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ORIGINAL ARTICALE

INTEGRATION OF AI IN ROBOTIC SURGERY SYSTEMS FOR PRECISION IMPLANT PLACEMENT: A PILOT OBSERVATIONAL STUDY IN DIGITAL DENTISTRY

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ABSTRACT

Background: Dental implant placement demanded an always a guide to high precision, especially in anatomically sensitive zones such as the posterior mandible. The integration of robotic assistance emerged as a promising technique to enhance surgical accuracy.

Aim: This pilot study evaluated the precision of dental implant placement using a robotic surgery system in comparison with digitally planned trajectories.

Materials and Methods: Ten partially edentulous patients, each desiring a single implant in the posterior mandibular region, were enrolled. Preoperatively cone-beam computed tomography (CBCT) and digital intraoral scanning reports were allowed to merged in CAD software for virtual implant positioning. Implant placement by the robotic arm guided by preloaded surgical plans and real-time navigation feedback was followed by postoperative regimen of CBCT imaging, to assess deviations between planned and actual implant positions.

Results: The mean deviation (implant platform) was 0.71 mm, while the apex deviation averaged 0.68 mm. The angular deviation from planned to placed implants was 1.56°. These results suggested high fidelity.

Conclusion: Robotic-assisted implant procedure demonstrated promising accuracy. Technology offers potential benefits in precision and predictability, particularly in challenging posterior mandibular sites.

Keywords: Dental, implants, robotic arm, digital planning, CAD/CAM, CBCT, intraoral scanner

INTRODUCTION

Precision for dental implant placement is significant assuring long-term prosthetic success and avoidance of anatomical complications. While conventional techniques continue to be widely practiced, they are prone to deviations. This is due to dependence on the clinician's skill, limited visibility, and anatomical variations[1]. To overcome these challenges, digital planning with guided implant placement systems have been introduced[2]. These systems will improve control but are still influenced by manual handling, cognitive load, and equipment calibration errors[2].

Robotic-assisted is the next evolution in implantology, integrating, haptic control, and digital planning to minimize surgical deviation[3]. Unlike static guides, which rely on pre-fabricated templates, or dynamic systems that require continuous tracking, robotic platforms can follow pre-planned trajectories autonomously or semi-autonomously, adjusting for intraoperative shifts in patient positioning or tissue compliance[4].

In a recent systematic review, Sankar et al. found that robotic systems demonstrated statistically significant improvements in angular and linear accuracy when compared to other placement modalities[1]. Furthermore, a multicenter trial by Chen et al. demonstrated that robotic surgery could reduce apical deviation to less than 1 mm, even in complex posterior cases[5].

Given the promising outcomes reported in the literature, this pilot study was conducted to evaluate the precision of implant placement using an AI-guided robotic surgery system in partially edentulous patients. The focus was on assessing positional and angular deviation between planned and actual implant positions in the posterior mandibular region using a CAD/CAM-based workflow.

MATERIALS AND METHODS

This prospective observational study was conducted at a single private dental center specializing in implantology and equipped with a robotic surgery system integrated with digital planning technology. A total of 10 adult patients, aged between 25 and 55 years, presenting with single-tooth edentulous spaces in the posterior mandible were selected based on specific inclusion and exclusion criteria. Eligible participants had sufficient bone volume for implant placement without the need for grafting and provided informed consent to undergo robotic-assisted surgery. Patients with systemic contraindications to implant surgery, severe gag reflex, limited mouth opening, or those requiring simultaneous bone augmentation or sinus lift were excluded. The preoperative workflow included obtaining digital impressions by an intraoral scanner (TRIOS 3Shape) and cone-beam computed tomography (CBCT) scans. These datasets were further, integrated into planning software for positioning digitally - the implants based on ideal angulation, depth, and alignment. The finalized plan was then exported to a robotic surgery system capable of translating this information into real-time surgical guidance. During the procedure, the robotic arm executed the osteotomy and implant insertion with dynamic feedback control, maintaining precise alignment as per the virtual plan. Postoperative CBCT imaging was performed within 48 hours, and pre- and postoperative scans were superimposed using specialized image registration software. Deviation between the planned and actual implant position was measured at the platform and apex levels, along with angular discrepancy, to assess surgical accuracy.

RESULTS

All ten implant procedures were completed successfully using the AI-guided robotic system without any intraoperative complications or equipment-related issues. Postoperative CBCT imaging and subsequent superimposition with the planned surgical trajectories revealed high precision in implant placement. The mean deviation at the implant platform was 0.71 ± 0.14 mm, while the apex deviation measured 0.68 ± 0.18 mm. The angular deviation from the planned trajectory averaged 1.56 ± 0.27 degrees. Importantly, all implants remained within clinically acceptable safety margins, defined as less than 2 mm deviation from the planned position. These findings reflect the system's reliability and consistency in maintaining spatial accuracy during the procedure. (Figure 1 & 2)

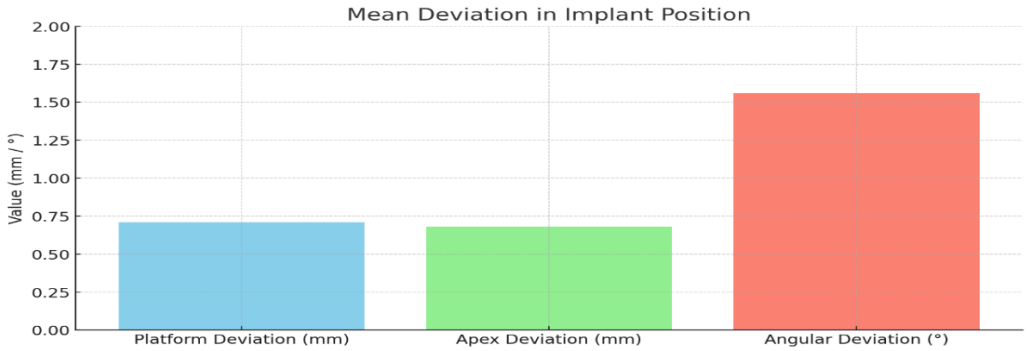

Figure1. Mean Deviation in Implant Position – Shows the average platform, apex, and angular deviations.

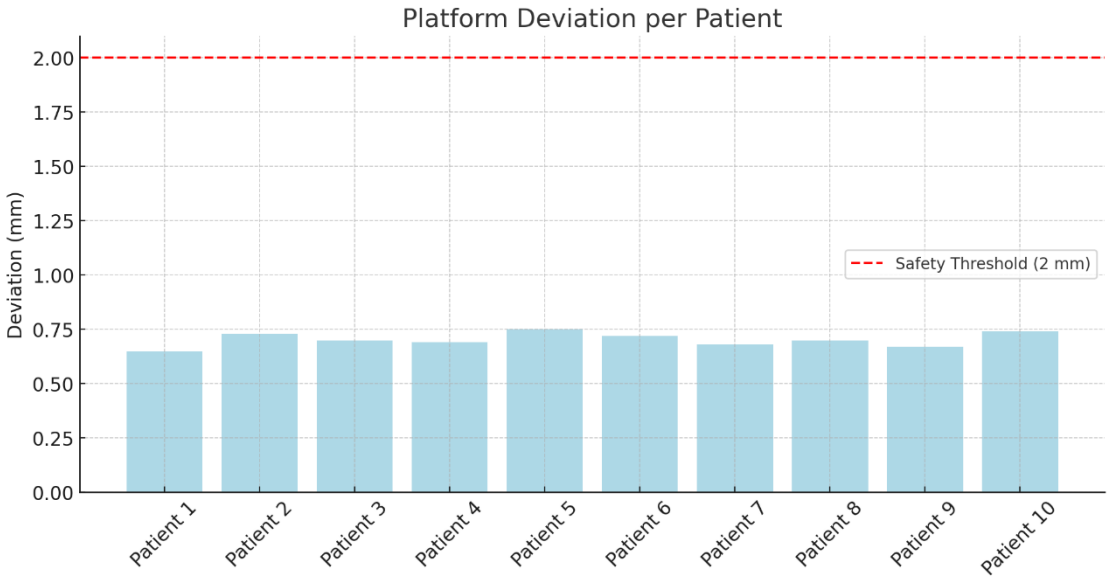

Figure 2. Platform Deviation per Patient – Illustrates individual patient deviations with a red line indicating the 2 mm safety threshold. All values are well within safe limits.

DISCUSSION

The integration of robotic-assisted systems with CAD/CAM digital workflows has shown substantial promise in enhancing the accuracy of dental implant placement. In this pilot study, the robotic system demonstrated highly predictable and precise implant positioning, with deviations at the platform and apex closely matching those reported in previous clinical trials and reviews. Our findings are consistent with those of Sankar et al., who conducted a comprehensive meta-analysis and reported a pooled angular deviation of approximately 1.6° and a platform deviation of around 0.7 mm for robotic-assisted implant placement[1]. These results reinforce the reliability of robotic systems in maintaining close alignment between planned and actual implant positions.

Compared to conventional static guides and dynamic navigation, robotic surgery offers several clinical advantages. Static guidance, while useful, often encounters limitations due to template misfit, positional errors during template fixation, and challenges in accommodating intraoral anatomical variations[2]. On the other hand, dynamic navigation systems require constant visual-motor coordination and a steep learning curve, which can introduce variability depending on the surgeon's experience[3]. The robotic approach employed in this study overcomes these challenges by providing automated, real-time control and adjustment during the drilling and placement phases. This is supported by earlier literature suggesting that robotic systems enable high precision through continuous feedback and adaptation to intraoperative changes[4].

A unique advantage observed in our study was the ability of the robotic system to make micro-adjustments during osteotomy, guided by intraoperative feedback on bone density and spatial positioning. This feature contributed to improved control and reduced operator dependency. Additionally, several benefits were noted from a clinical workflow standpoint: enhanced surgical precision with minimal manual intervention, reduced overall operative time, improved patient comfort, and minimally invasive soft tissue handling. These findings echo those of Chen et al., who demonstrated in a multicenter clinical trial that robotic-assisted surgery not only improved accuracy but also increased procedural efficiency and patient satisfaction[5].

Overall, the robotic approach presents a compelling advancement in the pursuit of predictable and minimally invasive implant surgery. While the results from this small cohort are promising, larger studies with longer follow-up periods are warranted to assess long-term outcomes, implant survival rates, and potential cost-benefit implications in routine clinical settings.

CONCLUSION

AI-enhanced robotic systems in dental implantology represent a transformative leap in digital dentistry, offering enhanced accuracy and safety. Even with a small sample size, our findings demonstrate the clinical viability and precision of such systems. Further multi-center trials with larger cohorts are recommended.
designs into future risk assessment protocols[27].

This work is restricted to short-term exposure under laboratory conditions. Future research should study the effect of long-term exposure, reproductive toxicity, transgenerational toxicology, and nanoparticle alteration in the real environmental conditions to enhance the risk assessment process.

DECLARATION

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CONFLICT OF INTEREST

None declared.

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