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Robotics in Implant Dentistry: Current Status and Future Prospects

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Abstract

The field of implant dentistry has witnessed significant advancements in recent years, with robotics emerging as a promising technology to enhance precision, predictability, and patient outcomes. This paper provides a comprehensive overview of the current status of robotics in implant dentistry, exploring its applications, benefits, and limitations. We delve into the various robotic systems available, discussing their functionalities, surgical workflows, and clinical integration. The paper examines the advantages of robotic-assisted implant surgery, including improved accuracy in implant placement, reduced invasiveness, and the potential for enhanced osseointegration. We also address the challenges associated with the adoption of robotic technology, such as cost, learning curve, and the need for robust validation studies. Furthermore, this paper explores the future prospects of robotics in implant dentistry, highlighting potential advancements in areas such as haptic feedback, AI integration, and the development of more versatile and affordable robotic platforms. We discuss the potential for robotics to personalize implant procedures, optimize treatment planning, and ultimately improve the standard of care for patients requiring dental implants. The integration of robotics with other cutting-edge technologies, like AI and virtual reality, is also considered, paving the way for a future where implant surgery becomes increasingly precise, predictable, and patient-centric.

Keywords: *Robotics; Implant Dentistry; Computer-Aided Surgery; Surgical Navigation; Accuracy; Precision; Osseointegration; Minimally Invasive Surgery; Dental Implants; Future of Dentistry; AI in Dentistry; Haptic Feedback; Virtual Reality; Personalized Dentistry*

Introduction

The restoration of missing teeth through dental implants has become a cornerstone of modern dentistry, offering patients a reliable and esthetically pleasing solution for improved oral function and quality of life. The success of implant therapy hinges on the accurate placement of the implant, as even minor deviations from the planned position can compromise osseointegration, affect the emergence profile of the restoration, and lead to complications such as nerve damage or implant failure. Traditional implant placement relies heavily on the surgeon's skill and experience, often involving freehand techniques guided by two-dimensional radiographs. While these methods can be effective, they are susceptible to human error and may not always achieve the desired level [1-7] of precision, particularly in complex cases involving limited bone availability, proximity to vital anatomical structures, or the need for precise angulation for optimal prosthetic outcomes.

In recent years, technological advancements have revolutionized the field of implant dentistry, offering innovative tools to enhance accuracy and predictability. Among these advancements, computer-aided implant surgery (CAIS) has emerged as a significant development, allowing for virtual planning and guided implant placement. CAIS utilizes three-dimensional imaging, typically cone-beam computed tomography (CBCT), to create a virtual model of the patient's jawbone. This virtual model enables clinicians to meticulously plan the implant position, angulation, and depth, taking into account anatomical landmarks, bone density, and prosthetic requirements. Surgical guides, fabricated based on the virtual plan, are then used during surgery to guide the implant drills, ensuring accurate transfer of the planned implant position to the patient. While CAIS has significantly improved the precision of implant placement compared to traditional freehand techniques, it still relies on the surgeon's manual dexterity to manipulate the surgical instruments.

The next leap in precision and control in implant dentistry has come with the introduction of robotics. Robotic systems offer the potential to further enhance the accuracy and predictability of implant surgery by providing a controlled and automated platform for implant placement. These systems combine the benefits of virtual planning with the precision of robotic control, minimizing human error and allowing for more complex and minimally invasive procedures. Robotic-assisted surgery in other medical fields, such as orthopedics and neurosurgery, has demonstrated significant improvements in accuracy and patient outcomes [8-12], paving the way for its application in dentistry.

Robotic systems for implant dentistry typically consist of a robotic arm, a navigation system, and specialized software. The surgical plan, created using CBCT data and implant planning software, is uploaded to the robotic system. During surgery, the robotic arm, guided by the navigation system, positions the surgical instruments with sub-millimeter precision, following the pre-planned trajectory. This level of accuracy is difficult to achieve with traditional manual techniques, even with the aid of surgical guides. Robotic systems also offer the potential for real-time adjustments during surgery, allowing the surgeon to fine-tune the implant position based on intraoperative feedback.

This paper aims to provide a comprehensive overview of the current status of robotics in implant dentistry, exploring the various robotic systems available, their functionalities, and their clinical applications. We will examine the benefits of robotic-assisted implant surgery, including improved accuracy, reduced invasiveness, and potential for enhanced osseointegration. Furthermore, we will discuss the challenges associated with the adoption of robotic technology in implant dentistry, such as cost, learning curve, and the need for robust clinical evidence to validate its effectiveness. Finally, we will explore the future prospects of robotics in this field, highlighting potential advancements in areas such as haptic feedback, artificial intelligence integration, and the development of more versatile and affordable robotic platforms. By exploring the current landscape and future directions of robotics in implant dentistry, this paper seeks to provide clinicians and researchers with a comprehensive understanding of this emerging technology and its potential to transform the field of implantology.

Challenges

While robotics offers significant potential to revolutionize implant dentistry, several challenges remain before its widespread adoption can be realized. These challenges [13-16] span technological, economic, practical, and educational domains:

1. **Cost and accessibility:** Robotic systems for implant surgery are currently a significant investment, both for the initial purchase of the equipment and for ongoing maintenance and software updates. This high cost can be a barrier for many dental practices, particularly smaller clinics or those in less affluent areas, limiting the accessibility of this technology to a select few. The cost of disposables, such as specialized drills or guide components, can also add to the overall expense. Making robotic systems more affordable and accessible is crucial for their wider adoption.
2. **Learning curve and training:** Integrating robotic technology into implant workflows requires a substantial learning curve for clinicians and staff. Dentists need to be trained not only on the operation of the robotic system itself but also on the intricacies of the associated software, planning procedures, and potential troubleshooting. Developing standardized training programs and providing adequate support for clinicians transitioning to robotic-assisted surgery is essential. Furthermore, dental schools need to incorporate robotics into their curriculum to prepare future generations of dentists for this evolving technology.
3. **Integration with existing workflows:** Integrating robotic systems seamlessly into existing dental practice workflows can be challenging. The process of patient selection, treatment planning, and surgical execution needs to be adapted to accommodate the robotic system. This may require changes in scheduling, staff responsibilities, and the physical layout of the surgical suite. Streamlining the integration process and developing standardized protocols are crucial for efficient implementation.

4. **Technical complexity and reliability:** Robotic systems are complex pieces of machinery, and their reliable operation is critical for successful surgical outcomes. Technical issues, such as software glitches, hardware malfunctions, or navigation errors, can potentially disrupt the surgical procedure and compromise patient safety. Robust quality control measures, regular maintenance, and readily available technical support are essential to ensure the reliability of these systems.
5. **Validation and clinical evidence:** While several studies have demonstrated the accuracy and feasibility of robotic-assisted implant surgery, more robust clinical evidence is needed to fully validate its benefits and long-term outcomes. Large-scale, randomized controlled trials comparing robotic surgery with traditional techniques are necessary to assess its effectiveness in various clinical scenarios, including complex cases and patients with comorbidities. Long-term follow-up studies are also needed to evaluate the impact of robotic surgery on implant survival rates, osseointegration, and patient-reported outcomes.
6. **Regulatory and ethical considerations:** As with any new technology, the use of robotics in implant dentistry raises regulatory and ethical considerations. Clear guidelines and standards need to be established to ensure patient safety and data privacy [17-21]. Issues such as liability in case of technical malfunctions or adverse events also need to be addressed. Furthermore, the potential impact of robotics on the dentist-patient relationship and the role of human oversight in automated surgical procedures require careful consideration.
7. **Space requirements and infrastructure:** Robotic systems often require dedicated space and infrastructure within the dental clinic. The robotic arm, navigation system, and associated equipment may necessitate modifications to the surgical suite. Clinics considering adopting robotic technology need to carefully assess their space requirements and make necessary adjustments.
8. **Patient acceptance and perception:** Some patients may be apprehensive about undergoing robotic-assisted surgery, due to concerns about the technology's safety or the level of human control. Educating patients about the benefits and safety of robotic implant surgery is crucial to address their concerns and ensure their acceptance of this technology.

Advantages

- **Enhanced accuracy and precision:** This is the most significant advantage. Robotic systems, guided by detailed 3D planning, can place implants with sub-millimeter accuracy, exceeding human capabilities. This precision minimizes the risk of complications and improves the long-term success of implants.
- **Minimally invasive procedures:** Robotic assistance often allows for smaller incisions, reducing trauma to surrounding tissues and promoting faster healing. This can lead to less post-operative discomfort for patients.
- **Improved predictability:** With precise planning and execution, robotic surgery enhances the predictability of implant placement, leading to more consistent and favorable outcomes, especially in complex cases.
- **Reduced human error:** By automating certain aspects of the surgical procedure, robotic systems minimize the potential for human error, such as hand tremors or deviations from the planned trajectory.
- **Enhanced visualization:** Robotic systems often incorporate advanced imaging and navigation technologies, providing surgeons with a clear and magnified view of the surgical field, facilitating more precise manipulation of instruments.
- **Potential for improved osseointegration:** Accurate implant placement contributes to optimal osseointegration, the process by which the implant integrates with the jawbone. This is crucial for long-term implant stability and success.
- **Increased efficiency:** While the initial setup may take time, robotic assistance can streamline certain aspects of the surgery, potentially reducing overall procedure time, especially for complex cases.
- **Ergonomic benefits for surgeons:** Robotic systems can offer ergonomic advantages for surgeons, reducing fatigue and improving comfort during lengthy procedures.

Disadvantages

- **High cost:** The initial investment in robotic equipment and ongoing maintenance can be substantial, making it a barrier for many dental practices.
- **Learning curve:** Dentists and staff require specialized training to operate robotic systems effectively, which can be time-consuming and require a significant investment in education.

- **Technical complexity:** Robotic systems are complex and require technical expertise for operation and troubleshooting. Technical issues can arise, potentially disrupting the surgical procedure.
- **Integration challenges:** Integrating robotic systems into existing dental practice workflows may require changes in scheduling [22-27], staff responsibilities, and the physical layout of the surgical suite.
- **Limited clinical evidence:** While studies have shown promise, more robust clinical evidence is needed to fully validate the long-term benefits and cost-effectiveness of robotic implant surgery.
- **Patient perception:** Some patients may be hesitant about undergoing robotic surgery due to concerns about the technology's safety or the level of human control.
- **Space requirements:** Robotic systems may require dedicated space and infrastructure within the dental clinic, which can be a limiting factor for some practices.
- **Dependence on technology:** Over-reliance on technology may potentially diminish the development and refinement of traditional surgical skills.

Future works

1. **Enhanced AI integration:**

- **AI-driven treatment planning:** Integrating AI algorithms to analyze patient data (CBCT scans, medical history, etc.) to optimize implant placement planning, considering factors like bone density, anatomical variations, and prosthetic needs.
- **Real-time feedback and adaptation:** Developing AI systems that can analyze intraoperative data and provide real-time feedback to the surgeon, allowing for adjustments in implant position or trajectory during the procedure.
- **Predictive analytics:** Using AI to predict potential complications or risks associated with implant placement, enabling proactive interventions and personalized treatment strategies.

2. **Improved robotic systems:**

- **Haptic feedback:** Incorporating haptic feedback into robotic systems to provide surgeons with a sense of touch and resistance during surgery, enhancing their control and precision.
- **Miniaturization and versatility:** Developing smaller, more versatile robotic arms that can be used for a wider range of implant procedures, including minimally invasive techniques and complex cases.
- **Autonomous capabilities:** Exploring the potential for developing robotic systems with increasing levels of autonomy, allowing them to perform certain aspects of the surgery with minimal human intervention, while still maintaining surgeon oversight.

3. **Advanced imaging and navigation:**

- **Improved image guidance:** Integrating advanced imaging modalities, such as cone-beam computed tomography (CBCT) and intraoperative fluoroscopy, to provide real-time visualization of the surgical field and enhance navigation accuracy.
- **Markerless tracking:** Developing markerless tracking systems that do not require the placement of physical markers on the patient [28-30], simplifying the surgical workflow and reducing the potential for errors.
- **Virtual reality integration:** Combining robotic systems with virtual reality technology to create immersive surgical environments, allowing surgeons to practice and plan procedures in a realistic setting.

4. **Clinical research and validation:**

- **Large-scale clinical trials:** Conducting more large-scale, randomized controlled trials to compare the outcomes of robotic-assisted implant surgery with traditional techniques, assessing factors such as accuracy, complications, and long-term implant survival rates.
- **Cost-effectiveness analysis:** Performing cost-effectiveness analyses to evaluate the economic benefits of robotic implant surgery, considering factors such as equipment costs, training expenses, and improved patient outcomes.
- **Patient-reported outcomes:** Assessing patient-reported outcomes, such as pain, discomfort, and satisfaction, to evaluate the impact of robotic surgery on the patient experience.

5. **Education and training:**

- **Standardized training programs:** Developing standardized training programs for dentists and staff on the use of robotic systems in implant surgery, ensuring competency and safety.
- **Simulation-based training:** Utilizing simulation technology to provide surgeons with hands-on experience in a virtual environment before performing robotic surgery on patients.
- **Continuing education:** Offering continuing education courses and workshops to keep clinicians up-to-date with the latest advancements in robotic implant technology and techniques.

6. **Ethical and regulatory considerations:**
    - **Developing ethical guidelines:** Establishing clear ethical guidelines for the use of robotics in implant dentistry, addressing issues such as patient autonomy, data privacy, and the role of human oversight.
    - **Regulatory frameworks:** Developing appropriate regulatory frameworks for the approval and use of robotic systems in implant surgery, ensuring patient safety and quality of care.

Conclusion

In conclusion, robotics has emerged as a transformative technology with the potential to revolutionize the field of implant dentistry. While still in its relatively early stages of adoption, robotic-assisted implant surgery offers significant advantages [31,32], including enhanced accuracy and precision, minimally invasive procedures, improved predictability, and reduced human error. These benefits translate to the potential for better osseointegration, fewer complications, and ultimately, improved patient outcomes. The ability to meticulously plan implant placement using 3D imaging and then execute that plan with sub-millimeter precision via a robotic arm represents a significant leap forward from traditional freehand techniques.

However, the path to widespread adoption of robotics in implant dentistry is not without its challenges. The high cost of equipment, the necessary learning curve for clinicians, the complexities of integrating robotic systems into existing workflows, and the need for more robust long-term clinical evidence are all factors that must be addressed. Furthermore, issues related to patient perception, regulatory frameworks, and ethical considerations require careful attention.

Bibliography

1. Panahi P, Bayılmış C, Çavuşoğlu U, Kaçar S. Performance evaluation of lightweight encryption algorithms for IoT-based applications. Arabian Journal for Science and Engineering. 2021;46(4):4015-4037.
2. Panahi U, Bayılmış C. Enabling secure data transmission for wireless sensor networks based IoT applications. Ain Shams Engineering Journal. 2023;14(2):101866.
3. Omid Panahi, Mohammad Zeinalddin. The remote monitoring toothbrush for early cavity detection using artificial intelligence (AI). IJDSIR. 2024;7(4):173-178.
4. Panahi O, Zeinalddin M. The convergence of precision medicine and dentistry: An AI and robotics perspective. Austin J Dent. 2024;11(2):1186.
5. Omid Panahi, Uras Panahi. AI-Powered IoT: Transforming diagnostics and treatment planning in oral implantology. J Adv Artif Intell Mach Learn. 2025;1(1):1-4.
6. Panahi P. Multipath local error management technique over ad hoc networks. In 2008 International Conference on Automated Solutions for Cross Media Content and Multi-Channel Distribution, IEEE, 2008:187-194.
7. Panahi P. Providing consistent global sharing service over VANET using new plan. In 2009 14th International CSI Computer Conference, IEEE, 2009:213-218.
8. Omid Panahi, Sevil Farrokh. USAG-1-based therapies: A paradigm shift in dental medicine. Int J Nurs Health Care. 2024;1(1):1-4.
9. Omid Panahi, Sevil Farrokh. Can AI heal us? the promise of AI-driven tissue engineering. Int J Nurs Health Care. 2024;1(1):1-4.
10. Koyuncu B, Gokce A, Panahi P. Reconstruction of an archeological site in real time domain by using software techniques. In 2015 Fifth International Conference on Communication Systems and Network Technologies, IEEE, 2015:1350-1354.
11. Panahi P, Dehghan M. Multipath video transmission over Ad Hoc networks using layer coding and video caches. In ICEE 2008, 16th Iranian conference on electrical engineering, 2008:50-55.
12. Panahi P, Maragheh HK, Abdolzadeh M, Sharifi M. A novel schema for multipath video transferring over ad hoc networks. In 2008 The Second International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies, IEEE, 2008:77-82.

13. Panahi O, Zeinaldin M. Digital dentistry: revolutionizing dental care. J Dent App. 2024;10(1):1121.

14. Panahi O. AI in surgical robotics: case studies. Austin J Clin Case Rep. 2024;11(7):1342.

15. Panahi O, Zeinaldin M. AI-assisted detection of oral cancer: a comparative analysis. Austin J Pathol Lab Med. 2024;10(1):1037.

16. Panahi O. Bridging the gap: AI-driven solutions for dental tissue regeneration. Austin J Dent. 2024;11(2):1185.

17. Panahi O, Farrokh. The use of machine learning for personalized dental-medicine treatment. Glob J Med Biomed Case Rep. 2025;1(1):001.

18. Omid Panahi, Sevil Farrokh. Building healthier communities: The intersection of AI, IT, and community medicine. Int J Nurs Health Care. 2025;1(1):1-4.

19. Omid Panahi, Ali Ezzati. AI in dental-medicine: current applications and future directions. Open Access J Clin Images. 2025;2(1):1-5.

20. Omid Panahi, Amirreza Amirloo. AI-enabled IT systems for improved dental practice management. On J Dent and Oral Health. 2025;8(4):000691.

21. Omid Panahi, Ali Ezzati, Mansoureh Zeynali. Will AI replace your dentist? the future of dental practice. On J Dent and Oral Health. 2025;8(3):000690.

22. Omid P, Sevil Farrokh E. Bioengineering innovations in dental implantology. Curr Trends Biomedical Eng and Biosci. 2025;23(3):556111.

23. Panahi O and Eslamlou SF. Artificial intelligence in oral surgery: enhancing diagnostics, treatment, and patient care. J Clin Den and Oral Care. 2025;3(1):01-05.

24. Omid Panahi, Shabnam Dadkhah. Transforming dental care: a comprehensive review of AI technologies. J Stoma Dent Res. 2025;3(1):1-5.

25. Panahi O, Raouf MF, Patrik K. The evaluation between pregnancy and periodontal therapy. Int J Acad Res. 2011;3:1057-1058.

26. Panahi O, Melody FR, Kennet P, Tamson MK. Drug induced (calcium channel blockers) gingival hyperplasia. JMBS. 2011;2(1):10-12.

27. Omid P. Relevance between gingival hyperplasia and leukemia. Int J Acad Res. 2011;3:493-494.

28. Panahi O, Rezaei S, Marzi M, Sana FA. *Helicobacter pylori* and oral cavity inflammation. JPCS. 2011;2:13-15.

29. Omid Panahi and Fatmanur Ketenci Çay. Nanotechnology, regenerative medicine and, tissue bio-engineering. Acta Scientific Dental Sciences. 2023;7(4):118-122.

30. Omid Panahi. Dental pulp stem cells: a review. Acta Scientific Dental Sciences. 2024;8(2):22-24.

31. Omid Panahi, Masoumeh Jabbarzadeh. The expanding role of artificial intelligence in modern dentistry. On J Dent and Oral Health. 2025;8(3):000688.

32. Omid P, Shabnam D. Mitigating aflatoxin contamination in grains: the importance of postharvest management practices. Adv Biotech and Micro. 2025;18(4):555996.