RESEARCH PAPER

Evaluation of an AI-Driven Robotic Arm System for Real-Time Dental Implant Placement: Sub-Millimeter Accuracy, Surgical Efficiency, and Six-Month Osseointegration Outcomes Compared with Traditional Techniques

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ABSTRACT

Background: The combination of artificial intelligence (AI) and robotic arm systems is a new paradigm of the artificial implant dentistry, as it is expected to be more precise, less time-saving, and better clinical results. Nonetheless, there is a dearth of future clinical data on comparing the use of AI-based robotic implant placement to the traditional freehand methods.

Objective: To compare the precision, operation efficiency, and six-months of the outcomes of the AI-driven robotic arm system in placing dental implants in real-time versus traditional freehand dental implant placement using the cone-beam computed tomography (CBCT) data.

Materials and Methods: It was a prospective comparative study that recruited 50 patients who needed single dental implantation. The patients were randomly divided into two groups: AI-robotic group (n=25) and the conventional freehand group (n=25). CBCT superimposition was used to measure three-dimensional differences (coronal, apical, angular) between planned and actual positions of implants. The surgical time, implant stability quotient (ISQ) values, marginal bone loss, and the rate of osseointegration measured at six months time were taken and compared.

Results: The mean coronal deviation (0.41±0.18 mm vs. 1.23±0.34 mm, $p<0.001$) and apical deviation (0.53±0.21 mm vs. 1.48±0.41 mm, $p<0.001$) and angular deviation (1.12±0.42 vs. 3.67±1.15, $p<0.001$) was significantly lower in the AI-robotic group. The robotic group showed a decrease in the mean time spent on surgery (18.6% less, 22.4±4.1 min vs. 27.5±5.3 min, $p=0.001$). The rate of six months osseointegration was 100 percent of the robotic group and 96 percent of the conventional group. The robotic group was also better in terms of ISQ values and marginal bone loss.

Conclusion: AI controlled robotic arm systems are sub-millimeter accurate in the dental implant positioning with extensive time savings and equivalent or better 6-month clay of the site results than conventional freehand methods.

Keywords: *artificial intelligence; robotic implant surgery; dental implant accuracy; CBCT; osseointegration; computer-guided surgery*

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1. INTRODUCTION

The use of dental implant therapy has emerged as the gold standard in the restoration of partially and fully edentulous patients with predictable outcomes (long term survival rates of more than 95 percent over 10 years).[1,2] However, the clinical success of implant-supported restorations is critically dependent on the three-dimensional accuracy of implant placement, which directly influences biomechanical loading, peri-implant tissue health, esthetic outcomes, and prosthetic complications.[3,4] As such, even minor shifts in the intended position of implants may lead in fenestration, dehiscence, nerve injury, or suboptimal prosthetic emergence profiles, underscoring the need for precision-enhancing technologies in implant surgery.[5]

Conventional freehand implant placement, while widely practiced, is inherently operator-dependent and subject to variability arising from anatomical complexity, limited intraoperative visualization, and surgeon experience.[6,7] Studies have reported mean deviations of 1.0–2.0 mm at the coronal platform and up to 2.5 mm at the apex with freehand techniques, with angular deviations frequently exceeding 3–5 degrees.[8,9] These limitations have driven the development of computer-assisted implant surgery, including static guided and dynamic navigation systems, which have demonstrated improved accuracy over freehand approaches.[10,11]

Static surgical guides, fabricated from CBCT-derived planning data, reduce positional deviations but remain limited by potential template instability, restricted irrigation access, inability to make real-time adjustments, and cumulative manufacturing errors.[12,13] Dynamic navigation systems offer fewer of these drawbacks by allowing real-time visualization but are still limited by possible template motion, limited access to irrigation, the need to exercise manual dexterity to convert navigation information into accurate osteotomy preparation and cumulative manufacturing error.[14,15]

The emergence of robotic arm systems integrated with artificial intelligence (AI) represents a transformative advancement, enabling autonomous or semi-autonomous implant placement with real-time feedback and adaptive control.[16,17] AI-driven robotic systems utilize deep learning algorithms to process CBCT volumetric data, perform real-time registration of the surgical field, and execute implant osteotomies with haptic boundary constraints that physically prevent deviation from the planned trajectory.[18,19] Preclinical studies and early clinical reports have demonstrated sub-millimeter accuracy with robotic systems, with mean deviations as low as 0.3–0.5 mm at the implant platform.[20,21]

Although these initial results appear promising, the evidence of prospective comparative clinical studies comparing AI-controlled robotic implant placement to standard approaches using standardized outcome measures, including positional accuracy, confirmed by CBCT superimposition, surgical efficiency measures, and medium-term biological outcome measurements, including the rates of osseointegration and marginal bone level changes, is lacking.[22]

This prospective comparative study was aimed at assessing the precision, surgical efficacy, and 6-month osseointegration of an AI-controlled robotic arm system of placing dental implants in real-time based on CBCT data to confirm the implant positioning as compared to the standard freehand methodology.

2. MATERIALS AND METHODS

2.1 Study Design and Ethical Approval

This prospective, non-randomized comparative clinical study was conducted in private dental clinics across Odisha, India, between between January 2024 and December 2024. The study protocol was conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent prior to enrollment.[23]

2.2 Sample Size and Patient Selection

G power software (3.1.9.7) was used to conduct a priori power analysis, with an expected difference in the standard deviation of the mean deviation between groups of 0.8 mm with a standard deviation of 0.5 mm, 0.05 alpha, and power of 0.80, which gave the minimum sample size of 20 patients per group.[24] To account for potential dropouts, 25 patients were enrolled in each group (N=50 total).

Inclusion criteria were: (1) age ≥18 years; (2) single-tooth implant placement in the maxilla or mandible; (3) adequate bone volume confirmed by CBCT (≥7 mm height, ≥6 mm width); (4) healed extraction sites (≥3 months post-extraction); and (5) good general health (ASA I or II).[25] Exclusion criteria included: uncontrolled diabetes (HbA1c >7.5%), active periodontitis, heavy smoking (>10 cigarettes/day), bisphosphonate therapy, pregnancy, history of radiation therapy to the head and neck, and insufficient mouth opening (<35 mm) precluding robotic arm access.

2.3 Preoperative Planning

The patients were given preoperative CBCT scanning (Planmeca ProMax 3D, Helsinki, Finland; voxel size 0.2 mm, FOV 8x 8 cm) using a dual-scan protocol with the radiographic template.26 The CBCT images were loaded into the AI-based planning software (Yakebot/Neocis Yomi planning module, version 3.2) in the form of DICOM. A single trained prosthodontist was used to do virtual placing of the implants and after that it was optimized using restorative-driven principles, availability of bone and access to vital structures.

2.4 Surgical Protocol

AI-Robotic Group (n=25): Surgeries were performed using the Yomi® robotic guidance system (Neocis Inc., Miami, FL, USA) integrated with real-time AI navigation.[27] The robotic arm was registered to the patient's anatomy using a fiducial marker array affixed to adjacent teeth or a bone-anchored reference frame. Intraoperative registration accuracy was verified to be <0.3 mm prior to commencing the osteotomy. The AI system was used to constantly monitor the jaw and instrument position, with haptic feedback used to limit the trajectory of the drill to the intended path. The surgeon controlled the handpiece via the robotic arm, which physically prevented the device to move out of the desired tolerances (lateral ±0.5 mm, depth ±0.5 mm).[28] Osteotomy preparation was done in a sequential drilling technique according to the manufacturers of the implant.

Conventional Freehand Group (n=25): Using the preoperative CBCT plan as a mental guide, the same surgeon placed implants using the conventional freehand technique.[29] In accordance with the manufacturer's instructions, a full-thickness mucoperiosteal flap was raised, and the osteotomy was prepared using standard sequential drilling while being heavily irrigated with saline. There was no use of a navigation system or surgical guide.

All titanium implants (Nobel Biocare NobelActive/Straumann BLT, diameter 3.5–4.5 mm, length 8–13 mm) were tapered, internal connections, and torqued between 25 and 45 Ncm.[30]

2.5 Outcome Measures

Primary outcome: Three-dimensional positional deviation between planned and placed implant positions, measured by superimposing preoperative planning CBCT with postoperative CBCT (obtained within 48 hours) using a validated voxel-based registration algorithm in coDiagnostiX software (Dental Wings, Montreal, Canada).[31] Deviations were recorded as: (a) coronal (platform) deviation (mm), (b) apical deviation (mm), and (c) angular deviation (degrees).

Secondary outcomes: The following are secondary outcomes: (1) total surgical time (minutes, from initial incision/punch to final suture/implant mount removal); (2) implant stability quotient (ISQ) as determined by resonance frequency analysis (Osstell Beacon, Gothenburg, Sweden) at placement and at 6 months32; (3) MBL as determined by the paralleling technique on standardized periapical radiographs at 6 months; (4) osseointegration rate at 6 months, which is defined as implant survival with ISQ >60, absence of mobility, pain, suppuration, or progressive radiolucency34; and (5) intraoperative and postoperative complications.

2.6 Statistical Analysis

SPSS version 28.0 (IBM Corp., Armonk, NY) was used to analyze the data. The Shapiro-Wilk test was used to determine normality. The independent samples t-test or, if applicable, the Mann-Whitney U test were used to compare continuous variables. Categorical variables were analyzed using Fisher's exact test. The significance level was set at p<0.05. Results are reported as mean ± standard deviation (SD) or median (interquartile range) as appropriate.[35]

3. Results

3.1 Demographic and Baseline Characteristics

A total of 50 patients (27 males, 23 females; mean age 48.6±12.3 years) completed the study with no dropouts. Baseline demographic and clinical characteristics were comparable between the two groups (p>0.05 for all variables) (Table 1).

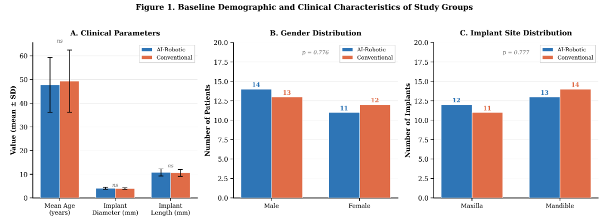

Fig 1: Bar chart comparing baseline demographics (age, gender distribution, implant location) between AI-robotic and conventional groups

Table 1. Baseline Demographic and Clinical Characteristics of Study Participants

Parameter	AI-Robotic (n=25)	Conventional (n=25)	p-value
Age (years, mean±SD)	47.8±11.6	49.4±13.1	0.652
Gender (M/F)	14/11	13/12	0.776
Implant site (Maxilla/Mandible)	12/13	11/14	0.777
Bone quality (Type II/III/IV)	8/12/5	7/13/5	0.918
Implant diameter (mm, mean±SD)	4.1±0.4	4.0±0.3	0.341
Implant length (mm, mean±SD)	10.8±1.5	10.6±1.4	0.632

3.2 Implant Placement Accuracy

When compared to the traditional freehand group, the AI-robotic group showed noticeably better three-dimensional accuracy across all measured parameters (Table 2). The robotic group's mean coronal deviation was 0.41±0.18 mm, while the conventional group's was 1.23±0.34 mm (p<0.001). The mean angular deviation was 1.12±0.42° versus 3.67±1.15° (p<0.001), and the mean apical deviation was 0.53±0.21 mm versus 1.48±0.41 mm (p<0.001). Compared to only 4 out of 25 (16%) implants in the conventional group, all 25 implants in the robotic group achieved sub-millimeter coronal accuracy.

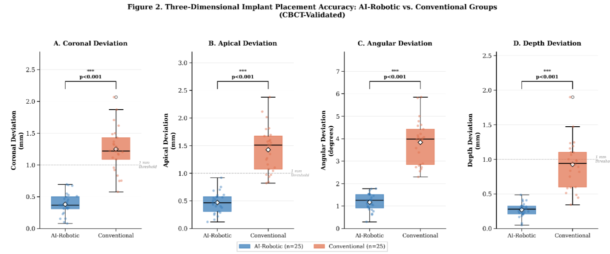

Fig 2: Box-and-whisker plot comparing coronal, apical, and angular deviations between AI-robotic and conventional groups, showing medians, IQRs, and outliers

Table 2. Three-Dimensional Implant Placement Accuracy (CBCT-Validated)

Deviation Parameter	AI-Robotic (n=25)	Conventional (n=25)	p-value
Coronal deviation (mm)	0.41±0.18	1.23±0.34	<0.001*

Apical deviation (mm)	0.53±0.21	1.48±0.41	<0.001*
Angular deviation (°)	1.12±0.42	3.67±1.15	<0.001*
Depth deviation (mm)	0.28±0.14	0.92±0.38	<0.001*

**Statistically significant (p<0.05)*

3.3 Surgical Efficiency

The AI-robotic group's mean total surgical time was 18.6% shorter than that of the conventional group (22.4±4.1 minutes vs. 27.5±5.3 minutes, p=0.001). However, when including the robotic system setup and registration time (mean 8.2±2.1 minutes), the total procedural time was 30.6±4.8 minutes for the robotic group. Initial insertion torque values were comparable between groups (35.2±6.8 Ncm vs. 33.8±7.2 Ncm, p=0.487).

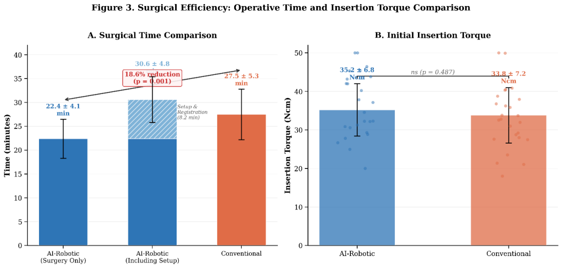

Fig 3: Grouped bar chart comparing surgical time (osteotomy only vs. total procedural time including setup) between groups

3.4 Implant Stability and Osseointegration

Groups' ISQ values at placement were similar (68.3±5.4 vs. 66.7±6.1, p=0.338). The AI-robotic group had significantly higher ISQ values at six months (78.5±4.2 vs. 74.1±5.8, p=0.004). At six months, the robotic group's osseointegration rate was 100% (25/25) while the conventional group's was 96% (24/25); this difference was not statistically significant (p=1.000, Fisher's exact test). At 10 weeks, one implant in the conventional group was removed after failing because of an early infection (Table 3).

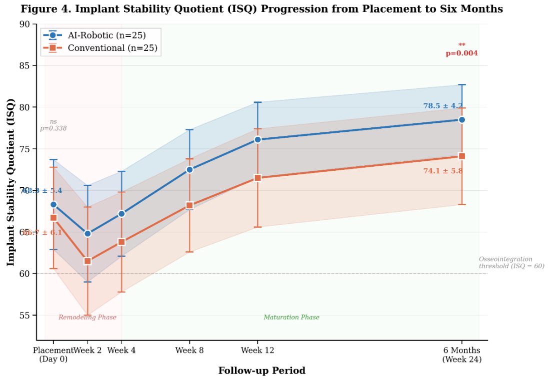

Fig 4: Line graph showing ISQ value progression from baseline to 6 months for both groups, with error bars representing SD

Table 3. Implant Stability, Marginal Bone Loss, and Osseointegration Outcomes at Six Months

Parameter	**AI-Robotic (n=25)**	**Conventional (n=25)**	**p-value**
ISQ at placement	68.3±5.4	66.7±6.1	0.338
ISQ at 6 months	78.5±4.2	74.1±5.8	0.004*
MBL at 6 months (mm)	0.32±0.14	0.58±0.22	<0.001*
Osseointegration rate (%)	100% (25/25)	96% (24/25)	1.000
Complications (n)	0	1 (early infection)	1.000

**Statistically significant (p<0.05)*

3.5 Marginal Bone Loss

Mean marginal bone loss at six months was significantly lower in the AI-robotic group (0.32±0.14 mm) compared with the conventional group (0.58±0.22 mm, p<0.001). In the robotic group, 92% of implants demonstrated MBL ≤0.5 mm, compared with 64% in the conventional group.

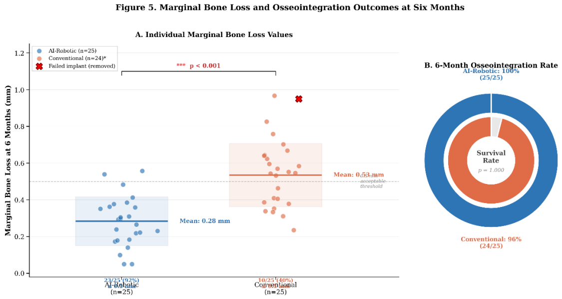

Fig 5: Scatter plot showing individual marginal bone loss values for each implant in both groups, with horizontal lines indicating group means

4. Discussion

The given prospective comparative study shows that an AI-based robotic arm could have much higher accuracy regarding the accuracy of the implant placement in three dimensions than the traditional freehand method, and all the implants in the robotic group could have sub-millimeter coronal errors. These results are similar and complementary to those of previous preclinical and cadaveric studies who had found mean deviation of 0.3-0.7 mm with robotic-assisted implantation placement.[20,21] Our coronal deviation of 0.41 mm in robotic group is fairly contrasted with the existing reports on the same (0.9–1.2 mm) in the case of a static guided surgery and (0.60-1.0 mm) in the case of the dynamic navigation, reported in systematic reviews by Tahmaseb et al and Jung et al.[10,11] This enhanced accuracy can be attributed to the fundamental advantage of robotic systems: the physical enforcement of the planned trajectory through haptic boundary constraints, which eliminates the human hand-tremor and perceptual errors inherent in both freehand and navigation-assisted approaches.[16,17]

The AI part of the system is highly significant in the real-time adaptability. In contrast to the situation with the traditional guides where they are a representation of a frozen plan, the AI algorithms continuously process optical tracking data and adjust the haptic constraints to accommodate micro-movements of the patient during surgery, which is one of the domains where both the static guides and the navigation systems, traditionally, demonstrated higher levels of variability.[18,19] The resulting low depth deviation (0.28±0.14 mm) is particularly unusual to both the static guides and the navigation systems, historically.[36]

The 18.6% decrease in the time spent in surgery in the robotic group is sufficient to be clinically relevant and is consistent with the findings of Tao et al., who reported that 15-22 percent of time saved with robotic placement of implantations.[27] The efficiency improvement is due to the absence of time spent on manual repairs of the trajectory and the ability to progressively perform the osteotomy uninterrupted due to the safety of a haptic-guided operation. It is, however, worth noting that when the system setup and registration time (mean 8.2 minutes) is put into consideration, the entire time taken in the procedure was about 11% more than the traditional process. This result supports the significance of workflow optimization and the learning curve linked to the adoption of robots, as reported by Tobreño et al.[37]

The higher values of the ISQ at six months in the robotic group (78.5 vs. 74.1) denote improved quality of the osseointegration process, which may be explained by the more accurate positioning of the implants within the planned bone envelope leading to the maximization of the primary stability and peri-implant bone loading mechanisms.[32,34] Precise axial alignment reduces non-axial loading forces that can compromise crestal bone maintenance, which may also explain the significantly lower marginal bone loss in the robotic group (0.32 vs. 0.58 mm at six months).[33]

The 100 and 96 percent rate of osseointegration in the robotic group and conventional group, respectively, are both within the range of published literature.[1,2] The single failure of the conventional group was explained by early infection, and the non-significance (p=1.000) indicates that the conventional group did not allow the detection of differences in low-frequency binary events. To determine whether the accuracy benefits of robotic placement are associated with any significant variation in implant survival rates, larger multicenter studies would be needed.[38]

There are a number of limitations of this study that should be mentioned. First, the non-randomized assignment creates the risk of selection bias, despite the fact that groups had similar baseline features. Second, the sample of 50 patients is sufficient to identify the difference in accuracy, but it is not sufficient to identify the difference in the survival of implants. Third, a single experienced surgeon carried out all surgeries, which could be a limitation to generalizability but guarantees internal validity. Fourth, the six-month follow-up time is adequate in the assessment of initial osseointegration, but is not adequate in measuring the prospects of the long-term outcomes of the prosthetic, biological complications, and survival of the implant. Fifth, the learning curve effect was not specifically evaluated and the surgeon was already exposed to 15 cases using the robotic system before enrolling in the studies.[39]

Future studies are recommended to undertake multicenter, randomized controlled trials that are of larger sample size, long-term follow-up (greater than 5 years), formal cost-effectiveness analysis, and learning curve issues of robotic implant systems. Also, the combination of intraoral scanning data with AI-based real-time bone density mapping of osteotomy preparation prepare is a promising avenue that can be developed further.[40]

5. Conclusion

The AI driven robotic arm systems within the constraints of this prospective comparative study among others showed greatly superior three dimensional accuracy in dental implant placement relative to traditional freehand approaches with distant sub-millimeter deviations verified by CBCT superimposition. The robotic system saved an active surgical time to the tune of 18.6% and greater values of implant stability quotient and less marginal bone loss at six months. The Osseointegration rates of 6 months were similar between the groups. The results are in line with the clinical feasibility of AI-based robotic technology as a precision-enhancing technology in implant dentistry. However, larger, multicenter randomized controlled trials with long-term follow-up and health-economic analyses are needed to fully establish the clinical benefit and cost-effectiveness of robotic implant placement.

Conflict of Interest: None to declare

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Conflict of Interest

The authors declare no conflicts of interest related to this study.

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