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Dental Robotics - The Future of Dentistry - A Narrative Review

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Abstract

Robots were introduced during the Industrial Revolution as supportive tools to assist human labour. In the dental field, the application of robotics began as early as 1967, when Jenkins first introduced their use. The integration of robotics in dentistry is steadily advancing, supported by essential technologies that are both adaptable and capable of further development. Dental robots offer exceptional precision in performing procedures, significantly reducing the margin for error—especially in complex treatments such as dental implant placement and root canal therapy. By automating various aspects of dental care, robotics helps minimize human error, leading to more consistent and predictable outcomes, fewer complications, and a reduced need for corrective procedures. Meanwhile, artificial intelligence (AI) supports accurate diagnosis, effective treatment planning, and better prediction of patient outcomes. There are several obstacles to this technology like technological advancements in medical/dental applications are extremely expensive, less patient acceptance and compliance among dentists, the motivation to receive such treatment is reduced with the increase in technique invasiveness. Another reason robotics is still considered a field of low interest in dentistry may be the lack of expert knowledge to program and control those systems as a non-professional. However, challenges like high costs, complex operability, limited sensory perception, and inadequate manipulation capabilities still hinder widespread adoption of robotics in dentistry.

Keywords: Artificial Intelligence, Artificial Neural Networks, Prediction, Robots.

Introduction

Robots were introduced during the Industrial Revolution as supportive tools to assist human labour. In the dental field, the application of robotics began as early as 1967, when Jenkins first introduced their use[1]. Today, smart

robots can function as dental assistants, performing tasks such as cleaning dental instruments, assisting with patient appointments, delivering pre-procedure dental education, and providing post-operative instructions. These functions are enabled through the integration of artificial intelligence, which allows robots to carry out these roles efficiently. This marks an important stepping stone in the evolving synergy between robotics and artificial intelligence, with promising potential for future advancements in dental care.

The integration of robotics in dentistry is steadily advancing, supported by essential technologies that are both adaptable and capable of further development. Several of these technologies are already in use, including image-based simulations for implant surgeries, surgical guides, digital impressions captured with intraoral scanners, and the fabrication of restorations using milling devices. Compared to medicine, the use of robotics in dentistry remains relatively limited. Currently, dentistry primarily utilizes semi-automated robotic systems that are operated manually through computer-based control interfaces. These manual robots offer enhanced safety and precision in procedures such as drilling, surpassing the accuracy of traditional methods. While significant progress is being made toward the development of autonomous robotic systems, especially in implant dentistry, most of these advanced technologies are still in the experimental stage and not yet accessible for routine clinical use.

Artificial intelligence in the contemporary of robotic technology, with the scientific formations of autonomous task planning containing methods from classical artificial intelligence such as tree-search algorithms and symbolic task planning that are used to autonomously plan a sequence of actions to achieve a desired goal. Most of these methods are taken from works that are unrelated to robotics yet very much applicable. Artificial neural networks (ANNs) are inspired by the human neural system or biological nervous system, which are highly interconnected networks of computer processor systems. Strong AI means a system that works in the same way as human intelligence through unnatural, software construction, and artificial hardware. It is a theoretical form of ma chine intelligence[2].

History

In the mid-1980s, NASA developed a remotely controlled robotic system designed to perform surgical procedures on soldiers in battlefield conditions and astronauts in space. A significant milestone was achieved in 2000 when the U.S. Food and Drug Administration (FDA) approved the first robotic system for laparoscopic surgery, enabling procedures to be performed in a doctor-robot setup. In 2001, the feasibility of this concept was demonstrated through a transcontinental live robotic cholecystectomy. Robot-assisted surgery has also prompted progress in minimally invasive surgery by providing equipment with high accuracy and freedom of movement, elimination of the negative effect of instrumental and hand tremors, and real-time stereoscopic vision of the surgical area[3]. More recently, the medical robotics industry has shifted toward autonomous robotic technologies—systems capable of performing procedures independently, without continuous human control or monitoring.

Emergence of Robotics in Dentistry

Dental training robot

Nowadays, robots are being used for dental therapy training. The so-called “phantoms” consisting of a simple functional cephalic region and an arrangement of teeth are used for clinical training of students[4].

Realistic human-like robots

Showa Hanako is a realistic robot which is designed to simulate a number of typical patient responses allowing dental students to experience what its like to work with a real patient. Other robotic inventions such as the Geminoid can be remotely controlled being equipped with advanced motion-capture technology. Another robot in the Geminoid family, the Geminoid-F is capable of mimicking human facial expressions and even laughing[5].

Simroid

An ideal addition for dental training is SIMROID which represents the next generation training model. It is a super-realistic dental training robot which is actually an upgrade version of Simuloid, a less sophisticated dental training robot which is created back in 2007. It is also capable of rate and evaluate the treatment with help of sensor being recorded throughout the procedure[5].

Figure 1:

Application of Robotics in Dentistry

The use of robotics in dentistry is steadily advancing, driven by the development of technologies aimed at enhancing diagnostic accuracy and improving treatment outcomes. Robotics contributes to greater surgical precision, streamlined procedures, and improved accessibility in dental care. Meanwhile, artificial intelligence (AI) supports accurate diagnosis, effective treatment planning, and better prediction of patient outcomes. Together, robotics and AI hold the potential to revolutionize clinical dental practices, and as these technologies continue to evolve, they are poised to reshape the future of dentistry.

1. Dental Implantology

The formation of computer-assisted dental implantology established on a combination of prosthodontics and dental implantology. The idea of CT-scan analysis and prosthetic-driven implant dentistry has been emerging. In 2002, Boesecke et al. presented the first robot-guided placement of dental implants. The robot system, having a working region of 70 cm, executed the implant drilling guide that help the surgeon during implant osteotomy, where 48 dental implants were placed within 1–2 mm of the apical border[6]. In 2012, an autonomous robotic system that has 6 degrees of freedom (DOF) used a volume-decomposition-based system to place a root-shaped dental implant[7]. And in 2017, Zhao introduced the world's first autonomous implant placement system. In this surgical procedures were executable without any intervention by a dentist and surgical tasks can be modified automatically with a high degree of autonomy[8]. Robotic implantology has also been used successfully in complicated implant cases with significantly decreased alveolar bone, to reduce errors in implant positioning, in reduced mouth opening. Robot-assisted implant surgery allows for increased flexibility, stability, precision and accuracy of implant placement.

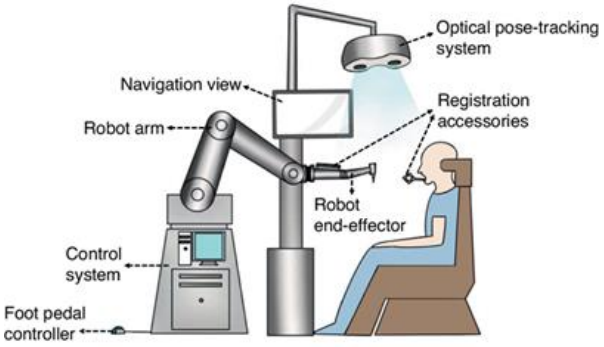

Figure 2:

2. Oral & Maxillofacial Surgery

A surgical robot system for maxillofacial surgery has been developed with which the surgeon interactively programs the robot during the surgery, after that the robot performs the preprogrammed surgery or any tasks given by surgeon. Robotic technique is used for milling of bone surfaces, drilling of holes, deep saw osteotomy cuts, selection of osteosynthesis plates, bending and intraoperative positioning in defined position, and orthognathic surgery planning[4]. Robot-assisted surgery can also provide excellent local control in the treatment of low-risk oral squamous cell carcinoma. Some studies reported that robot-assisted surgery resulted in decreased morbidity and is well-tolerated by patients. Transoral robotic surgery, having a stereoscopic vision, multi-articulated instruments, and robotic arms, permits intervention of the oropharynx with minimal invasiveness. It also helps to increase the safety and precision in oral and maxillofacial surgery by decreasing human-associated factors including decreased vision, distraction, trembling, or decreased concentration.

3. Prosthetic & Restorative Dentistry

Robots in prosthetic dentistry could help in manufacturing partial or complete dentures. The skilled dental technician and experienced dentist are incorporated into the software of prosthetic dentistry expert model. A single-manipulator robotic system for tooth arrangement of complete dentures is consist of the following parts: (a) light-sensitive glue; (b) light source device; (c) denture base; (d) control and motion planning; (e) robot modulation software for arranging tooth and a core control system having tooth-arrangement; (f) computer; (g) electromagnetic gripper; and (h) 6-DOF CRS robot. The virtual 3D tooth-arrangement software carried out the following functions like: (a) create or select file related to the medical history of the patient, formulate dental arch curves and a jaw arch as per the patient's jaw arch measures; (b) view 3D virtual teeth on the screen and modify the position of each tooth[9]. A tooth preparation robotic system was presented by Yuan and colleagues, which consisted of the following hardware parts: (a) a tooth fixture that connects the target tooth with the robotic tool and safeguards the adjoining tooth from laser-cutting; (b) a 6-DOF robotic arm; (c) an efficient low-heat laser appropriate for the preparation of hard tissue; (d) a CAD/CAM software to generate a 3D motion path of the laser and to design the target shape for tooth preparation; and (e) an intraoral 3D scanning machine for obtaining the 3D information of the subject's teeth fixture, opposing teeth, adjoining teeth, and the target tooth[10].

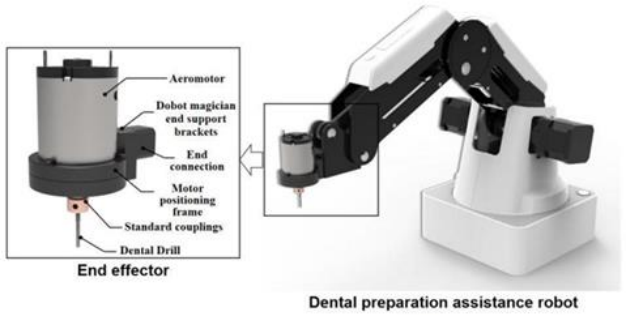

Figure 3:

4. Orthodontics

Sure Smile OAW bending robot consists of a robot installed onto to base support surface. Robot system for bending the OAW is based on MOTOMAN UP6 and consists of the arch-wire bending actuator, computer, and MOTOMAN UP6. The actuator is connected to the periphery of the MOTOMAN robot. The clamping and bending of the arch-wire are performed by the arch-wire bending actuator, which is attached to the MOTOMAN robot end. The bending characteristics of the arch-wire, the kinematics of the robot, angle optimization, and the bending position of the arch-wire are examined and simulated[11,12].

5. Endodontics

A micro endodontic robot can provide safe, accurate, and reliable root canal treatment for patients by preventing problems identified with conventional techniques, such as inadequate mouth opening and excessive tooth removal. With online monitoring and intelligent management, this robot will perform the automatic probing, drilling, cleaning, and filling of root canal. The specific objectives for the microrobot design include: a. Decrease the reliance on the skills of the dentist b. Reducing human error c. Increasing precision of diagnosis and treatment.

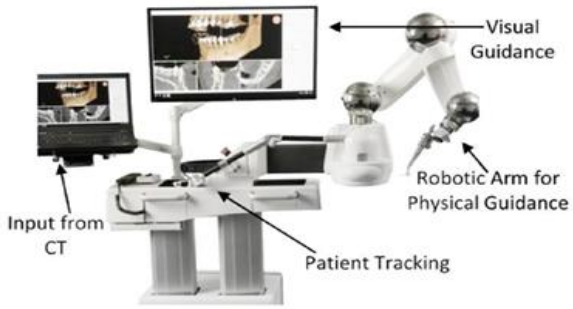

Figure 4:

6. Oral Radiology

There are several benefits of employing robots in radiology a. decrease the radiation exposure b. help in in teeth with complex morphology and anatomy, the radiographic tools would be safer, simpler, and easier c. reduce repeatability of x-ray shooting and increase accuracy. The positioning of the X-ray source and sensor/film was suggested to be performed by a 6-DOF robot arm and no side effect was reported[6].

7. Dental Education

ROBOTUTOR is a dental education robotic system. This robot was an alternative system to a dentist for showing tooth-cleaning procedures (i.e., tooth brushing) to patients. According to a study, it was reported that the ROBOTUTOR is the most attractive technique for dental education than other techniques (i.e., audio-video tutorial or dentist). However, the ROBOTUTOR was found to be less efficient as compared to the dentist[13]. Also some studies concluded that, virtual reality training combined with human instructor verbal feedback and haptic feedback could be the most effective way of learning the fundamental motor skills for dental students and help increase efficiency of the dental students[13].

8. Dental Assistance and Dental Materials

It helps to analyze the radiograph, CBCT and compare the bone volumes to match the bone pre-and post-augmentation procedure. There is a growing likelihood of active robotic assistance in dental procedures, where instrument exchange is facilitated through a multi-nodal communication model tailored for clinicians. This model incorporates visual gestures, speech input, touch screen interaction, and bilateral physical communication between the robot and the dental professional.

Nanorobotics

During the first decade of the twentieth century, Zsigmondy made a first detailed observation and size measurement of nanoparticles[14]. Nanorobotics is a rapidly developing in the late 1990 s. The word "Nano robot" was coined by the robotics community in late 90 s. Prof Erick Drexler created the term nanotechnology. Eric k. Drexler and Robert A. Freitas are two leading innovators in nanorobotics[15]. Nano robots are made up of a variety of components, like carbon, hydrogen, sulphur, oxygen, Nitrogen, silicon, fluorine and Carbon (C) in the form of diamond is the most prominent element on the Nano robots' outer surface[16].

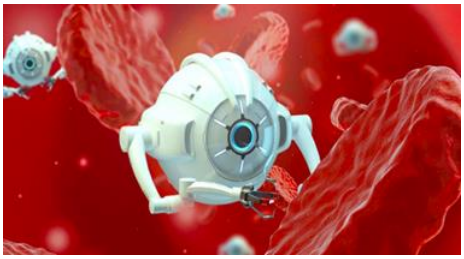

Figure 5:

Applications of nanodentistry

1. Nanocomposites: Nanotechnology allows the fabrication of Nano nanodimensional filler particles that are introduced to composite resin either alone or in nanoclusters. After polishing, nanoparticles generate a composite with a smooth surface and excellent aesthetic quality. The nanoparticles not only improved the remineralizing characteristics of the composites, but they also kept the same amount of Ca and P release[17]. They have better strength, abrasion resistance and prevent secondary caries.
2. Nano diagnosis: At the molecular and cellular levels, Nano diagnostic instruments can be utilised to detect disease early. Nano devices could be placed inside the body to confirm the appearance of disease early or to detect harmful substances, cancer cells, and other things in- vivo[18]. Digital imaging has expanded largely due to nanotechnology. It also help in early diagnosis and treatment of oral cancer.
3. Nano robotic dentifrice (dentifrobots): It is very interesting to use dentifrobots in the field of dentistry. Using toothpaste, a sub occlusal-dwelling Nano robotic dentifrice could scan all supra gingival and subgingival surfaces and converts trapped organic materials into odourless and non-toxic fumes[14]. It also help to debrides calculus on a continuous basis.
4. Nano anaesthesia: Currently, in nano dental world, a colloidal solution comprising millions of active analgesic micron-size dental robots are injected into the gingiva of the patient. When Nano robots come into contact with the tooth or mucosa, they can enter the pulp via the gingival sulcus, lamina propria, or dentinal tubules. This will anaesthetized the targeted tooth as soon as the dentist clicks the key on the remote and restore all sensation and re-establish nerve traffic control after the procedure is completed[19]. This will reduce pain and discomfort of patient.
5. Nano impression materials: Impression materials can be modified using nanomaterials. Nano fillers are mixed into vinyl poly siloxanes to different kind siloxane impression materials. The main advantage of this material is that it has improved flow and hydrophilic properties which result in fewer defects at the margins, good model pouring, and even more accurate placement[15].
6. Orthodontic treatment: In Orthodontic Nano robots can handle periodontal tissues such as gums, periodontal ligament, cementum, and alveolar bone directly which allow rapid and painless straightening, rotating, or vertical position changes between minutes and hours during orthodontic therapy.

Advantages of Using Robotics in Dentistry

Dental robots offer exceptional precision in performing procedures, significantly reducing the margin for error—especially in complex treatments such as dental implant placement and root canal therapy. By automating various aspects of dental care, robotics helps minimize human error, leading to more consistent and predictable outcomes, fewer complications, and a reduced need for corrective procedures. Moreover, robotic systems can lower the risk of cross-contamination in dental settings by limiting instrument handling and exchanges during procedures. Integrated with advanced imaging technologies, these systems provide high-resolution 3D visuals and real-time data, enhancing diagnostic accuracy and treatment planning. Additionally, robotic platforms can collect and analyze intraoperative data, delivering real-time feedback to assist dentists in decision-making and post-procedure evaluation. Some

systems are also equipped with AI and machine learning capabilities, allowing for personalized treatment plans tailored to each patient's unique dental anatomy and clinical needs[20,21].

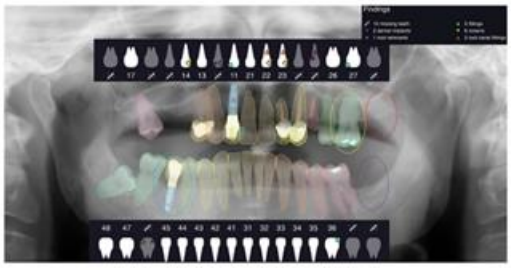

Figure 6:

Safety Considerations in Robotics

AI-driven robots working alongside humans (cobots) pose a risk of accidental contact, which can cause injuries. Unpredictable behaviour means that AI-based robots, especially those using reinforcement learning, may develop unexpected actions that are hard to anticipate. A robotic system's failure in industrial or medical settings could lead to life-threatening situations. Robots connected to networks and cloud services are vulnerable to cyberattacks like hacking, leading to data breaches or operational disruptions. Manipulated training data can cause robots to behave incorrectly or fail critical tasks. The integration of AI robots in industries can lead to performance pressure, fear of job loss, and long-term mental health concerns. There is also a lack of universal standardization and AI models continuously evolve, making traditional certification and safety validation methods inadequate. There is legal liability gaps that is current laws do not clearly define responsibility in the event of an AI-related accident or failure[22].

Figure 7:

Limitation of Robotics Dentistry

There are several obstacles to this technology like technological advancements in medical/dental applications are extremely expensive, less patient acceptance and compliance among dentists, the motivation to receive such treatment is reduced with the increase in technique invasiveness. Furthermore, robotic systems are complex and require expertise for their proper operation and function. And it is challenging to maintain this system. In case of nanodentistry, several nanomaterials can cause serious medical or dental problems. It can be the occupational hazard for the people that work for companies making nanoparticle-containing materials who are most vulnerable[15]. Accessibility and Equity may also a problem as remote and underserved communities may have limited access to the necessary infrastructure and technology[20]. The automation of specific dental tasks through robotics and AI has sparked concerns about potential job displacement among dental professionals, including dental assistants. Additionally, the integration of AI and remote systems in dental care involves the collection and storage of sensitive patient data, raising significant concerns regarding data privacy, security, and the risk of data breaches[23].

Conclusion

Dentistry is making its way towards a new world of robot-assisted and data-driven medicine. Robotics are used in dentistry to enhance human activity and

overcoming the shortcomings of manual labour and enabling more accurate and refined movements than are possible with a human hand. AI based robots can certainly be tool in making significant progress in delivering better healthcare to the patient, but in no way can replace human knowledge, skills, and power of judgment. Dentists must work alongside robotics, not only as operators but as decision-makers who ensure precision, patient safety, and ethical considerations in dental care. Robotic systems have not still been entirely introduced to dental research nor have they achieved cost-effectiveness and technological readiness so that it can be fully incorporated into the dental market. Another reason robotics is still considered a field of low interest in dentistry may be the lack of expert knowledge to program and control those systems as a non-professional. However, challenges like high costs, complex operability, limited sensory perception, and inadequate manipulation capabilities still hinder widespread adoption of robotics in dentistry.

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