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From Eye To Arm: Vision-Guided Robotics In Precision Implant Dentistry

Dr Samitha S, Dr Gopika S, Dr Riswana Resvi, Dr Aby Mathew T,
Dr Rene Kuriakose
(Pg Resident, Department Of Prosthodontics And Crown And Bridge, Pushpagiri College Of Dental Sciences, Thiruvalla)
(Professor And Head, Department Of Prosthodontics And Crown And Bridge, Pushpagiri College Of Dental Sciences, Thiruvalla)
(Reader, Department Of Prosthodontics And Crown And Bridge, Pushpagiri College Of Dental Sciences, Thiruvalla)

Abstract:
Robotics has emerged as a transformative innovation in implant dentistry, offering new opportunities to enhance surgical precision, predictability, and patient outcomes. In recent years, the field has evolved significantly, with robotic systems being increasingly integrated into dental practices.This article presents a detailed overview of the current state of robotics in implant dentistry, covering its clinical applications, surgical workflows, advantages, and inherent limitations. It also examines the challenges to adoption, including high implementation costs, steep learning curves and the need for extensive clinical validation through robust studies.The discussion further explores the future prospects of robotics in this domain, with advancements expected in haptic feedback technology, AI integration, and the creation of more versatile, cost-effective robotic platforms. The synergy between robotics and other emerging technologies, such as artificial intelligence and virtual reality, holds the potential to make implant surgery increasingly precise, predictable, and patient-centered.Thus the integration of vision-guided robotics is poised to revolutionize dental implantology by bridging the gap between human surgical expertise and intelligent automation
Key Words: *Robotics, Yomi, Robot assisted implant placement, Accuracy, Precision, Haptic feedback, Virtual reality*

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I. Introduction

Dental implantology has undergone considerable advancement over recent decades, evolving from freehand implant placement to digitally guided workflows. A significant advancement in precision implant dentistry is the adoption of vision-guided robotic systems. Unlike static surgical guides, these systems integrate real-time imaging, computer vision, and robotic control to assist clinicians in achieving highly accurate and safe implant placements.These vision-guided robotic platforms employ 3D imaging techniques including CBCT scans, optical scanners, and augmented reality cameras to create live maps of the patient's anatomy. Computer vision algorithms continuously monitor the surgical field, while robotic arms guide or physically support the clinician during drilling and implant insertion, ensuring strict adherence to the planned implant trajectories even when conditions change dynamically.The success of robotic-assisted surgery in medical fields such as orthopedics and neurosurgery where it has significantly enhanced accuracy and patient outcomes has paved the way for its application in dentistry. Typically, robotic systems for dental implants comprise a robotic arm, a navigation system, and dedicated software[1]. The use of robotics in implantology enhances surgical accuracy by reducing human error, minimizing deviation from planned implant trajectory and safeguarding critical anatomical landmarks such as the mandibular canal and maxillary sinus. Robotic implant systems allow for real-time intraoperative adjustments, providing the surgeon the flexibility to fine-tune implant positioning based on immediate surgical feedback, enhancing both safety and outcome predictability. Furthermore, vision-based feedback improves the adaptibility of the robotic system, making procedures less invasive, reducing surgical time, and potentially accelerating recovery.

II. Pioneering Surgical Robotics

The development of dental implant robots has made remarkable progress over the last twenty years[4]. The concept of robot-assisted surgery originated in the mid-1980s with NASA's development of remotely controlled robotic systems for use in battlefield and space missions.

In 2000, the U.S. Food and Drug Administration (FDA) approved the first robotic system for laparoscopic surgery, the da Vinci Surgical System (Intuitive Surgical California). This system acts as an extension of the surgeon's hands, using robotic arms equipped with surgical tools to perform highly precise operations through small incisions. Since its introduction, the da Vinci system has undergone multiple upgrades, adding features like enhanced anatomical visualization, advanced imaging, and tremor reduction.

In 2002, Boesecke and colleagues at the University Hospital of Heidelberg introduced one of the earliest prototypes: a robotic system with a 700 mm reach, operated through PC-based TomoRob software (Medical Intelligence, Germany)[4]. This system was designed to maintain drill template alignment based on preoperative planning[4].

Dental implant robotics have progressed to include various systems with different degrees of automation and user involvement. According to Troccaz and colleagues, these robots are classified based on how much control the user has during tool movement: active robots perform pre-planned motions independently; passive robots require full manual operation; semi-active robots allow movement within constrained limits; and teleoperated robots are remotely controlled by the user[4].

In 2017, an autonomous dental implant robot was created through collaboration between the Fourth Military Medical University Hospital in Xi'an and the robotics institute at Beihang University in China. This robot aimed to address the shortage of skilled dentists in the country and demonstrated excellent accuracy, with errors ranging between 0.2 and 0.3 mm[10]. Moreover in 2017, the first FDA-cleared robotic system for dental implant surgery in the United States, known as Yomi (Neocis, Inc., Florida), was introduced[5]. Yomi is a haptic robotic-guided system that drills based on a coordinate system mapped to a patient's teeth[4]. The system provides software for surgical planning and navigational guidance, while offering haptic feedback to control the position, depth, and angle of the implant osteotomy[8].Following Yomi's success, other dental implant robot systems such as Remebot and Dentbo have also been developed and introduced to the market[3].

III. Stages Of Robotic Assisted Dental Implant Surgery

Preoperative planning

➢**Perform the CBCT:** The preoperative planning starts by performing a CBCT scan, which is used to generate a 3D image of the jawbone, allowing the surgeon to achieve a detailed view of the patients oral cavity[2](Fig 1)

Fig 1: Perform the CBCT

- ➢ **Define the implant:** Once the CBCT data are available, the next step is to define the implant position and orientation. This step involves selecting where the implant will be placed and determining its proper angle, depth, and alignment within the bone[2](Fig 2)

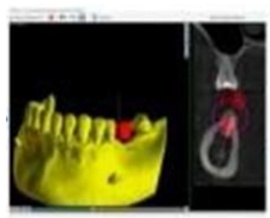

Fig 2: Define the implant

- ➢ **Design of the marker holder guide:** During this step, a guide for the video camera marker is designed. This guide uses the 3D model of the jawbone to perfectly be attached to 3 or more teeth. This guide is generated similarly to a classical surgical guide, but it does not contain a guiding hole for the drill; its purpose is to create a reference system between the 3D camera marker and the site of the implant[2](Fig 3)

Fig 3: Design marker holder guide

- **Design of marker support:** The navigation system requires several markers in order to dynamically adjust the position of the robot with respect to the implant site. This system uses a single marker that allows the determination of the position and orientation of the robot's end-effector with respect to the marker. The marker is placed on a special plate attached to the holder guide. By determining the position of the robot with respect to the camera marker and, at the same time, knowing the position of the implant site with respect to the same marker, the robot can be registered to the implant site[2](Fig 4)

Fig 4: Design marker support

- **Determine implant position:** The position of the implant site with respect to the camera marker is determined using specialized software. In this stage, the orientation angles and the depth of the implant are extracted, and the surgeon provides a list of necessary tools (drills, tapers, wrenches) to be used by the robot during the procedure, based on bone analysis, the density of the bone is determined, and the force and speed required for each drill are computed[2] (Fig 5)

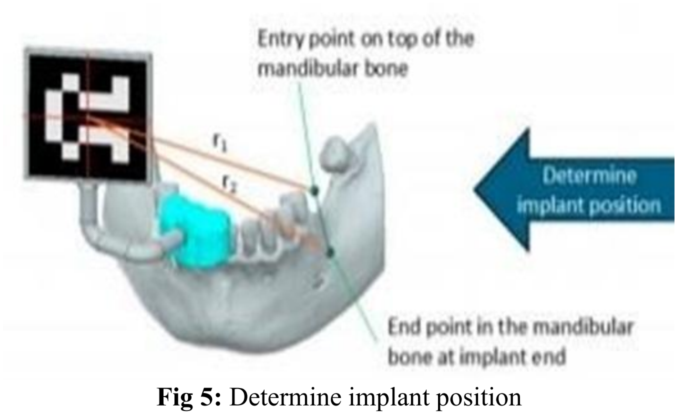

Fig 5: Determine implant position

The marker's guide is obtained using Blue Sky Plan 4. A segmentation of the lower base of the mouth is required for the software to align the STL resulting from the segmentation with the position of the teeth in the CBCT[2]. Once the STL is imported into the program, the alignment is performed automatically, but it still needs manual fine positioning for accurate placement[2]. After the proper alignment, the tooth that will use the implant is selected, and the software places the implant in the selected position[2]. The maker holder guide is obtained by selecting several contour points and is generated based on these points. Using the generated guide, an extension required for marker mounting is also designed and attached to the guide, which results in an assembly of a soft, elastic part (the guide) and a hard part, the marker support[2]. The marker support is designed as a fixed attachment to the guide and through a bent thin pipe to extend outside the oral cavity where the visual marker is positioned, enabling the robot to permanently adjust its position relative to its spatial location[2].

Robotic-Assisted Dental Implant Site Preparation

Following the preplanning phase, after the robotic system is initialized, the surgical procedure begins. At this point, the robotic system has the handpiece and the 3D camera mounted on its end-effector[2]. The collaborative robot has hand-guiding capabilities, and the surgeon will move the robot by hand to a predefined (approximate) position from where the vision system can identify the video marker placed on the guide[2](Fig 1)

Fig 1

After identifying the marker position, the robotic system requests the first tool (the spear drill for cortical perforation), which is mounted by the surgeon in the dental handpiece and confirmed[2](Fig 2)

Fig 2

By acknowledging the tool attachment, the surgeon allows the robot to begin the surgical procedure. The robot will move, using real-time visual feedback, close to the oral cavity of the patient, validating once more the position of the camera marker (Fig 3)

Fig 3

Before entering the oral cavity, the robotic system waits for surgeon supervision, which must be confirmed on the interface[2]. After the robot receives surgeon validation, it enters the oral cavity and positions the surgical tool 3 mm above the insertion point using the orientation angles (Fig 4)

Fig 4

The surgeon actuates the physiodispenser set to drilling speed by pressing the foot pedal, and the drilling procedure begins. The robot moves on a linear trajectory toward the insertion point (Fig 5)

Fig 5

The insertion point is reached when a force condition is raised within the robot controller, which remains raised during the entire drilling procedure[2]. The instantaneous drilling force is continuously monitored to remain within predefined limits during the entire procedure. The drilling force, in this stage of the development, was determined regarding drilling forces in different bone densities (D1 type: 30–50 N, D2, and D3 type: 20–40 N, D4 type: 10–20 N)[9]. After the drilling depth is reached, the robot retracts the dental handpiece on the same trajectory with the drill still revolving until the tool reaches the starting location above the insertion point. The robot moves outside the oral cavity, where the surgeon places the next drill in the dental handpiece (Fig 6), and the procedure is repeated until the threading diameter is reached.

Fig 6

After reaching the threading diameter, the surgeon mounts the tapper into the dental handpiece, and the robot performs the threading of the implant hole, repeating the steps from the drilling phase[2]. When the threading of the implant cavity is finished, the robot moves outside the oral cavity, the surgeon mounts the torque wrench for the implant screw (Fig 7), and the robot screws the implant (Fig 8). The procedure is finalized by the surgeon, who checks the positioning of the implant and sutures the affected area[2].

Fig 7 **Fig 8**

IV. Challenges

Although robotics holds great promise for transforming implant dentistry, several obstacles must be addressed before it can achieve widespread adoption. These challenges encompass technological, economic, practical, and educational aspects

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[1].
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[1].
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[1]. 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[1]. 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 longterm 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[1]. 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[1]. 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[1].
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[1]. Educating patients about the benefits and safety of robotic implant surgery is crucial to address their concerns and ensure their acceptance of this technology.

V. Advantages

- Enhanced accuracy and precision: This is the most significant advantage. Robotic systems, guided by detailed 3D planning, can place implants with submillimeter 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[1].
- 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[1].
- 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[1].
- 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[1]. 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[1].
- Ergonomic benefits for surgeons: Robotic systems can offer ergonomic advantages for surgeons, reducing fatigue and improving comfort during lengthy procedures[1].

VI. Disadvantages

- High cost: The initial investment in robotic equipment and ongoing maintenance can be substantial, making it a barrier for many dental practices[1].
- Learning curve: Dentists and staff require specialized train ing to operate robotic systems effectively, which can be time consuming and require a significant investment in education[1].
- Technical complexity: Robotic systems are complex and require technical expertise for operation and troubleshooting[1]. Technical issues can arise, potentially disrupting the surgical procedure.
- Integration challenges: Integrating robotic systems into existing dental practice workflows may require changes in scheduling, staff responsibilities, and the physical layout of the surgical suite[7].
- Limited clinical evidence: More robust clinical evidence is needed to fully validate the long-term benefits and cost-effectiveness of robotic implant surgery[1].
- 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[1].
- Space requirements: Robotic systems may require dedicated space and infrastructure within the dental clinic, which can be a limiting factor for some practices[1].
- Dependence on technology: Over-reliance on technology may potentially diminish the development and refinement of traditional surgical skills

VII. 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[1].
- 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[1].
- Predictive analytics: Using AI to predict potential complications or risks associated with implant placement, enabling proactive interventions and personalized treatment strategies[1].

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[1].
- 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[1].

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[1].
- Markerless tracking: Developing markerless tracking systems that do not require the placement of physical markers on the patient, simplifying the surgical workflow and reducing the potential for errors[1].
- 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[1].

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[1].
- 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[1].
- Patient-reported outcomes: Assessing patient-reported outcomes, such as pain, discomfort, and satisfaction, to evaluate the impact of robotic surgery on the patient experience[1].

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[1].
- Simulation-based training: Utilizing simulation technology to provide surgeons with hands-on experience in a virtual environment before performing robotic surgery on patients[1].
- Continuing education: Offering continuing education courses and workshops to keep clinicians up-to-date with the latest advancements in robotic implant technology and techniques[1].

VIII. Conclusion

Robotic-assisted implant surgery represents a significant advancement in modern surgical practice, offering enhanced precision, improved patient outcomes, and reduced intraoperative and postoperative complications. By combining the expertise of the surgeon with the accuracy of robotic systems, these procedures allow for minimally invasive techniques, better implant positioning, and faster recovery times. Clinical evidence continues to demonstrate the benefits of robotic-assisted surgery in terms of reduced blood loss, smaller incisions, lower infection rates, and greater consistency in surgical outcomes. As technology continues to evolve, the integration of robotics with artificial intelligence, 3D imaging, and augmented reality holds the promise of further improving surgical planning and execution. Despite the high initial costs and the learning curve associated with these systems, the long term advantages for both patients and healthcare providers are becoming increasingly clear. As adoption expands and more data becomes available, robotic assisted implant surgery is likely to become a standard of care in various specialities.

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