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ADVANCEMENTS IN ROBOTICS FOR PRECISION DENTAL IMPLANTOLOGY: OPPORTUNITIES EXPLORED, CHALLENGES IDENTIFIED

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Abstract

Robotics in dental implantology represents a rapidly advancing field that combines precision engineering, artificial intelligence, and digital planning to improve surgical accuracy and patient outcomes. This review explores the evolution of robotic systems from passive and semi-active platforms to fully autonomous and AI-integrated technologies. Current applications, such as haptic guidance, computer-assisted navigation, and 3D-printed surgical guides, demonstrate significant benefits in reducing surgical errors, optimizing workflows, and enhancing predictability of implant placement. However, widespread adoption faces barriers including high costs, steep learning curves, limited accessibility for smaller practices, and technical limitations in challenging clinical scenarios. Emerging trends—such as micro–nano robotic systems, multifunctional platforms, and AI-driven decision support—highlight future opportunities to revolutionize implantology. To achieve broader clinical integration, further research must focus on cost-efficiency, simplification of workflows, validation of outcomes, and patient acceptance, ensuring that robotics becomes an essential tool in precision dentistry.

Keywords

Dental implantology, robotics, surgical navigation, computer-assisted implant surgery, artificial intelligence, haptic guidance, robotic-assisted surgery, 3D printing, micro–nano robotics, precision dentistry

1. Introduction

1.1 Background

The evolution of robotics: research and application progress of dental implant robotic systems

The history of robots can be traced back over 3 000 years. Throughout history, scientists and craftsmen have designed and manufactured robot prototypes that simulate animal or human characteristics. However, these inventions can only be classified as mechanical devices that primarily achieved automated functions through mechanical and physical principles with the lack of intelligence and autonomy of modern robots. These inventions demonstrate the level of engineering technology and mechanical manufacturing in ancient times, laying the foundation for later research on robots.[1]

"Robot" is a new term that emerged in the 20th century. In 1920, the Czech writer Karel Capek published the science fiction script ˇ Rossum's Omnipotent Robots, in which the word "robot" was first coined from the Czech word "Robota," with a meaning similar to "labor" or "drudgery". [1] Joseph Engelberger, recognized as the Father of Robotics, founded Unimation Corporation in 1958, the world's first robot-manufacturing factory, which marked the official start of the industrialization of robots. At the first robotics conference held in Japan in 1967, Masahiro Mori put forward a representative definition of robots: "A robot is a flexible machine with seven characteristics: mobility, individuality, intelligence, versatility, semi-mechanical, semi-human, automatic, and a slave." The American National Standards Institute defines a "robot" as a mechanical device that can be programmed and can perform certain operations and mobile tasks under automatic control. In 1978, Unimation developed a Programmable Universal Machine for Assembly (PUMA) which represents a significant milestone in the development of international industrial robotics. In recent years, robotics has expanded significantly due to the continued development of sensor types, intelligent algorithms, and multidisciplinary integration. The technology has advanced from the initial industrial robotic arms to bionic robots, soft robots, nanorobots, and other forms.[2]

1.2 Problem statement

The integration of robotics into dental implantology faces several challenges despite its potential to enhance precision, efficiency, and patient outcomes. Key issues include the high cost of robotic systems, limiting their accessibility for small to medium-sized dental practices. There is also a lack of standardized training for dental professionals to operate robotic systems effectively, which can hinder adoption and optimal utilization. Moreover, the compatibility of robotic systems with diverse clinical scenarios, such as complex anatomical variations and patient-specific needs, remains a significant concern. Finally, addressing patient acceptance and trust in robotic-assisted procedures is essential to ensure widespread adoption in the field of dental implantology.

This highlights the need for research and development to make robotic systems more cost-effective, user-friendly, and adaptable while promoting education and trust among practitioners and patients. [3]

The use of robotics in dental implantology is an emerging field, offering significant advancements in precision, efficiency, and patient outcomes. However, it also faces several challenges and limitations.[4]

1.3 Objectives of the literature review

Various technologies have been introduced to improve the process of implant placement, including computer-assisted implant surgery. This technology has been well-documented for its ability to significantly enhance the accuracy of implant placement.[5]The goal of computer-assisted implant surgery is to achieve better clinical outcomes by reducing failures, complications, and adverse effects, such as damage to adjacent anatomical tissue and surgical complications[5,6] Computer-assisted implant surgery includes two main technological approaches: static and dynamic computer-assisted implant surgery. In static computer-assisted implant surgery, a surgical guide is used to guide the osteotomy and implant placement. Conversely, the computer-assisted implant surgery system, also known as real-time navigation, assists surgeons in real-time by using optical tracking devices to provide live imaging during the procedure. Both systems are widely used and extensively studied, showing their capability to help surgeons achieve higher accuracy in implant placement compared to free-hand surgery.[5,6] While computer-assisted technologies have improved preoperative planning, surgical templates, and video navigation, they still have some limitations.[5,7] One challenge is ensuring real-time accuracy and stability during drilling and cutting procedures. Additionally, guided dental implant placements are typically performed manually by dentists, which can be affected by human factors and the instability of hands.

2. Types of Robotic Systems Used in Dental Implantology

The International Federation of Robotics (IFR) classifies robotics into two distinct categories: industrial robotics and service robotics, in accordance with the international standard ISO 8373:2012.[8] Industrial robotics are multipurpose manipulators with automatic control and programmability, which can operate with fixed or autonomous mobility and are primarily used in industrial production.[8

]Service robotics are driving mechanisms that can perform useful tasks but do not include industrial automation applications. The IFR has classified

service robotics into different segments to meet the diverse requirements of various industries (Fig[. 1]).

Medical robotics are classified by IFR as special robotics with a combination of medical diagnosis methods with new technologies, such as artificial intelligence (AI) and big data, to provide services such as surgery, rehabilitation, nursing, medical transportation, and consultation for patients. Medical robotics are categorized into the following five types based on their functions: surgical robotics, rehabilitation robotics, diagnostic robotics, laboratory analysis automation, and other robotics (robotics used for medical transportation are not included in this category).[9]

Robotic applications in implantology can be broadly classified into robot-assisted and

fully automated implantation robots. [10] Recently, different types of dental implant robots have been introduced, such as active, passive, and semi-active systems, depending on the level of interaction between the dentist and the robot[.9,11,12]

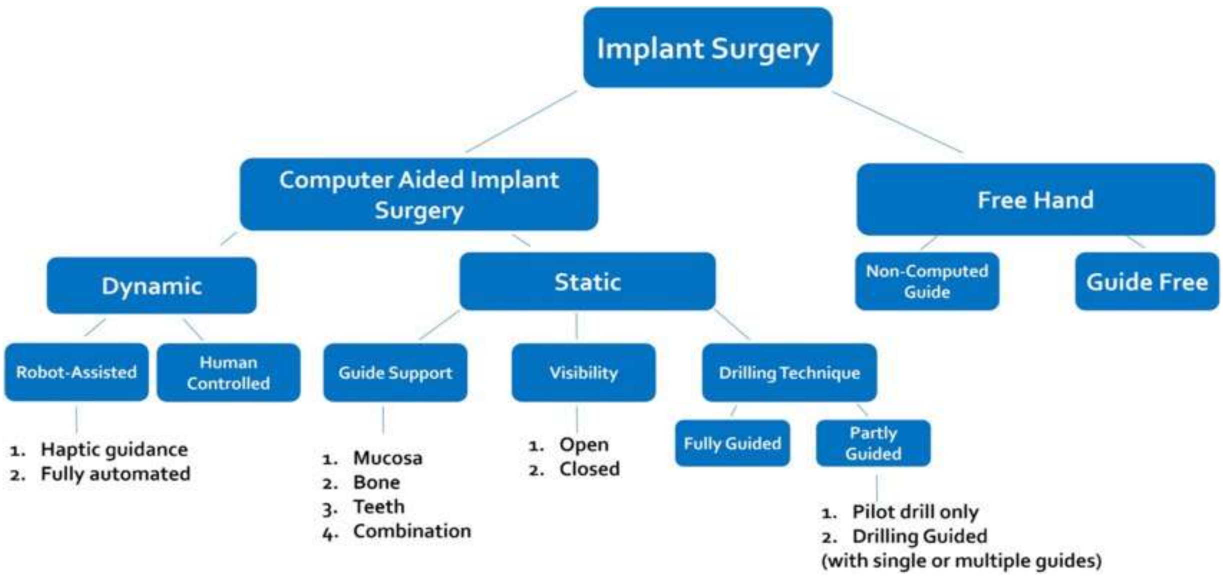

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Table 2. The autonomous level of commercial dental implant robotics

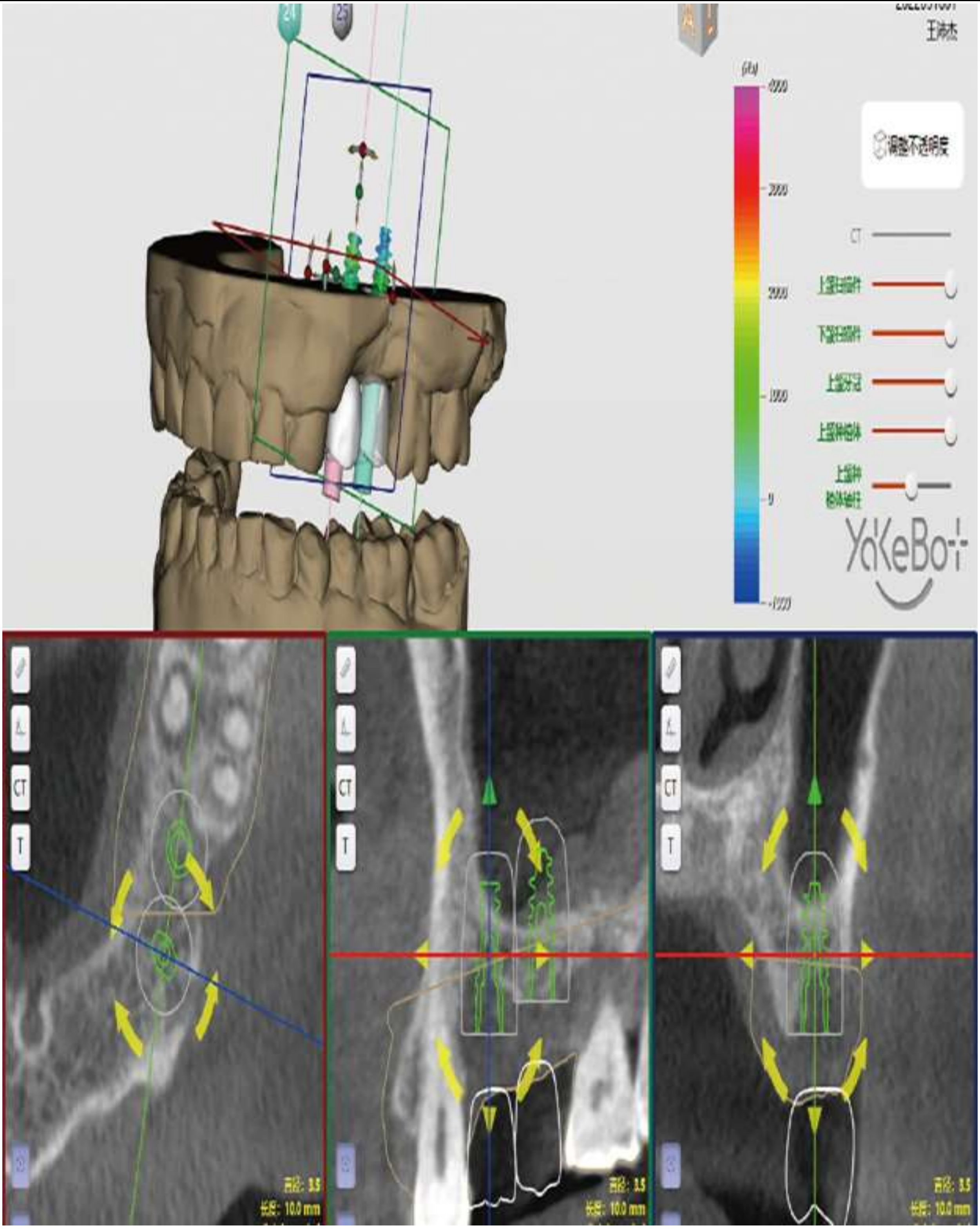
Robotic platform	Country	Autonomy level	Perception system	Robot arm
Yomi	USA	Level1: robot assistance	Haptic guidance	Unpublished
Theta	China	Level1: robot assistance	Two-eye infrared camera	UR3e
Dcarer	China	Level1: robot assistance	Two-eye infrared camera	UR5
Cobot	China	Level1: robot assistance	Haptic guidance and single-eye infrared camera	UR3 (main arm) and micro infrared single-eye tracking probe (auxiliary arm)
Remebot	China	Level2: task autonomy	Two-eye visible camera	UR5
Yakebot	China	Level2: task autonomy	Two-eye infrared camera	UR5

2.1 Fully Autonomous= Robots (e.g., Yomi,YekeBot)

Active robots: Examples include YekeBot (YekeBot Technology Co., Ltd, Beijing, China). These robots can independently enter and exit the mouth, prepare the implant site, and place the implant. The operator's role is primarily to replace the drill, provide instructions, and monitor the robot's operation.

YekeBot dental surgery robot: YekeBot, developed by Yekebot Technology Co., Ltd (Beijing, China), is an advanced robotic system specifically designed to assist

dental surgeons in the precise placement of dental implants. This robot features a robotic arm that is capable of autonomously entering and exiting the patient's mouth, as well as performing drilling and implants placement tasks.[13,14] During robotic arm then moves to the designated area and automatically adjusts the position of the implant handpiece based on the pre-operative plan. The robot the procedure, the dental surgeon activates the robot using a foot controller. The proceetre ds to prepare the implant site by drilling at a predetermined rate. Once the desired position is reached, the robotic arm returns the handpiece to its initial position. The surgeon then replaces the drill and repeats the process until the implant is successfully placed. Throughout the surgery, the YekeBot manages the movement of the robotic arm, the preparation of the implant site, and the placement of the implant, while the surgeon oversees the operation and provides instructions. This collaborative approach allows for enhanced precision and efficiency in dental implant procedures, potentially reducing the risk of human error and improving patient outcomes.[13,15]


CT
YaKeBot

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Passive robots: Robots such as Yomi (Neosis Inc., Miami, United States) and DentRobot (Dcarer Medical Technology Co., Ltd, Suzhou, China) require the operator to guide their robotic arms during the procedure. The operator is responsible for the robot's entry and exit from the mouth, preparation of the implant site, and placement of the implant.

Yomi dental surgery robot: Yomi is a passive implant robot developed by Neocis in the United States. It is specifically designed for dental surgery and utilizes a coordinate measuring machine (CMM) arm to assist with the precise positioning of a dental implant. The Yomi system consists of an operational arm that is manually controlled by surgeons and a CMM arm that automatically positions the implant.[16,17] During implant surgery procedures such as drilling and implant placement, the surgeons use the operational arm to perform the drilling while the CMM arm ensures accurate positioning the dental implant. It's worth noting that the CMM arm is more expensive and occupies a narrow space in the patient's oral cavity.[13]Yomi obtained approval from the U.S. Food and Drug

Administration (FDA) in 2017, indicating that it meets safety and effectiveness standards.[18]

2.2 Semi-Autonomous Robots (e.g., Robodent, da Vinci)

Semi-active robots: Semi-active implant robots, like the Remebot implant robot (Baihui Weikang Technology Co., Ltd, Beijing, China), can autonomously perform implant site preparation and implant insertion. However, these robots require the operator's assistance in maneuvering the robotic arm during mouth entry and exit.[13,18, 19]

Remebot dental surgery robot: In 2023, Baihui Weikang Technology Co., Ltd (Beijing, China) introduced Remebot, a semi-active implant robot.17 Remebot is specifically designed to assist in the preparation and insertion of dental implants. While it can independently perform certain tasks, it still requires manual assistance from the operator during certain stages of the procedure. To operate Remebot, the surgeon uses a foot controller to guide and pull the robotic arm into the patient's mouth. Once inside, the robotic arm takes over and automatically adjusts the position of the implant handpiece, as well as prepares the implant site at a

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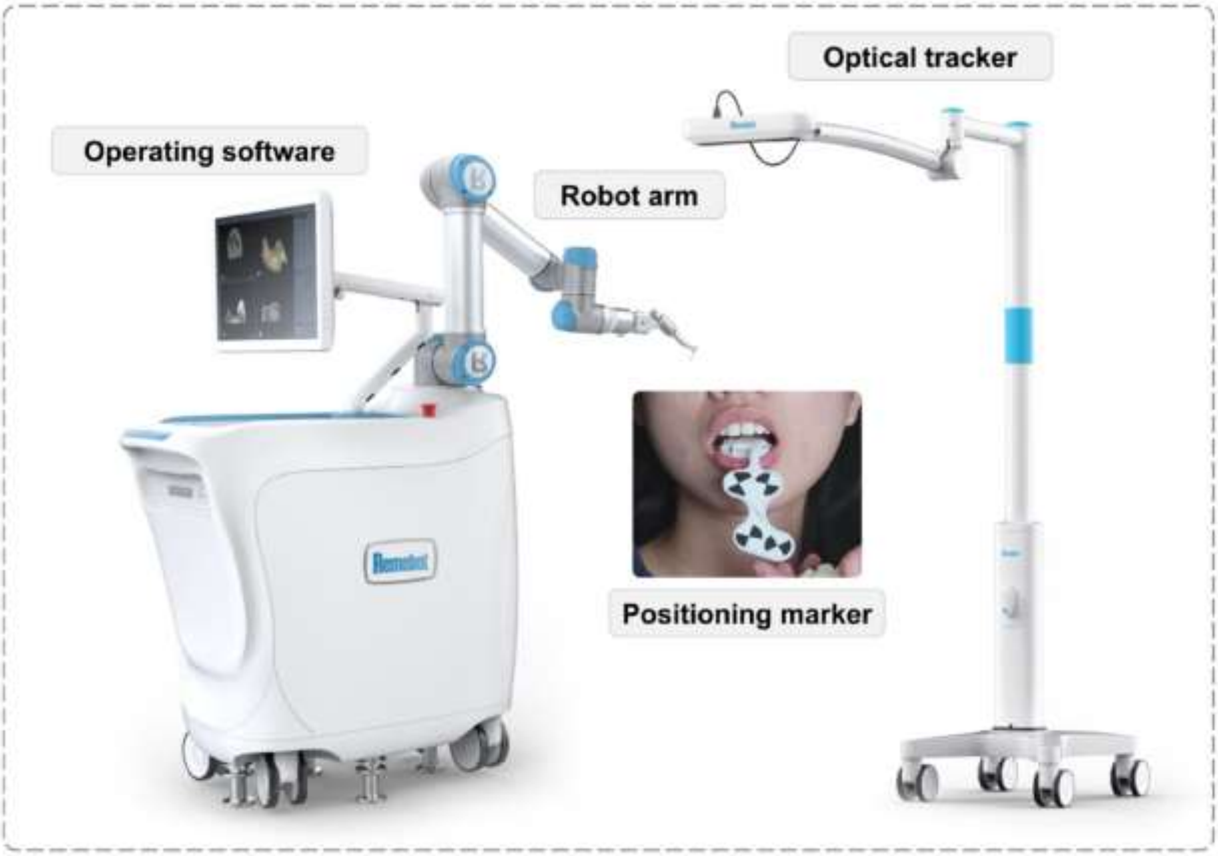
predetermined speed based on the pre-operative plan. The central control system ensures the accurate positioning of the drill. After the implant site is prepared, the robotic arm returns the handpiece to its initial position within the mouth. The process continues with the replacement of the drill, and this cycle is repeated until the implant is successfully placed. Throughout the procedure, the surgeon's primary responsibilities include guiding the robotic arm, replacing the drill, assembling the implant driver and implant, providing instructions, and supervising the overall operation of the robot. It's worth noting that Remebot represents advancement in dental implant technology by automating certain aspects of the procedure. However, it is still reliant on the expertise and oversight of a trained surgeon to ensure optimal results and patient safety.[13,20,21]



2.3 Computer-Assisted Navigation Systems (e.g., NobelClinician, Navident)

The usefulness of navigation relies on its high accuracy, which is particularly necessary in some specific surgical situations: (I) when anatomic structures must be taken into account and depth control is important, (II) when clinicians wish to use a flapless approach, (III) when placement requires high accuracy of angulation and spacing between implants and adjacent teeth, (IV) when implants must be placed in a tight interdental space and static guide tubes will interfere with the ideal implant

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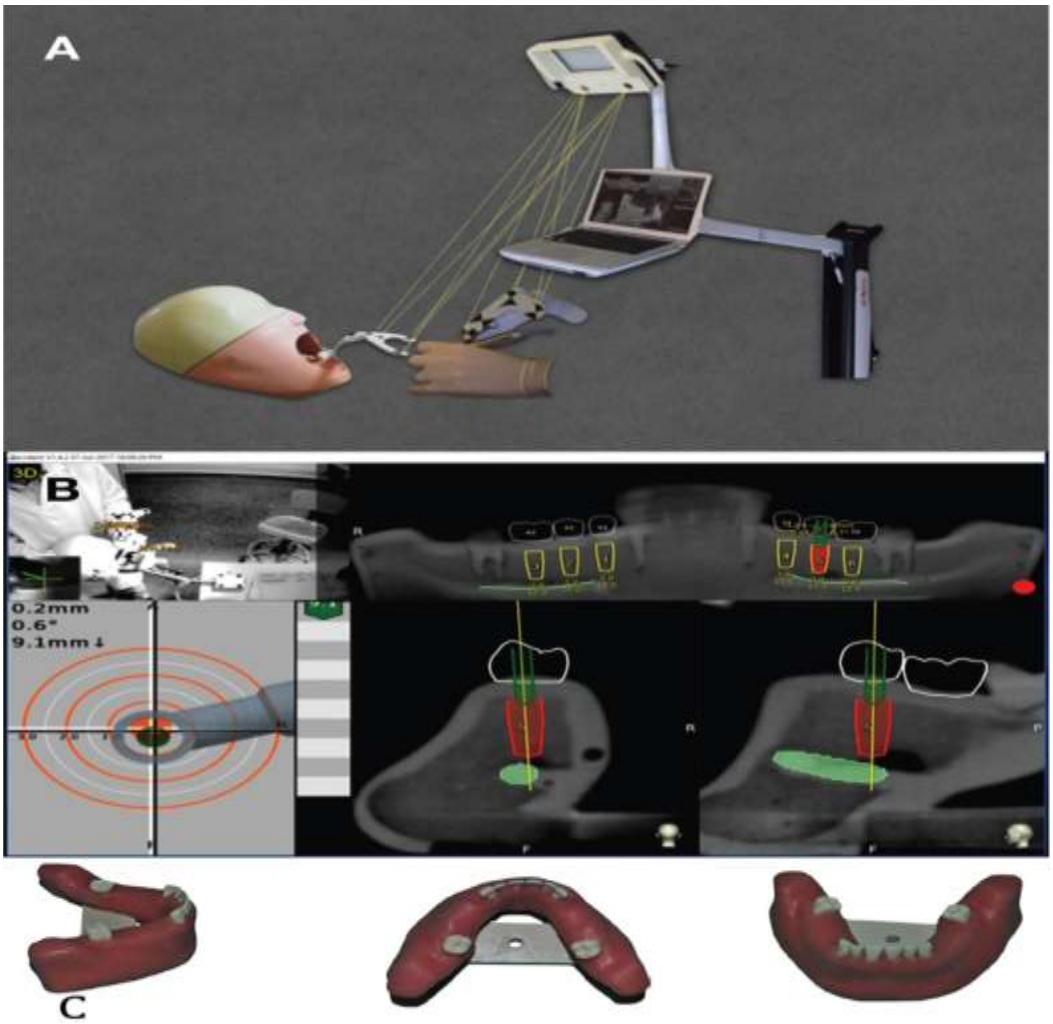
position due to its size, (V) when direct visualization is expected to be difficult, such as in patients with limited mouth opening [22,23].

An in-vitro study published in 2015 [24] tested the accuracy of the Navident® system and reported similar findings. Again, the results regarding depth deviation were disappointing (the deviation ranged from 0 to 3.3mm). The improvement observed in the present sample may be related to the software updates provided by the company and to small developments in the system in the past 3 years.



The Straumann® Guided Surgery instruments are used for guided implant bed preparation and guided placement of dental implants of the Straumann® Dental Implant System. Cutting instruments for the site and implant bed preparation can be used guided either directly through the Ø5.0mm T-Sleeve of the Surgical Template (Mucosa Punch), through a Guided Drill Handle (Milling Cutter and Drills) or in conjunction with a Guided Adapter (Profile Drills and Taps). Straumann® implants with a Loxim® Transfer piece can be placed guided with the help of a Guided Adapter, for TorcFit™ Implant a Guided Implant driver can be used.

2.4 Preoperative Planning and Simulation Systems (e.g., SimPlant, Blue Sky Bio)

A variety of digital planning systems are already available on the market, such as Keystone Dental's 3D Diagnostix [25], OnDemand3D [26] Dental Wings DWOS Implant[27], Exocad Dental CAD [28], Planmeca Romexis® Implant [29], 3Shape Implant Studio [30], Noble Clinician [31], coDiagnostiX [32], Blue Sky Plan [33], Simplant software [34], and R2Gate software [35]. All of these software options provide 3D visualisation, virtual implant placement, prosthetic-driven planning, simulation tools, and collaboration features. They are available at varying costs with excellent customer support. However, they may vary in user interfaces and integration with other implant systems. Some software options that are likely to be available in India include OnDemand3D [26], Dental Wings DWOS Implant [27], Exocad Dental CAD [28], Planmeca Romexis® Implant [29], 3Shape Implant Studio [30], Noble Clinician [31], Blue Sky Plan [33], Simplant software [34], and R2Gate system [35]

While the advantages of digital planning software are common in most software options, each software also offers unique features and strengths. Let's take a look at some examples:

• Keystone Dental's 3DDiagnostix [25]: Keystone Dental's 3D Diagnostix software stands out for its customisable user interface,user-friendly experience, and excellent customer support. It integrates with various systems, such as intraoral scanners, and offers collaboration features for enhanced teamwork.

• On Demand 3D [26]: On Demand 3D software is known for its intuitive navigation, easy integration with CAD/CAM systems, and comprehensive customer support. It provides a simplified user interface and streamlined workflow for efficient treatment planning.

• Dental wings DWOS implant [27]: Dental Wings DWOS implant software offers a user-friendly interface, seamless integration with Dental Wings CAD/CAM systems, and comprehensive implant planning capabilities. Its focus on comprehensive planning ensures accurate and efficient treatment workflows.

• Exocad DentalCAD [28]: Exocad DentalCAD software provides a customisable interface, workflow-oriented design, and seamless integration with various CAD/CAM systems. Its flexibility allows users to adapt the software to their preferences and optimise their workflow

• PlanmecaRomexis® implant [29]: PlanmecaRomexis® Implant software offers an intuitive and streamlined user experience, integration with Planmeca CAD/CAM systems, and excellent customer support. Its user-friendly interface simplifies treatment planning and collaboration.

• 3Shape implant studio [30]: 3Shape Implant Studio software is known for its modern and intuitive user interface, integration with 3Shape CAD/CAM systems,advanced implant planning capabilities. It provides a comprehensive suite of tools for precise treatment planning.

•Noble clinician [31]: Noble Clinician software offers a user-friendly interface, comprehensive implant planning features, and integration with various systems, such as intraoral scanners. Its emphasis on comprehensive treatment planning ensures accurate and efficient implant placement.

•coDiagnostiX [32]: coDiagnostiX software offers an intuitive user interface, comprehensive planning capabilities, and extensive integration with systems such as intraoral scanners and CAD/CAM systems. Its user-friendly design promotes efficient treatment planning and collaboration.

• Blue sky plan [33]: Blue Sky Plan software is known for its user-friendly and simplified interface, seamless integration with intraoral scanners, and comprehensive implant planning features. Its streamlined design ensures easy treatment planning and intuitive navigation .

• Simplant software [34]: Simplant software provides advanced features, rich simulation tools, and seamless integration with various systems. It offers precise implant placement, virtual planning, and surgical guide design capabilities. Simplant’s strength lies in its comprehensive implant planning and simulation tools, allowing clinicians to visualise the final outcome and assess anatomical structures for optimal implant placement.

•R2Gate [35]: R2Gate software offers an intuitive user interface, comprehensive implant planning features, and advanced integration capabilities. It provides tools for accurate virtual implant placement, bone density analysis, and prosthetic-driven planning. R2Gate’s unique feature is its emphasis on bone density analysis, allowing clinicians to assess bone quality and plan implant placement accordingly.

2.5 Emerging Micro-Nano Robotic Systems (Experimental phase)

The development of micromanipulation and micro–nano robots involves the intersection of many disciplines. The assembly, observation, and monitoring of micro–nano robots are inseparable from microscope science; micro–nano fluid mechanics includes Brownian motion, diffusion motion, laminar and turbulent flow, stoke flow, and capillary phenomena; in micro–nano scale, it is necessary to consider intermolecular forces, including Vander Waals force, Coulomb force, electrostatic and electrophoretic force, optical dielectrophoretic force. The production of micro–nano robots requires the assistance of materials science technologies. In the design of materials, often, hydrophilicity, contact angle, and other factors often need to be considered. The development of biomimetic surface technology has also expanded the scope of micro–nano robots.[36] The processing, manufacturing, and assembly requirements of micro–nano robots have urged related precision processing and manufacturing technologies, including photolithography, 3D printing, self-assembly, and microfluidics.

2.6 3D-Printed Surgical Guides (e.g., Straumann® guides)

Guided surgery contributes to the success of oral implants because it is based on 3D planned rehabilitation using minimally invasive procedures in the maxilla and/or mandible with surgical guides.[37]

The ideal treatment protocol for a dental implant is one that both achieves osseointegration and provides the most favorable implant position for optimal functional and esthetic prosthodontic restoration.[38]

Successful rehabilitation with implants is dependent on diagnosis and accurate planning.[39,40] Inadequate planning can produce undesirable outcomes. Incorrectly placed implants result in nonaxial distribution of forces, causing inadequate loading, and increased stress and can sometimes cause loss of osseointegration.[41,42]

Surgical guides for partially dentate patients can be manufactured in the laboratory on cast models (conventional guides). When virtual planning is used, cone-beam computed tomography (CBCT) in combination with specific software programs (ImplantViewer), can be used to create surgical guides that are designed in virtual models after scanning the patient's mouth, reliably reproducing tissues in 3D images. [43]

By planning surgical guides virtually, placement of implants can be based on the most favorable angles and ideal positions of restorations and their relationships with teeth, determined in advance.[44] This is only possible because virtual planning enables visualization of the relationships between surgical positioning of the implant to be fitted and the position of the prosthetic restoration that will be manufactured.[37]

3. Discussion: Strategies and Initiatives to Overcome Barriers in Dental robotic implantology

Current issues with dental implant robotic systems.

Need for further simplification of robotic surgical procedures.

Although robotic-assisted dental implant surgery can improve accuracy and treatment quality[45] It involves complex registrationcalibration, and verification procedures that prolong the durationof surgery. These tedious processes may introduce new errors,[46] and lower work efficiency, especially in single tooth implant placement [47]that could extend visit times and affect patient satisfaction.[47] Besides, surgeons are required to undergo additional training to familiarize themselves with the robotic system.[49]

Need for improved flexibility of dental implant robotic system. During implantation, the drill tips at the end of the robotic arms cannot be tilted, and this can increase the difficulty of using robots in posterior sections with limited occlusal space.[46,47] In addition, currently available marker systems require patients to wear additional devices to hold the marker in place. If these markers are contaminated or obstructed by blood, the visual system may not be able to detect them, limiting surgical maneuverability to some extent. During immediate implant placement or in cases of poor bone quality in the implant site, the drill tips may deviate towards the tooth sockets or areas of lower bone density, seriously affecting surgical precision. Currently, only one study has developed a corresponding force-deformation compensation strategy for robots,[48]but clinical validation is still lacking. Additionally, the dental implant robotic system, along with other dental implant robots developed for prosthetics, endodontics, and orthodontics, is currently single-functional. Multi-functional robots are required for performing various dental treatments.[50]

Difficulties in promoting the use of dental implant robotic system. Despite the enormous potential of robotic systems in the medical field, similar to the development of computer-aided design/computer-aided manufacturing technology, introducing and applying this technology faces multiple challenges in the initial stages. The high cost of robotic equipment may limit its promotion and application in certain regions or medical institutions. Surgeons require specialized technical training before operating robotic systems, which translates to additional training costs and time investment.[51]

A key advantage of robotic systems is the lack of fatigue or variability inherent in human operators. Factors like exhaustion, stress, or distractions do not affect the precision of robots like they would a human surgeon. The robotic arm can also avoid natural hand tremors that could lead to inadvertent deviations.[52,53] However, all of the robotic systems still require some level of human supervision or collaboration. Most utilized a "semi-active" approach where the robot performs drilling and implant placement but the surgeon monitors progress and can intervene if necessary.[54,55]Regarding preparation and operation times, while clinical data were limited, the in vitro studies showed reasonably quick preparation times. Surgery duration was comparable to human-performed surgeries.

4. Future Trends in Robotic Dental Implantology

Current Benefits:

Enhanced Precision: Robotic systems like YOMI, an FDA-approved dental robot, assist in accurate implant placement by providing real-time tracking and feedback, reducing manual errors and improving implant success rates.

Improved Efficiency: Robotics optimize surgical workflows, reducing procedure times and enhancing patient comfort.

Customizable Treatments: Artificial intelligence (AI) integrated with robotics enables detailed preoperative planning and adaptive responses during surgery, improving outcomes for complex cases[56,57]

Challenges:

1. High Costs: Robotic systems require significant investment, making them less accessible for smaller dental practices.

2. Complex Training: Dentists must undergo specialized training to operate these systems effectively, which can be a barrier to adoption.

3. Technical Limitations: Current systems may lack full autonomy and rely on human oversight, limiting their scalability.

4. Ethical and Regulatory Concerns: AI integration raises issues around data privacy, decision-making accountability, and legal compliance[56,58]

While robotic-assisted implantology has shown great promise, further advancements in cost-efficiency, usability, and validation of outcomes are necessary for widespread adoption in clinical practice[56,58].

1. Evaluating Current Applications: To identify how robotics is being used in dental implantology, such as for precision implant placement, reducing surgical errors, and improving workflow efficiency[56,57]

2. Assessing Benefits and Outcomes: To analyze the advantages of robotic systems, including increased precision, reduced surgery times, and improved patient satisfaction and implant longevity[56,58].

3. Identifying Challenges and Limitations: To explore the technical, financial, and practical barriers to the adoption of robotics, such as high costs, need for specialized training, and limitations in current technology[56,58].

4. Reviewing Technological Advances: To examine advancements like AI integration, real-time navigation, and autonomous systems, and their impact on dental practice and patient care[56,57]

5. Highlighting Research Gaps: To identify areas where further research is needed, such as validation of robotic systems, cost reduction strategies, and patient acceptance[58].

6. Discussing Ethical and Regulatory Issues: To address concerns related to data privacy, decision-making accountability, and the ethical use of AI-driven tools in clinical settings[56].

5. Conclusion

In conclusion, dental implant robots have limitations including cost, difficulty in accessing hard-to-reach areas (e.g. second molars), and the inability to manage complex cases (e.g. compromised sinus/nerves, esthetic zone, and insufficient bone quality and quantity) and perform advanced reconstructive procedures. These tasks still require human expertise. However, dental implant robots have demonstrated good accuracy in implant positioning. To ensure long-term safety and efficacy, further high-quality clinical studies are needed. Moreover, since existing studies are limited to laboratory settings or simple cases, no specific recommendations have been made regarding the suitability of dental implant robots for specific conditions. Conducting more studies and exploring different cases would be beneficial. Additionally, there is a need for new robots with more options and functionality compared to current dental implant robots. These new robots should have a smaller size, be able to assist dentists during auxiliary surgeries such as GBR and sinus lift procedures and incorporate AI. The integration of AI into dental implant robots has the potential to revolutionize the field by providing real-time guidance, dynamic decision-making, and autonomous surgical capabilities.

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