

The Role of Robotics in Revolutionizing Dental Practice: A Literature Review

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KEYWORDS

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ABSTRACT:

Robotics in dentistry is a rapidly advancing field that promises to revolutionize the practice by enhancing precision, reducing human error, and improving patient outcomes. The integration of robotic systems into various branches of dentistry, including oral and maxillofacial surgery, implantology, restorative dentistry, endodontics, orthodontics, oral radiology, and dental education, offers numerous benefits. This review paper explores the technical aspects of robotics in dentistry, detailing the hardware, software, and digital tools involved in robotic systems. It also highlights the diverse applications of robotics across different dental specialties, emphasizing their role in improving accuracy and efficiency. Despite the promising benefits, challenges such as high costs, integration complexities, and the need for specialized training remain barriers to widespread adoption. The paper concludes with a look at the future of robotics in dentistry, including potential innovations and the need for further research to overcome current limitations.

Introduction & History of Robotics in Dentistry:

The integration of robotics into dentistry represents a transformative shift in the way dental care is delivered.¹ Technology in dentistry has evolved rapidly, moving from basic tools and machinery to sophisticated systems that enable greater precision, control, and efficiency.² Robotics in dentistry refers to the use of robotic devices to perform or assist in dental procedures, enhancing the accuracy of treatment while minimizing human error. These robotic systems assist clinicians in performing complex procedures, improving surgical outcomes, reducing recovery time, and increasing overall patient satisfaction.³ With robotics, dentists are now able to provide more predictable and consistent results, particularly in procedures that demand high precision such as implant placement, surgery, and restorative procedures. This technological advancement has the potential to revolutionize the field of dentistry by offering more effective, less invasive, and more efficient treatments that can lead to enhanced patient outcomes⁴.

Historical Development

The history of robotics in dentistry traces its roots back to the mid-20th century when the first attempts at applying automation to dental procedures were made. Initially, the focus was on simple mechanized tools and computer-aided designs to assist in the planning of dental treatments. These early technologies laid the foundation for more complex robotic systems that would emerge in the coming decades.^{5,6}

- **Early Developments:** The first robotic devices used in dentistry were relatively simple machines designed to aid in tasks like drilling and cutting. These tools were designed to assist in specific procedures but lacked the precision and versatility that would later define modern dental robots. Early robotic systems were more focused on enhancing the workflow rather than replacing human interaction in surgery or treatment⁷.
- **Key Milestones:** One of the key milestones in the history of dental robotics was the introduction of robotic surgical systems in the 1990s. The development of systems such as Aptix (a robotic system for dental implant placement) and RoboDent marked a significant shift towards more autonomous systems.⁸ These robotic systems were equipped with advanced sensors, haptic feedback, and preoperative planning tools, allowing for greater precision during surgery. This era also saw the rise of computer-aided design (CAD) and computer-aided manufacturing (CAM) tools that facilitated the creation of custom prosthetics and surgical guides with high accuracy.⁹
- **Integration of Digital Technologies:** As the 2000s progressed, the integration of digital tools like cone beam computed tomography (CBCT), 3D imaging, and advanced software for virtual treatment planning played a crucial role in refining the capabilities of robotic systems. With the ability to accurately map the patient's oral anatomy, robotic systems could plan and execute dental procedures with remarkable precision. This marked a critical turning point in the adoption of robotics in clinical practice.¹⁰
- **Current Trends:** Today, robotic systems in dentistry have evolved to perform a variety of functions, from performing precise dental implant surgeries to assisting in restorative procedures. Systems like Yomi, a robotic system for dental implant surgery, and Robot-Assisted Orthodontics systems represent the forefront of robotic applications in dentistry. These systems not only improve the accuracy and safety of procedures but also enhance the speed of treatment, reduce recovery times, and improve patient experiences.¹¹

Technical Aspects of Robotics in Dentistry:

Mechanics of Robotic Systems

Robotic systems in dentistry are composed of a variety of components that work synergistically to perform dental procedures with precision. These systems typically include hardware and software, which together ensure accurate treatment planning and execution.¹²

- **Hardware Components:** The most fundamental aspect of robotic systems is the robotic arm or robotic surgical platform. These robotic arms are designed to hold and manipulate dental instruments during a procedure. They are equipped with precise motors, actuators, and sensors that enable them to move in a highly controlled manner. Some systems are equipped with a haptic feedback system, which allows the surgeon to feel the tactile response of tissues as the robot performs tasks, thereby ensuring that the procedure is carried out with sensitivity and care¹³.

In addition to the robotic arms, the system also incorporates surgical tools that can be customized for specific dental procedures, such as drills, scalers, or implant placement

devices. The flexibility of these robotic tools allows for fine adjustments in depth, angle, and pressure, ensuring precision during surgery.

- **Software Components:** The software in robotic dental systems includes Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) tools, which help design customized surgical guides or prostheses. Haptic feedback systems are integrated into the software to provide real-time sensory input to the dentist, simulating the touch and resistance encountered during a manual procedure. The robotic software works in tandem with digital imaging and diagnostic tools to create a detailed 3D model of the patient's anatomy, ensuring that every movement of the robotic arm is optimized for the individual patient's needs.¹⁴

Precision and Control

One of the most significant advantages of robotic systems in dentistry is their ability to improve the precision of procedures. Robotics plays a pivotal role in reducing human error and increasing the accuracy of complex dental treatments, especially in the esthetic zone where millimeter-level adjustments can make a significant difference.

- **Automation and Real-Time Imaging:** Robotic systems enable automated precision during dental procedures. This automation ensures that dental implants are placed with exceptional accuracy, reducing the risk of misalignment or improper positioning. Real-time imaging techniques, such as cone beam computed tomography (CBCT), allow the robot to update its position and orientation dynamically throughout the procedure. This integration ensures that the robotic arm adjusts accordingly to any subtle changes in the patient's anatomy, improving the overall result¹⁵.
- **Feedback Mechanisms:** Feedback mechanisms within robotic systems provide dentists with continuous data on the movement of the robotic arm and the progress of the procedure. Force sensors within the system allow for real-time monitoring of the force applied to the tissue, bone, or implant, providing corrective measures if excessive force is applied. The feedback mechanism, often integrated into the robotic system, can also trigger alerts for the operator if any part of the procedure deviates from the intended plan, further enhancing precision.¹⁶

Integration with Digital Tools

Robotic systems in dentistry work in conjunction with other advanced digital tools, which enhance their effectiveness and provide valuable support during planning and execution. The interaction between these tools is a defining feature of modern robotic surgery¹⁷.

- **3D Imaging:** High-definition 3D imaging plays a crucial role in planning dental procedures with robotic systems. 3D imaging systems, such as cone beam CT (CBCT), provide detailed, high-resolution scans of the patient's oral structures, including bone density, root canals, and soft tissue. The robotic system uses this 3D data to map the precise location for implant placement or other dental procedures. By utilizing this comprehensive digital model, the system can plan the most optimal path for surgery.¹⁸
- **Virtual Planning Software:** Before the procedure, virtual planning software is used to simulate and design the entire procedure in a virtual environment. Using data from the patient's CBCT scan and other diagnostic tools, the software enables the creation of a highly detailed surgical plan. This plan is then translated into actionable instructions for

the robotic system, ensuring that the robotic arms follow the most accurate and efficient path during surgery.¹⁹

- Integration with CAD/CAM: Once the surgery is planned, CAD/CAM technologies are used to design customized surgical guides, prostheses, or crowns. These tools allow for the creation of highly personalized dental devices that fit the patient's unique anatomy. By integrating CAD/CAM with robotics, dentists can perform highly precise surgeries and deliver custom-made prosthetics in a streamlined and efficient manner.²⁰

Applications:

I) Oral and Maxillofacial Surgery

Robotics in oral and maxillofacial surgery allows for minimally invasive procedures, crucial in complex cases such as tumor resections, reconstructive surgery, and trauma repair. Robotic systems provide enhanced dexterity, precision, and stability, which are vital when navigating sensitive areas around the face and jaw. By allowing for smaller incisions and accurate tissue manipulation, robotics reduces recovery time and lowers the risks associated with human error in complex surgical interventions.²¹ Recent developments have led to the usage of robotics in doing biopsies. Robotic biopsy provides numerous advantages over the contemporary manual method by automating some of the procedure which can result in higher accuracy due to the accuracy of implanting the needle into the site.²²

II) Implantology

Robotic systems in implantology offer unparalleled accuracy in implant placement, particularly in positioning, angulation, and depth control. These systems minimize the risk of damage to surrounding structures, such as nerves or sinuses, by using guided implant surgery that aligns with pre-surgical plans. Robotics significantly contributes to outcomes in the esthetic zone, where small inaccuracies can compromise both function and appearance. This precision in implant placement improves both immediate and long-term outcomes, reducing the likelihood of complications.²³ It can also help clinicians perform precise osteotomies, improving the accuracy of dental implant placement by providing the surgeon with real-time feedback mechanisms by integrating advanced imaging technology, thereby increasing the success of dental implant therapies worldwide.²⁴

III) Restorative Dentistry

In restorative dentistry, robotic technology enhances precision in crafting dental restorations, including crowns, bridges, and veneers. Robotics helps automate milling processes for restorations, yielding a better fit and durability. The integration of robotic systems can streamline workflows, reduce procedural time, and ensure high-quality restoration, all of which contribute to increased patient satisfaction and reduced error rates.²⁵ A major transformation is combining robotic systems with cutting-edge laser technologies like picosecond lasers. These systems enable automatic, highly precise full-crown preparations, achieving cutting depths of approximately 60 μm on resin teeth and 45 μm on natural teeth. These preparations can be done in under 20 minutes.²⁶ The development of mechatronic systems' robotic arms work hand in hand with the dentist solving problems like fatigue and unsteady movements that can impact the quality of dental work. These robotic arms provide real-time adjustments and support during procedures, improving tool stability and precision during tasks such as cavity preparation.²⁷ The combination of speed, accuracy, and safety offered by these robotic innovations is setting a new benchmark for restorative dentistry.

IV) Endodontics

Robots offer precision in navigating the intricate anatomy of root systems, which is often challenging due to complex canals and curvature. By enhancing accuracy in cleaning, shaping, and filling, robotic systems increase the success rate of endodontic treatments and reduce the risks of instrument fractures or procedural failure.²⁸ One noteworthy development is the endomicro robot, a system that incorporates advanced features such as computer graphics, tooth modeling for pre-procedure planning, micro-positioning capabilities, ultrasonic cleaning tools, and flexible drills. This robotic system minimizes human intervention while ensuring precise apical preparation and effective cleaning—critical factors for successful root canal treatments.²⁹ An automated tool management system is another innovation that works like a tool vending machine, streamlining tool selection, conserving workspace, and making the procedures more efficient by minimizing the time taken for treatment. AI-driven deep learning models are also proving highly effective in identifying vertical root fractures (VRFs) and periapical lesions.³⁰

V) Orthodontics

Robotic technology in orthodontics allows for precise placement of brackets, archwire bending, and even the creation of customized aligners. Robots ensure that the treatment plan is executed accurately, which can reduce treatment time and improve overall outcomes. The first wire bending robot Sure Smile robot was developed by Butscher et al. in 2004.³¹ Icoognito, LAMDA, Isignia, and BRIUS have also been created to optimize the field of orthodontics with the help of CAD/CAM technology to create customized wires for patients. The LAMDA system is another technology developed for the rapid and precise bending of archwires, utilizing a robotic apparatus capable of bending the archwire in two planes.³² Nanorobotics allow painless tooth movements and rapid tissue repair ultimately leading to an accelerated tooth movement.³³ Robotics is also being used in aligner manufacturing which can improve efficiency, enabling timely delivery of treatment adjustments and ensuring patient comfort.³⁴

VI) Oral Radiology

In oral radiology, robotics improves diagnostic accuracy by integrating with imaging systems such as CBCT and digital radiography. Robotic systems can assist in positioning patients for optimal imaging angles and analyzing complex radiographs or scans, thereby enhancing diagnostic accuracy. Robotics also enables clearer interpretation of detailed anatomy, which supports more effective treatment planning.³⁵

VII) Dental Education

Robotics is transforming dental education by providing simulation-based training for students. Robotic systems can simulate surgical procedures, providing real-time feedback on technique and positioning, which enhances hands-on learning experiences.³⁶ Robotics in education ensures that students can practice complex procedures in a controlled environment, helping them build confidence and competence before engaging in real patient care.³⁷ PediaRoid — a pediatric simulation robot — was released in Japan to teach dental students how to handle a jittery or emotional first-time patient which can accurately replicate child behavior and common conditions. Another geriatric patient oral care manikin MANABOT has an elderly patient like oral cavity with multiple conditions including a partial denture, gingival recession, and missing teeth. These approaches ensure a high level of precision and a highest quality of instruction leading to best outcomes.

Challenges and Limitations

Robotics in dentistry brings notable advancements, yet it faces several challenges that limit its widespread adoption and integration. One of the primary barriers is the high cost of robotic systems. The initial investment required to acquire and maintain these advanced technologies is significant, which makes it difficult for smaller practices to adopt them.⁷ This cost barrier restricts accessibility, often confining robotic technology to larger or specialized dental centers and limiting the potential reach and benefit to a wider patient population.

In addition to costs, the integration of robotic systems into existing dental workflows presents another hurdle. Robotic technology often requires modifications to the standard workflow, which can disrupt established practices. Compatibility with existing tools and systems may be limited, and the adaptation process can be complex and time-consuming, which deters some practices from making the switch.³⁸

Another challenge is the need for specialized training to effectively operate robotic systems. Dentists and their teams must develop new technical skills to handle these sophisticated devices, which often involves a steep learning curve and significant time investment.³⁹ Currently, there is a limited number of practitioners proficient in robotic technology, which restricts its broader implementation and full utilization.

Finally, technological limitations persist within robotic systems in dentistry. Although they have advanced greatly, these systems still face issues with precision, autonomy, and adaptability.⁷ Certain dental conditions or patient needs may pose challenges for robotic systems that lack the flexibility of human operators, and autonomous capabilities remain limited. As a result, robotics in dentistry must continue to evolve to address these limitations and more closely meet the needs of diverse clinical scenarios and patient conditions.

Addressing these challenges will be crucial to maximizing the potential of robotics in dental care, paving the way for broader accessibility and optimal integration within the profession.

1. Conclusion

Robotics is profoundly impacting the field of dentistry, transforming how dental care is provided across various specialties. Through precision and enhanced control, robotic systems are advancing the quality of procedures in implantology, oral and maxillofacial surgery, restorative dentistry, and more. By offering greater accuracy and consistency, these technologies are not only improving treatment outcomes but also contributing to higher levels of patient satisfaction. Robotics is also playing a pivotal role in dental education, providing a controlled and responsive environment for training new practitioners.

Looking to the future, the trend in dental robotics points toward the development of more autonomous and adaptable systems that can further streamline complex procedures with minimal manual intervention. Innovations in artificial intelligence and machine learning hold promise for refining robotic capabilities, enabling systems to make data-driven decisions in real time and adapt to unique patient conditions. As robotic systems continue to evolve, the potential for improved patient outcomes will grow, with fewer complications, quicker recovery times, and heightened esthetic results.⁴⁰

However, for robotics to reach its full potential in dentistry, ongoing research and development are essential. Addressing current challenges, such as cost barriers, integration complexity, and the need for advanced training, will require innovative solutions to make robotics more accessible and user-friendly. Future advancements could lead to more affordable and efficient robotic systems, which would make high-tech dental care available to

a broader patient base. With sustained progress, robotics is likely to become a cornerstone of modern dentistry, reshaping patient care and clinical outcomes for years to come.

Annexure 1- table summarizing the applications of robotics in various dental specialties:

Specialty	Application of Robotics	Key Benefits
Oral and Maxillofacial Surgery	- Assists in minimally invasive surgeries for tumor removal, reconstructive surgery, and trauma care.	- Enhanced precision, reduced human error, improved patient safety and recovery.
Implantology	- Facilitates precise implant placement with accurate angulation and positioning.	- Minimizes error, improves implant stability, and enhances esthetic outcomes in critical zones.
Restorative Dentistry	- Utilized in creating crowns, bridges, and veneers with high precision.	- Improved fit and longevity of restorations, faster treatment times.
Endodontics	- Enhances access to complex root systems, especially for root canal therapy.	- Increased accuracy in cleaning and shaping, reduced risk of procedural errors.
Orthodontics	- Aids in bracket placement, archwire adjustments, and automated aligner creation.	- More accurate treatments, shorter treatment duration, and increased patient comfort.
Oral Radiology	- Integrates with imaging tools like CBCT for detailed imaging and pathology detection.	- Improved diagnostic accuracy and visualization of complex anatomical structures.
Dental Education	- Provides simulation and real-time feedback for dental students learning surgical techniques.	- Enhanced hands-on training, better skill development, and safer learning environment.

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