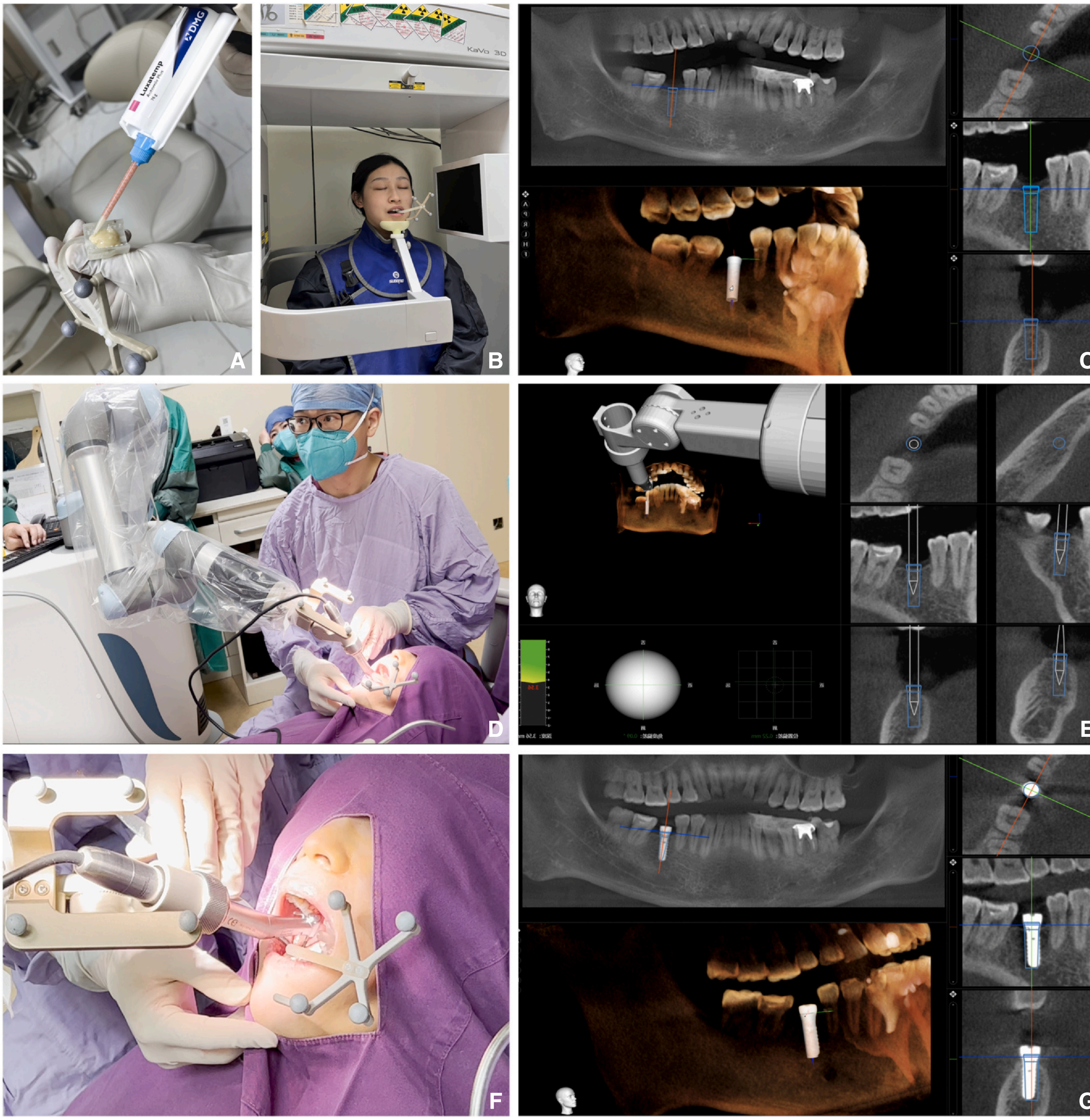

Figure 2. Surgical process of autonomous dental implant robotic system. A, Positioning marker fixed to contralateral tooth of same jaw at patient's implant site using interim crown material. B, Preoperative CBCT examination of participant with positioning maker. C, Treatment plan designed before surgery. D-F, Autonomous dental implant robotic system in use. G, Postoperative evaluation: comparing accuracy of preoperatively planned implant position (*in blue*) with actual postoperative position.

and the others by S.Q.Z. Postoperative CBCT imaging indicated precise placement of the implant in the intended position, with no occurrence of surgical complications.

Accuracy was assessed by the signed global coronal deviation, global apical deviation, and global angular deviation. The mean ±standard deviation of the global coronal deviation was 0.61 ±0.20 mm (95% CI: 0.23 to 1.0 mm), the global apical deviation was 0.79 ±0.32 mm (95% CI: 0.17 to 1.41 mm), and the angular deviation was 2.56 ±1.10 degrees (95% CI: 0.42 to 4.70 degrees) (Table 1). Findings from the GLMM revealed that global coronal deviation, global apical deviation, and angular deviation were not significantly impacted by the implant region (premolar, molar; maxilla, mandible; left, right), implant length, or surgeon (P>.05) (Table 2).

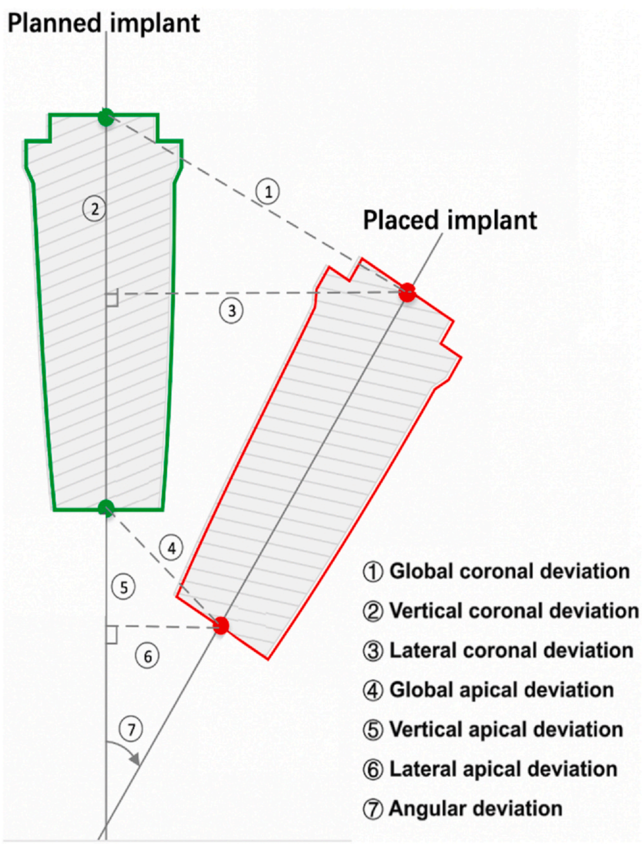

Figure 3. Schematic representation of deviation measurements between planned and placed implants.

Table 1. Descriptive statistics of implant deviations

Metric	Global Coronal Deviation (mm)	Global Apical Deviation (mm)	Angular Deviation (Degree)
Mean ±SD	0.61 ±0.2	0.79 ±0.31	2.56 ±1.09
Sample size (n)	86	86	86
Min - Max	0.13–0.95	0.15–1.39	0.46–4.72
95% CI	0.23–1.0	0.17–1.41	0.42–4.70

CI, confidence interval; SD, standard deviation.

Table 2. Generalized linear mixed model (GLMM) included implant region (premolar, molar; maxilla, mandible; left, right), implant length, and surgeon as independent variables and global coronal deviation, global apical deviation, and angular deviation as dependent variables

Generalized Linear Mixed Model	Global Coronal Deviation	Global Apical Deviation	Angular Deviation
	P	*P*	*P*
Premolar/molar	.721	.410	.169
maxilla/mandible	.728	.651	.709
Left/right jaw	.864	.227	.696
implant length	.543	.714	.584
surgeon	.727	.496	.536

DISCUSSION

By integrating the computerized surgery planning platform, visual surgery tracking platform, and robot operation platform, osteotomies and implant placement were autonomously conducted by the ADIRS according to preoperative 3-dimensional position planning. This process was facilitated by navigation guided by the robotic arm control of the implant drill. During drilling, the needle automatically halted upon reaching the specified depth. Real-time displacement capture by the optical tracking locator allowed for calibration if slight head movement occurred, ensuring drilling precision. The results revealed a mean global coronal deviation of 0.61 mm, mean global apical deviation of 0.69 mm, and mean angular deviation of 2.56 degrees. These findings were consistent with those of previous clinical studies on ADIRS implantation accuracy in patients with a single missing tooth or with edentulous jaws, particularly regarding angles.[16] However, the maximum deviations in this study for global coronal, apical, and angular deviations were 0.95 mm, 1.39 mm, and 4.72 degrees. This underscores the importance of adhering to Worthington's recommendation of maintaining a 2-mm safe distance during preoperative planning to safeguard surrounding anatomic structures during surgery.[25]

The present study found that the source of the deviations of ADIRS can be divided into the system's inherent errors and clinical correlation errors. The inherent errors of the system's tools include potential errors in CBCT, inaccurate alignment between CBCT data and surface scans, and inherent inaccuracies of the optical tracker and the robotic arm. Manufacturers need to address these aspects for further improvement. More importantly, clinical correlation errors occurred during the clinical procedures, with 2 primary errors being identified. First, errors may arise if the positioning marker becomes loose in the patient's mouth. In this study, participants were required to have at least 3 stable teeth on the contralateral side of the same jaw to secure the positioning marker. The positioning markers were fixed to the teeth using interim crown material. Thus, verification of the firm attachment of the positioning marker after polymerization of the interim crown material is essential. The surgeon must pay close attention to detect any looseness of the positioning marker throughout the entire procedure before a postoperative CBCT scans is made. Should any looseness of the positioning marker be identified during the operation, immediate cessation of the surgery is warranted to mitigate the risk of drill deviation. In one participant in this trial, a notable error between the actual drill needle position in the patient's oral cavity and the preoperatively planned position displayed on the computer screen was observed by the operator. This error was attributed to loosening and displacement of a positioning marker, and a change to freehand implantation was made. In another participant, a loose positioning marker was observed after the preoperative CBCT scan.

Subsequently, the positioning marker was refixed, and the preoperative CBCT scan was remade.

Additionally, consideration should be given to errors potentially arising from sudden head movement during drilling. During surgery, the patient's head, particularly the mandible, inadvertently shifted slightly after experiencing stress during the operation. While the robotic arm has a "follow-up" function, it requires time to autonomously detect and correct head movement trajectories. Errors may occur during this period, emphasizing the importance of the operator or assistant stabilizing the patient's head or mandible throughout the drilling process with the mechanical arm to minimize stress-induced movement. The development of rapid movement tracking by the robot is required. Theoretically, the temporomandibular joint makes the mandible more prone to movement under stress. The impact of the implant region (maxilla, mandible) on the primary outcome variables was analyzed by using GLMM, which indicated statistical similarity across different implant regions in the study. However, a study evaluating ADIRS for implant placement in edentulous individuals revealed slightly higher accuracy of depth and angular placement of implants in the maxilla than in the mandible, presumably because the maxilla is more stable than the mandible.[16]

A lack of linear relationships between ADRIS accuracy and surgeon was found. Previous research has indicated that after familiarizing themselves with approximately 20 patients with dynamic navigation, novices can attain implant accuracy similar to that of experienced professionals.[7] The learning of ADRIS is less complex and could shorten the learning curve and facilitate rapid attainment of expert-level accuracy in implant placement for novices. Novices should be able to achieve high implant accuracy by mastering the ADIRS operation and under supervised guidance without requiring extensive implant expertise.

Compared with computer-aided dynamic navigation, the ADIRS, which features a 6-dimensional robotic arm, offers superior maneuverability in 3-dimensional space. The ADIRS ensures precise control over depth and angle, which is crucial for navigating tight surgical spaces. The ADIRS enhances surgical accuracy and promotes minimally invasive dental implant therapies by mitigating issues such as operator fatigue, visual obstructions, and ergonomic challenges.

Limitations of the ADIRS include that the preoperative preparation procedures are time-consuming, leading to extended surgical durations. Additionally, the equipment necessitates ample space and a sizable operating room, along with the involvement of additional coordination personnel during the operation. Moreover, the high cost of ADIRS may result in additional surgical expenses, increasing the financial burden on patients. Furthermore, it may not be suitable for patients with restricted mouth-opening.

Limitations of this trial included that no comparative cohort was enrolled. Future studies should compare ADIRSs with sCAIS or dCAIS technologies. This trial focused on a relatively straightforward clinical scenario (partial edentulism without severe bone defects). To acquire high-level clinical evidence, more special implant sites, such as extraction sockets or severe bone defects, should be considered in future investigations. Therefore, a large-scale multicenter randomized control trial is necessary.

CONCLUSIONS

Based on the findings of this clinical trial, the following conclusions were drawn:

1. The ADIRS showed high accuracy for implant placement with partial edentulism. The system effectively controlled angular deviation and axial errors.
2. The implant region, implant length, and surgeon had no significant influence on the accuracy of implant placement (P>.05).
3. These findings suggest that the ADIRS can be a reliable and efficient option for dental implant surgery. However, it is imperative to recognize that the use of ADIRSs is still in an early stage, necessitating extensive clinical investigations and larger-scale studies.

PATIENT CONSENT

Informed patient consent has been obtained.

REFERENCES

1. Sailer I, Karasan D, Todorovic A, et al. Prosthetic failures in dental implant therapy. *Periodontol 2000*. 2022;88:130–144.
2. Chackartchi T, Romanos GE, Parkanyi L, et al. Reducing errors in guided implant surgery to optimize treatment outcomes. *Periodontol 2000*. 2022;88:64–72.
3. Buser D, Martin W, Belser UC. Optimizing esthetics for implant restorations in the anterior maxilla: Anatomic and surgical considerations. *Int J Oral Maxillofac Implant*. 2004;19:43–61.
4. Monaco C, Arena A, Corsaletti L, et al. 2D/3D accuracies of implant position after guided surgery using different surgical protocols: A retrospective study. *J Prosthodont Res*. 2020;64:424–430.
5. Chee W, Jivraj S. Failures in implant dentistry. *Br Dent J*. 2007;202:123–129.
6. Aydemir CA, Arısan V. Accuracy of dental implant placement via dynamic navigation or the freehand method: A split-mouth randomized controlled clinical trial. *Clin Oral Implants Res*. 2020;31:255–263.
7. Block MS, Emery RW, Lank K, Ryan J. Implant placement accuracy using dynamic navigation. *Int J Oral Maxillofac Implants*. 2017;32:92–99.
8. Kaewsiri D, Panmekiate S, Subbalekha K, et al. The accuracy of static vs. dynamic computer-assisted implant surgery in single tooth space: A randomized controlled trial. *Clin Oral Implants Res*. 2019;30:505–514.
9. Kivovics M, Takács A, Pénzes D, et al. Accuracy of dental implant placement using augmented reality-based navigation, static computer assisted implant surgery, and the free-hand method: An in vitro study. *J Dent*. 2022;119:104–110.
10. Tencati E, Moy P. Accuracy of dynamic computer-aided navigation system for dental implant placement. *J Oral Maxillofac Surg*. 2019;77:e68–e69.
11. Jorba-García A, González-Barnadas A, Camps-Font O, et al. Accuracy assessment of dynamic computer-aided implant placement: A systematic review and meta-analysis. *Clin Oral Investig*. 2021;25:2479–2494.
12. Sigcho Lopez DA, Garcia I, Da Silva Salomao G, Cruz Lagana D. Potential deviation factors affecting stereolithographic surgical guides: A systematic review. *Implant Dent*. 2019;28:68–73.

13. Gargallo-Albiol J, Barootchi S, Salomó-Coll O, Wang H lay. Advantages and disadvantages of implant navigation surgery: A systematic review. *Ann Anat*. 2019;225:1–10.
14. Cassetta M, Bellardini M. How much does experience in guided implant surgery play a role in accuracy? A randomized controlled pilot study. *Int J Oral Maxillofac Surg*. 2017;46:922–930.
15. Block MS, Emery RW, Cullum DR, Sheikh A. Implant placement is more accurate using dynamic navigation. *J Oral Maxillofac Surg*. 2017;75:1377–1386.
16. Bolding SL, Reebye UN. Accuracy of haptic robotic guidance of dental implant surgery for completely edentulous arches. *J Prosthet Dent*. 2022;128:639–647.
17. Stefanelli L, DeGroot B, Lipton D, Mandelaris G. Accuracy of a dynamic dental implant navigation system in a private practice. *Int J Oral Maxillofac Implants*. 2019;34:205–213.
18. Sun TM, Lee HE, Lan TH. The influence of dental experience on a dental implant navigation system. *BMC Oral Health*. 2019;19:1–11.
19. Li Z, Xie R, Bai S, Zhao Y. Implant placement with an autonomous dental implant robot: A clinical report. *J Prosthet Dent*. 2025;133:340–345.
20. Jia S, Wang G, Zhao Y, Wang X. Accuracy of an autonomous dental implant robotic system versus static guide-assisted implant surgery: A retrospective clinical study. *J Prosthet Dent* 2023.
21. Deng H, Bian H, Li C, Li Y. Autonomous dental robotic surgery for zygomatic implants: A two-stage technique. *J Prosthet Dent* 2023.
22. Tao B, Feng Y, Fan X, et al. Accuracy of dental implant surgery using dynamic navigation and robotic systems: An in vitro study. *J Dent*. 2022;123:104170–104177.
23. Yang S, Chen J, Li A, et al. Accuracy of autonomous robotic surgery for single-tooth implant placement: A case series. *J Dent*. 2023;132:104451–104458.
24. Yu W, Shi QZ, Xiao W. Preliminary application of dental implant robot in dental implant operation. *Chin J Min Inv Surg*. 2021;21:787–791.
25. Worthington P. Injury to the inferior alveolar nerve during implant placement: A formula for protection of the patient and clinician. *Int J Oral Maxillofac Implant*. 2004;19:731–734.

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Yu Wu: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review and editing. **Shiqi Zou**: Conceptualization, Investigation, Data curation. **Pin Lv**: Methodology, Investigation, Data curation. **Xiao Wang**: Conceptualization, Supervision. Project administration. Writing - review and editing.