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Review Article

The digital dentist: robotics in dental practice

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ABSTRACT

The integration of robotics into dentistry marks a significant technological advancement, leading to transformation in traditional dental practices. This review explores the varied applications of robotics in dentistry, including surgical procedures, implantology, orthodontics, prosthodontics, and endodontics, highlighting their ability to improve accuracy, reduce human error, and streamline workflow. Robotic systems, such as surgical assistants, CAD/CAM-enabled devices, and AI-powered diagnostic tools, are revolutionizing patient care by providing minimally invasive options and superior treatment outcomes. However, these innovations are not without challenges. High initial costs, a steep learning curve, and concerns about the loss of human touch in dental care hinder widespread adoption. Patient skepticism and fear, coupled with ethical considerations about replacing traditional methods with automated systems, also pose barriers. Additionally, technical limitations, such as extended preparation times and the need for robust maintenance, underscore the complexity of integrating robotics into clinical practice. The current trend emphasizes the growing collaboration between robotics, artificial intelligence, and digital dentistry, aiming to create more accessible and reliable solutions. With advancements in autonomous systems and AI, robotics holds the potential to bridge gaps in accessibility, provide care in remote areas, and redefine the scope of dental practice. This review highlights the need for further research, interdisciplinary collaboration, and public education to address existing limitations and foster acceptance of robotics in dentistry, ultimately paving the way for a future of more precise and patient-centered dental care.

Keywords: AI in dentistry, Digital dentistry, Robots, Robotics, Robot-assisted implantology

INTRODUCTION

With the rapid technological advancement, robotics has become an indispensable part of our daily life. The term "Robotics" was first used by Isaac Asimov in his science fiction novel I, Robot published in 1950. The Robot Institute of America defines a robot as "a reprogrammable, multifunctional manipulator designed to move materials, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks".[1]

Robotics has advanced significantly since the 1960s, beginning with the introduction of the first industrial robot. The cross-integration of medicinal drugs, engineering, science, and other battlefields have become a driving force for the advancement of clinical medicine, thereby providing new opportunities for the development of dental aesthetics as well. Robots now play diverse roles in healthcare, including surgical robots, rehabilitation robots, and service robots, demonstrating their growing impact on the medical field. Robotic-assisted surgery has now been a groundbreaking innovation in medicine, offering greater precision, efficiency, minimally invasive procedures, and enhanced safety compared to traditional methods.[2]

Robots have helped us to design and perform various oral surgical procedures such as precise implant placement, as well as the tasks such as tooth restoration that requires great dexterity and accuracy. Dental professionals may experience physical and mental exhaustion after hours of demanding procedures in ergonomically challenging positions, potentially leading to mistakes in the oral examination, disease diagnosis, and treatment planning.[3] Also, in dentistry, the small oral opening, awkward seating positions, repetitive tasks, alongside patient pain, fear, and discomfort, allow many opportunities for robotics to benefit both patients and dentists.[4] These technologies have not only revolutionized dental healthcare system but also helped in enhancing the diagnostic accuracy, treatment outcomes, and workflow efficiency.[5] Additionally, the use of robot in dental clinic, as a dental assistant, may constitute one of the important role for robotic dental medicine.[3]

This review aims to identify the present status and development of robotic applications in dentistry and provide insights into future implementation and advancement, limitations, and strategies for enhanced clinical adoption and technical advancement.

ROBOTICS IN DENTISTRY

Surgery

Robotics is a great revolution in the field of surgery. Currently, robotic surgery is mainly used in the head and neck region in head and neck neoplasms or cysts that can be sufficiently exposed via a robotic approach, therapeutic and selective neck dissection, and obstructive sleep apnea syndrome (OSAS).[6]

A landmark of robot-assisted maxillofacial surgery was set in Germany in 1998, when Burghart et al introduced a complex expert system including a planner for generating treatment plans, infrared navigation for monitoring patients, robots and surgical tools, and a surgical robotic system that works on bones.[7] In 2009, the US-FDA approved the Da Vinci system for transoral surgeries of selected malignant and non-malignant lesions of the oropharynx, even when located at the base of the larynx and the tongue.[8] Gui et al developed a robotic system for Le Fort I osteotomies.[9] Zhang et al developed a robotic system for mandibular reconstruction with fibula grafts to help the surgeon hold and locate the free bone.[10]

Robotic procedure has shown many advantages: reduced fatigue, stable and accurate position with decreased tremor, procedure automation, less experience for efficiency, decreased variations in technical skills among physicians, and increased chance of performing the procedure at remote hospitals.[11]

Prosthodontics

Application of robots in prosthodontics can be summarized as per the procedures in which they are used. Tooth preparation is the mechanical alteration of a defective, injured, or diseased tooth. Tooth preparation when performed by using high-speed dental handpieces, risk of damaging the soft tissues in the narrow space of the oral cavity and difficulty in achieving accurate tooth preparation standards simultaneously takes place.[12] In China, an automatic robotic system for 3D tooth crown preparation has been developed by using a picosecond laser and researched its appropriate parameters. This system, the LaserBot, is composed of many components like a miniature robotic end-effector, tooth fixture, laser generator, laser transmission arm, laser scanner (3Shape D700, Denmark), and computer console.[13] *Otani et al* evaluated the accuracy and precision of an automated robotic tooth preparation system for porcelain laminate veneers. [14] In this system, tooth models were scanned by a 3D laser scanner, and the tooth preparation was designed on a 3D image, improving safety and efficiency.[12-14] Even though, the robotic system was able to generate satisfactory tooth preparation, further researches are required to determine the ablation efficiencies for different layers of teeth like dentin, enamel, and other dental materials.[15]

Similarly, the most important step in complete denture is to arrange the artificial teeth in the appropriate position and direction. With the development of computer-aided design/computer-aided manufacturing (CAD/CAM) technology, virtual artificial tooth-arrangement systems have been evolving. In recent years, using 3D digital technology, it has been possible to achieve more complex jaw position recording and proper tooth arrangement. The whole dentition, local dentition, and single tooth can be moved freely in the horizontal, sagittal, and coronal planes by using the software.[12] The first robotic system using Visual C++ and RAPL robot languages was developed in 2001 and was based on the CRS-450 6-DOF robot, produced by CRS Robotics Corporation in Canada.[15] This virtual 3D tooth-arrangement software carries out the following functions: create or select file of the medical history of the patient, formulate dental arch curves and a jaw arch by the experience of an expert as per the patient's jaw arch measurements; and view 3D virtual teeth on the screen and modify the position of each tooth.[3] In 2011, a multi-manipulator tooth-arrangement robot was developed for complete dentures.[15]

After arrangement of teeth in the CAD software, the occlusal relationship is adjusted by simulating jaw opening and closing movements and forward/backward and lateral movements using the virtual articulator. Along with virtual articulators, Robotic articulators are also being studied. A new type of robotic articulator uses a precise six-axis micro positioning stage to replicate the patient's functional mandibular movement with six DOF. A full veneer crown restoration is fabricated without the need for intraoral occlusal adjustments to the setup by this articulator system. Since the articulator accurately reproduced dynamic jaw movements during functional jaw movements, the system has the potential to improve the accuracy of denture occlusion. But, only one patient has been examined, therefore, further research is needed to evaluate this technique.[12]

Oral implantology

Recently, robot-assisted dental surgery has gained remarkable attention in dental implant therapy as an alternative to conventional free-hand surgery operation. It overcomes some of the challenges that human operators face, such as poor visibility and operator fatigue, and provides rich experience which may lead to low errors.[16] Robot navigation is a clinically reliable method of implant placement. Coronal, apical, and angular deviations of robot-assisted implant surgery were significantly lower compared to computer-assisted implant surgery in human phantoms.[17] The dental implant robot gives further improvement in precision, efficiency, and stability, promoting the accuracy of the implant and reducing surgical risks.[2]

In 2017, YOMI^{TM}, [Neocis, Miami, FL, USA] was the world's first FDA-approved computerized navigation robotic system to enhance the clinical accuracy of dental implant surgery. YOMI provided physical guidance of the depth, orientation, and position of the drill, therefore avoiding the custom fabrication of surgical guide and hand deviation of the operator. The navigation system allows high predictability and precision in preparing dental implant osteotomy by employing vibrational feedback. However, the YOMI system is relatively expensive and operates under supervision.[18] At the same time, Zhao introduced the world's first autonomous implant placement system. Surgical procedures were executable without any intervention by a dentist, and surgical tasks can be modified automatically with a high degree of autonomy.[19] Robotic application in implantology includes robot-assisted and fully autonomous implant robots. Robot-guided implantology enhances accuracy and aesthetics in procedures via digital guidance.[20] On the other hand, a fully autonomous implant robot works on its own accord under the supervision of a dentist.[21]

Technological advances show that robots will soon be cost-effective for widespread use in dental implantology, but many more cadaveric trials are needed before practical application.

Endodontics

AI in endodontic treatment planning and prediction of treatment outcomes

AI has been applied to assess root canal morphology and number of canals. Hiraiwa et al reported 87% accuracy using AI on panoramic radiographs to identify single or multiple distal roots in mandibular first molars.[22] Additionally, AI has been used to measure root canal curvatures and three-dimensional changes after instrumentation.[23]

Determining the apical limit of the root canal system is crucial in root canal treatment. Canal length is typically determined using electronic apex locators and periapical radiographs. Although apex locators are highly accurate, their readings can be affected by wet canals, metallic restorations, or defective cables.[24] AI algorithms are being developed to assist clinicians in identifying the apical terminus on radiographs. In a cadaver model study, Saghiri et al found that AI achieved 100% accuracy in determining root length compared to actual measurements after tooth extraction and successfully located the minor apical constriction in 96% of cases.[25]

Detecting periapical lesions radiographically can be challenging due to the subjective nature of interpretation. Cone beam computed tomography (CBCT) offers greater accuracy compared to conventional periapical radiographs. Patel et al in their study showed that the overall sensitivity for the detection of periapical lesions was up to 100% for CBCT.[26] Using AI segmentation, each voxel was classified as "periapical lesion," "tooth structure," "bone," "restorative material," or "background." This deep learning system achieved 93% accuracy and 88% specificity in lesion detection.[27] A recent systematic review and meta-analysis found that CBCT imaging has a 78% accuracy in diagnosing vertical root fractures (VRF).[28] Fukuda et al reported a 75% sensitivity and 93% positive predictive value using AI to detect VRF on panoramic radiographs.[29]

AI has been utilized to predict outcomes in endodontic treatment. Campo et al used a case-based reasoning model, which involves solving current problems by referencing solutions to similar past cases, to evaluate the benefits and risks of nonsurgical root canal retreatment.[30] For endodontic microsurgery, Qu et al analyzed eight common predictors—such as tooth type, lesion size, bone defect type, root filling density and length, apical extension of post, age, and sex—using various machine learning models. Their study demonstrated an 80% accuracy in predicting the prognosis of endodontic microsurgery.[31]

Orthodontics

Smart technologies in robotics can lead to the development of new treatment techniques and rearranging of applications in orthodontics. A robot called AcceleDent (OrthoAccel Technologies Inc., Bellaire, TX) is a novel micro pulse vibration robotic system that applies cyclic forces to move teeth faster through accelerated bone remodeling and reduce the discomfort associated with orthodontics.[15]

In the context of orthodontics, the use of robots are: better X-ray imaging and positioning, automated 3D cephalometric evaluation, bionic robots for simulation of the stomatognathic system including masticatory and swallowing robots , tongue robots , mandibular and condylar movement simulation robots, dental articulation robots, and robotic remote control of mandibular advancement appliances in obstructive sleep apnea (OSA) patients in order to efficiently reach the target protrusive position.[32-34]

Accurate arch wire bending is the predecessor of successful orthodontic treatment. The last decade, in particular, has marked magnificent growth in the field of robotic wire bending and robotic customization of CAD/CAM appliances, which has increased the effectiveness and accuracy of arch wire bending and treatment. Sure Smile robot by Butscher et al in 2004 was the pioneer of wire bending robot which was followed by other robots used by different labial and lingual customized CAD/CAM appliances like the Sure Smile, Incognito, LAMDA, Insignia, and BRIUS appliances.[1] Along with reducing the fatigue of the doctor, it also prevents the fatigue fracture of the archwire caused by repeated bending, and thus improves treatment efficiency.[12] In 2011, a robotic system was patented by Hillard for forming features in orthodontic aligners. This invention offers possibilities of automation for installing activation features and other features needed for polymeric shell orthodontic aligners to receive auxiliary devices that expand their usefulness, range, and duration of application.[1]

Others

Masticatory robots, devices mimicking the human chewing motions, are used in dentistry, food science, and biomechanics. They record jaw movements in order to help in the prosthetic rehabilitation of patients and to make a diagnosis of TMJ diseases, and to study mandibular kinematics during speech.[12] In studies performed in clinical settings, Conserva et al validated that a mechanical chewing simulator was able to mimic mandibular movements and could determine the stresses applied by three different restorative materials-acrylic resin, composite resin, and glass-ceramic-at the simulated bone-implant interface.[35] Also, the author assessed the force transmission of four different occlusal materials to a simulated peri-implant bone using a masticatory robot.

Rehabilitation robotics is one among the important aspects of medical robotics, next to surgical robotics. They fall under two categories: therapeutic and assistive robotics. Therapeutic robotics offer psychological or physical therapy to enhance the specific function of patients and are increasingly used in physical exercise and functional rehabilitation of patients with paralysis and in enhancing the interactive capacity of autistic children by behavioral induction.[36] Assistive robotics assists to enhance the quality of life for those with musculoskeletal or neuromuscular disabilities by compensating for or replacing their mobility or functionality.[37]

CURRENT STATUS OF ROBOTICS IN DENTISTRY

Technological advancements have enabled robots to assist in complex procedures, improving accuracy and reducing human error.[38] The integration of AI, machine learning, and sensor technologies has led to the development of sophisticated robotic systems capable of performing complex dental procedures with minimal human intervention.[39] The United States leads in developing and clinically applying dental robots, followed by European and Asian countries.[15]

A detailed description of the application of robotics in various fields of dentistry have been well described above in the review. Robotics has significantly enhanced various dentistry fields by improving precision, efficiency, and treatment outcomes. In surgical procedures, robotic systems offer 360° movement, tremor reduction, 3D magnification, motion scaling, and remote operation, addressing human limitations while reducing surgeon strain and improving patient outcomes.[40] In implantology, robots ensure precise placement of dental implants, minimizing complications such as nerve damage and bleeding while increasing success rates.[41] Orthodontic applications include automated arch wire bending, which shortens treatment time and delivers better results compared to conventional methods.[42] In prosthodontics, systems like LaserBot enable precise 3D tooth preparation and automated tooth arrangement with CAD/CAM technology, improving design accuracy and workflow efficiency.[43] Additionally, in endodontics, robotic assistance enhances accuracy in canal shaping and reduces procedural errors, further advancing dental care.[44]

CHALLENGES AND BARRIERS

Dentistry often lags behind other fields in adopting new technology, unlike medicine, where robotics is widely used in various surgical specialties like gynaecology and orthopedics. This hesitation may arise from high initial costs and the difficulty of learning.[1]

The adoption of robotics in dentistry faces numerous challenges and barriers across various domains. Technological issues include calibration difficulties, limited dexterity compared to human clinicians, and challenges integrating robotic systems into existing workflows, particularly for complex clinical scenarios.[12] Economic and financial barriers, such as the high cost of robotic systems, ongoing maintenance expenses, and limited affordability for smaller clinics, further hinder widespread implementation.[45] Regulatory and legal challenges, including varying approval processes across countries and questions of liability in case of errors, add another layer of complexity. Additionally, a steep learning curve, lack of standardized training programs, and resistance to adopt new technology due to traditional practices pose significant adoption hurdles.[46]

PATIENT PERSPECTIVES AND ETHICAL CONSIDERATIONS

Robotic systems help reduce fatigue, minimize errors, and enable care in remote settings.[47] In dentistry, patients can choose between sophisticated robotic assistants and AI diagnostic help software or conventional dental practice based on their preferences. However, concerns and fears may prevent them from fully accepting or seeking the use of such advanced technologies in dentistry.[48] In this context, it is important to understand the current consumer perception and level of acceptance of robotic dentistry.

Researches have shown disparities in the comprehension and conceptualization of the robot-assisted surgical procedure between males and females. A significant gender disparity was seen in the acceptance of robots and AI therapy, with male participants showing higher levels of acceptance compared to female participants.[49] One possible explanation could be that females may be more concerned about the accuracy of artificial intelligence in the field of medicine. Another potential rationale is that females may exhibit more worry over the ethical implications and privacy concerns associated with the use of such technological advances.[48]

According to a study, the robot-assisted dental procedures that were most well accepted by patients were diagnostic and treatment planning and radiograph taking whereas they were less willing to undergo invasive procedures such as gum surgery using robotics. Also, roughly one-third of participants strongly disagreed with the idea of robots independently performing dental procedures, even if such treatments were available at a lower cost than conventional options.[48]

The concerns of those participants who were not willing to try the treatment performed by a robot alone was the trust issue, followed by safety, unfamiliarity, fixation on the traditional way, high cost, uncomfortable feeling, fear of dental treatment and dissatisfaction with the result.[50]

AI and robotics have revolutionized healthcare, and dentistry is no exception. Their integration in dental education has enhanced learning, diagnostics, treatment planning, and patient care. However, addressing the ethical implications related to robotics and AI is of utmost importance. Key concerns, including patient privacy, data security, algorithmic bias, and the risk of dehumanizing healthcare, require thorough evaluation and solutions accordingly to ensure their responsible and equitable application.[51]

ETHICAL THREATS POSED BY ROBOTICS AND AI

Privacy and data security concerns persist due to the potential compromise of patients' sensitive information, necessitating secure protection, storage, and sharing to meet legal and ethical standards. AI's impact on human cognition is dual-faceted—it can enhance perception and reasoning or diminish knowledge acquisition, risking a loss of understanding.[52] While AI provides valuable insights, it should complement rather than replace professional judgment and human connection in dentistry, ensuring that personal interactions remain integral to patient care and education.[53]

ETHICAL CONSIDERATIONS IN PRACTICE

Ethical considerations in dental education require transparency and explainability when integrating AI and robotics, ensuring openness about algorithms, data sources, and decision-making processes.[51] Obtaining informed patient consent is crucial, allowing patients to understand how their data will be used, the role of AI in their treatment, and any associated risks. Addressing bias in AI systems is essential to maintain ethical practice, necessitating regular assessments to detect and mitigate biases that may impact decision-making and education. Clear accountability for AI development and use is vital, requiring institutions and regulatory bodies to establish ethical frameworks, conduct audits, and regularly evaluate AI systems to uphold ethical standards and ensure patient safety.[54]

FUTURE TRENDS AND RESEARCH OPPORTUNITIES

The future of robotics in dentistry is brimming with potential, particularly in enhancing precision and improving treatment outcomes. In addition to accurate, efficient, and accessible dental services, robots provide advantages of reduction of hand tremors and fatigue, enhanced 3-D high-definition visualization, decrease of blood loss and postoperative pain, reduced risk of wound infection and aberrant scars.[55] However, till date, the only dental robot FDA-Approved in the US is the YOMI robot (Neocis, Miami FL).[56] Currently, there is a burgeoning development of artificial intelligence (AI) technology for voice commands, exemplified by the advanced system, DEXvoice (DEXIS LLC, Alpharetta, GA, USA), which enables the effortless retrieval of X-rays, patient records, and charts by dentists, without requiring them to remove their gloves or engage with the computer manually.[12] Even though the future prospective of robots in dentistry is promising, relevant research and case reports are limited.

If we expect further standardization, industrialization, and wide application in the daily teaching and clinical practice of dental robotics technology, the development of new structures, sensors, control theories and other related technologies and theories is essential. Further research should be done on the size, structure, tactile feedback, cost efficiency and inclusion of imaging to enhance the integration of robots into dental practice.[57] To conduct the operation efficiently, a friendly human-computer interaction software should be designed to provide operator humanization input and feedback.[58] In the future, more extensive clinical trials will be needed to observe and evaluate the long-term effect continuously.[2]

Already, robotics is making inroads at dental schools. In 2019, the Boston University Henry M. Goldman School of Dental Medicine became the first U.S. dental school to acquire the Yomi system. In the coming years, the technology undoubtedly will affect the way new generations of dentists are educated. Research on dental educational robotics in university setup appears to be a capable propagator to introduce robotic dentistry and exponentiate the acceptance of robotic systems among future dentists.[3] However, it still requires a lot more research and financial support for the actual implementation of robots in our practice. In no way, AI and robots can replace humans, but their integration in our field will lead to a successful and stress-free practice.

CONCLUSION

This review emphasizes on the application of robots, current status & challenges, ethical considerations and future trends in detail. Robotic technology has great potential to revolutionize dental care. It can offer notable advantages of greater precision, accessibility, reduction on dentist's fatigue and minimally invasive dentistry. To some extent, Robots have been explored in dentistry but still requires more research and clinical trials. Challenges such as high cost, patient and dentist's acceptance, regulatory and ethical aspects should be addressed. With the advancing technology and trials, the importance of robotics in dentistry is certain to grow resulting in safer, more effective, and precise dental care.

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