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REVIEW ARTICLE

Extending Arms In Prosthodontics: Artificial Intelligence

Sujata Pandey[1], Ragini Pandey[2], Soumitra Agarwal[3], Aniket Mone[2]

ABSTRACT

Artificial intelligence (AI) is the data-driven technology of modern times. It is has gained tremendous traction over the past few years globally. Not only is it a breakthrough in the aspect of intelligence innovation but AI is also revolutionizing every field from space science to dentistry for the ease of both doctors and patients.Prosthetic dentistry or prosthodontics deals with replacing and rehabilitating not just missing teeth with the help of fixed and removable prostheses or biocompatible substitutes like implants but also helps to restore hard tissues and maxillofacial tissues, thereby improving the overall health status of the oral cavity. This review is planned in order to shed light on the implementation of AI in prosthodontics and highlight the present-day technology of AI and machine learning in dental prosthetics presenting its efficacy in diagnosing and constructing more patient-specific prostheses. In conclusion, it helps dental health care professionals to work smarter not harder.

Introduction

There is a high demand for improving healthcare efficiency and quality while standardizing the current methods. Building intelligent software or computers that can carry out activities that traditionally require human intellect to simulate the process of resolving problems, is the goal of artificial intelligence (AI) and dentistry offers multiple opportunities for robotic automation, artificial intelligence and assistive technology to enhance the quality of dental care.[1] The foundation of artificial intelligence is the replication of human cognition and behaviour using computer algorithms and is a type of mathematical model that is based on data. The model can make predictions since it has been trained on previously collected digitalized data that is now growing daily and aids in training AI models to produce more accurate outcomes.[2]

AI model is similar to the neural network of the human body and is referred as an **artificial neural network (**ANN) consisting of three layers. (Figure 1)

1.Senior Lecture
2 .Post graduate student
Department of Prosthodontics and Crown & Bridge.
3.Senior Lecturer
Department of Orthodontics & Dentofacial Orthopedics.
Kothiwal Dental College and Research centre

Correspondence address
Dr. Sujata Pandey
Senior Lecturer
Department of Prosthodontics
Kothiwal Dental College and Research Centre

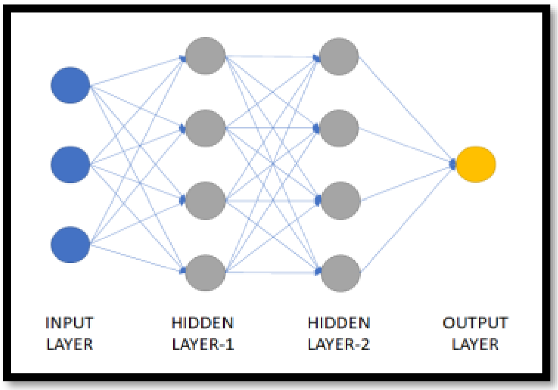

Figure 1: A schematic representation of ANN model.[2]

Strong AI refers to a system "that was operated in the same way as human intelligence through the building of non-natural, artificial hardware, and software." On the other side, weak AI allows people to benefit from the advantages of medical and logical algorithms rather than trying to completely replicate human intellect. It differentiates between human and computer-integrated technologies.[3,4](Figure 2)

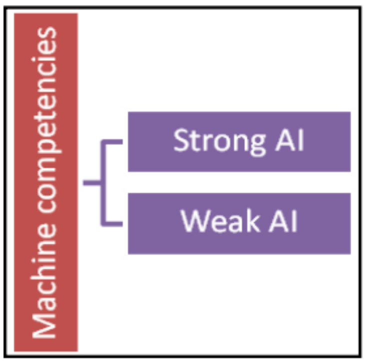

Figure 2: Depicting machine competencies.[5]

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Artificial intelligence (AI) applications are widely used in numerous engineering sectors and are a common part of modern digital life, such as in the form of virtual assistants like "Siri" or "Alexa." [4] AI algorithms are frequently employed in the field of medicine to analyse photos by extracting features from particular photographs and conducting target studies. Although still limited in comparison to medical technology, technological advancements in dentistry are becoming more apparent.[3]

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. In order to improve accuracy robotic automation and assistive technology have been introduced in dentistry. Robots might free up human resources for other crucial activities, such working with patients or other duties requiring advanced cognitive abilities. Robotics-enabled digital dentistry and medicine reduce mistakes and improve overall patient care.[1] People's oral health may change, and be a lot safer.

The primary areas of attention for prosthodontics are the treatment and construction of fixed and removable dental prostheses, the preparation of finishing margins next to the tooth for improved fitting of the prosthesis, implant surgery, and the conception of maxillofacial prostheses, keeping the right maxillo-mandibular relationships and choosing a tooth colour for greater looks. AI has several benefits that may be used in different treatment protocols.[2]

Robotic systems are not intended as replacements for human doctors, but rather as smart surgical tools. They help to increase the precision, quality and safety of surgical procedures (Lea et al. 1995), and accomplish some work where humans are not competent. Their most valuable function may be their capacity to create an information link from preoperative surgical plans to the surgical arena. [7,8]
This review focuses on the employment of robots in several prosthodontic procedures & other dental specialties.[6]

History

Year(s)	Events
1955	Term **"Artificial Intelligence"** was first used by **John McCarthy**
1959	**Machine Learning** is a field of artificial intelligence. Defined by **Arthur Samuel**
1980	Remotely controlled robotic system was developed by NASA for surgically operating soldiers on the battlefield as well as astronauts in space
1988	**PUMA560** systems used successfully for **neurosurgical biopsy.** It was the first documented case of a robot assisted surgical procedure
1994	USA FDA Approved the **Automated Endoscopic System for Optimal Positioning (AESOP)** robotic system for its endoscopic surgical procedure
2000	FDA Approved **Da Vinci Surgical (DVS)** system. It facilitated complex surgery using a minimally invasive approach, surgeons controlled it via a console.
2000	FDA approved the first **robotic system** for **performing laparoscopic surgery**
2001	Validation of the doctor-robot concept was performed via a transcontinental live **robotic cholecystectomy.** First Instance of **"Telepresence"**
In Dentistry, Robotics is still in its infancy, even though all the necessary technologies have already been developed and could easily be adapted. In prosthodontics, the application of robots are limited mainly to the tooth arrangement in partial and complete dentures, and in dental implantology	

Scope of AI in prosthodontics

Every field is implementing AI for the ease of both doctors and patients. Prosthetic dentistry or prosthodontics is one of the branches of dentistry which mainly deals with replacement and rehabilitation of missing teeth with the help of fixed and removable prosthesis or with biocompatible substitutes like implants.[2]

With the advent of implantology, various limitations of the fixed and removable prosthesis can be solved. Acceptance of implant prothesis has been increased in recent years due to better aesthetics and stability. There are overall 4000 dental implants that are marketed worldwide. CAD-CAM and panoramic radiographs are the primary methods to classify the implant structure.[2,8]

Hong et al conducted a study todetermine the efficacy of convolutional neural network (CNN) models to classify the implants with the help of panoramic and periapical radiographs. From the results of this study, it was concluded that the deep CNN model can be a helpful aid in classifying implant systems with almost equal or greater accuracy compared to humans.[9,11]

The medical robotic industry has lately been shifting its focus to autonomous robotic technology, that is robots capable of performing a procedure themselves without the constant control or active monitoring by a natural person. Also, remote-control injectable medical microrobots have been envisioned for the delivery of cytotoxic agents to cancer cells. The opportunities that emerge from a combination of robotics, artificial intelligence, machine learning and dentistry referred to as Dentronics[12,] is described in figure 3 below.

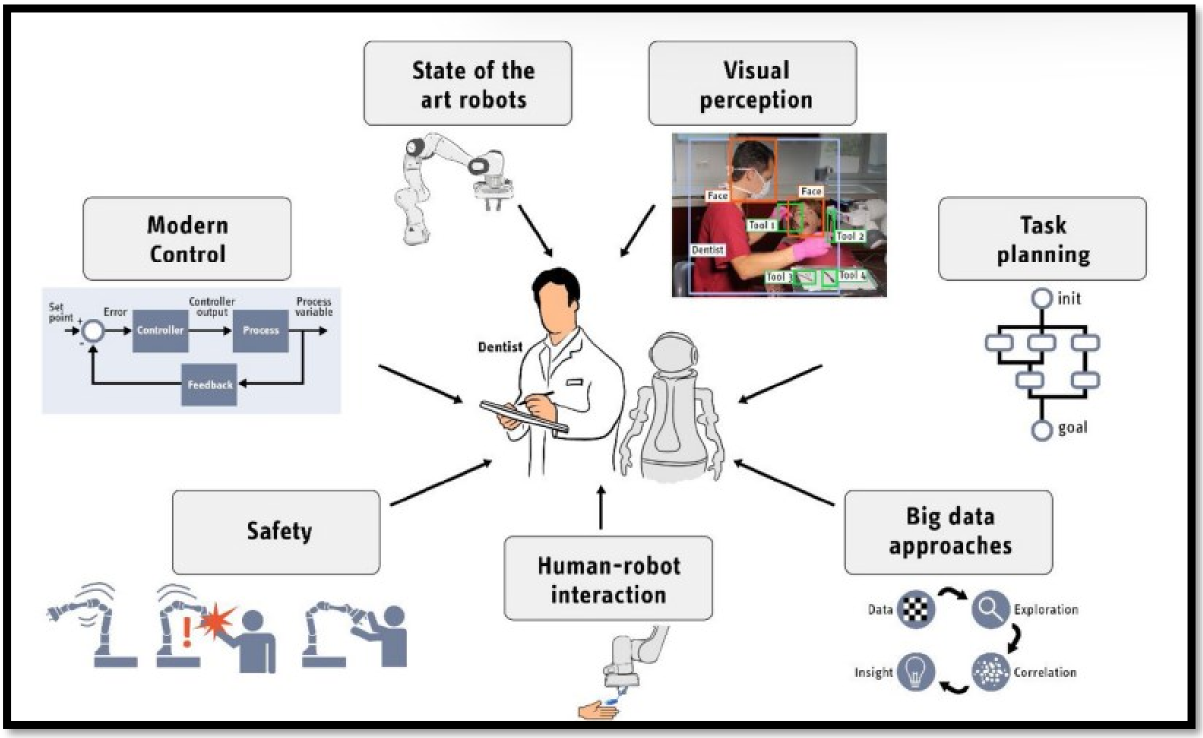

Figure 3: Vision of possible robots and artificial intelligence service network to support future dentistry.[9]

APPLICATION OF AI IN PROSTHODONTICS

1. Role in fixed dental prosthesis

Dental Implantology

Applications of computer assisted pre-operative procedures like CAD/CAM are followed in dental implantology for long. But the use of robots for the surgical procedure is relatively new.

It is considered a step forward in utilizing the applications of computer assisted pre surgical planning to the usage of robots in the surgical phase. Several prototype systems were developed in many centres like University of Kentucky, Ecole des Mines de Paris, Umea Universitet, University of Coimbra and University of Duesseldorf (Zhang et al. 2011, Pires et al. 2006).[7]

A new model was proposed by researchers at the Finnish Center for Artificial Intelligence (FCAI), the University Hospital of Tampere, Planmeca and the Alan Turing Institute to accurately and automatically identify the exact position of the mandibular canal for dental implant operations. [5]

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.[13] Subsequently, a 3-DOF robotic system with a stereo camera was developed that could detect and Sensors 2021, 21, 3308 3 of 15 modulate the dental handpiece to ensure implant placement according to the preoperative protocol. The planned surgical procedure was applied automatically by the computer to ensure the correct cutting site and properly applied force.[1]

The first commercially available and state of the art robotic system for dental implantology, named as Yomi was developed by Neocis Inc, USA and approved by FDA in 2017 (U.S. Food and Drug Administration, 2017). Yomi is a computerized navigational system intended to provide assistance in both the planning (pre-operative) and the surgical (intra-operative) phases of dental implantation surgery.[7,8]

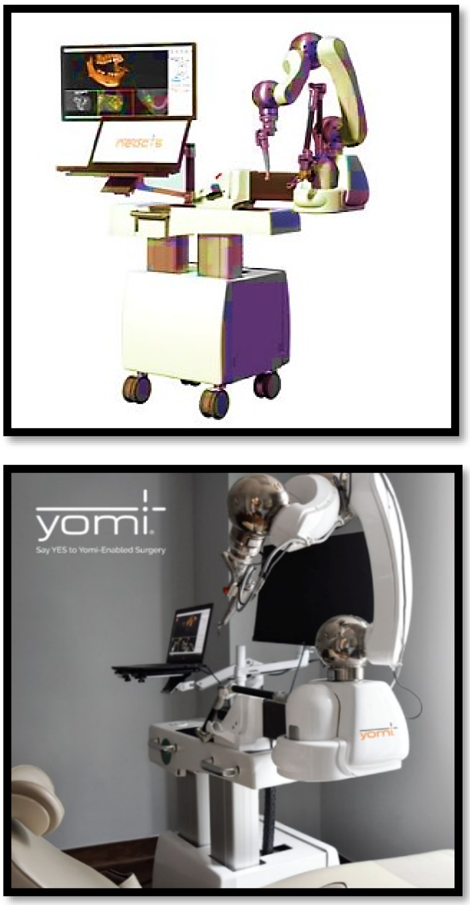

Figure 4: Yomi dental implantology robotic system

Yomi enables dentists to bridge the digital imaging preoperatively into their operating environment through the use of haptic robotic technology.[14] They receive real-time physical and visual guidance throughout the surgery. This provides accuracy and reliability without the need to manufacture a custom plastic guide or worry about performing an unguided freehand approach.

Tooth Preparation

Despite being standard work for professionals with years of clinical training, tooth preparation for a crown or bridge is nonetheless difficult. The main difficulty is to reduce the tooth sufficiently to create room while causing the good tooth substance the least amount of damage. The idea of a robotic device being used for tooth preparation appeals to dentists as being practical and alluring.

An in vitro testing of a mechatronic system has been conducted to aid the clinician in tooth drilling. The report demonstrated good outcomes; however, its validation has not been performed so far in the clinical setup. With a mechatronic system, the accuracy of the clinician's position was 53% more efficient than without it.[1]

Yuan et al. described a robotic tooth preparation system with
(1) An intraoral 3D scanner (TRIOS, 3Shape A/S, Copenhagen, Denmark) to obtain the 3D data of the patient's target tooth, adjacent teeth, opposing teeth and the teeth fixture;
(2) A computer-aided design (CAD)/computer-aided manufacturing (CAM) software for designing the target preparation shape and generating a 3D motion path of the laser;
(3) An effective low-heat laser suitable for hard tissue preparation;
(4) A 6 DOFrobot arm;
(5) A tooth fixture connecting the robotic device with the target tooth and protecting the adjacent teeth from laser cutting, designed using Solid works software.

A system with micro robots, controlling a picosecond laser showed a preparation accuracy that met clinical needs, the error was about (0.089 ± 0.026) mm. Another tooth preparation system for veneers with a rotating diamond instrument mounted on a robotic arm was compared to hand crown preparation and showed better results than the tooth preparation carried out by the dentist. The average repeatability of the system was about 40m.[9]

2. Role in removable prosthesis

Teeth-Arrangement Robot

The most significantstep in the (manual) conventional method of creating complete dentures is inserting artificial teeth into a tooth pad in the proper orientation. Thiscan only be done effectively by specialised dentists and trained technicians. Robotic production of denture systems has now supplanted the conventional method. The size of the teeth, how each tooth is positioned and oriented in relation to the others, and how the teeth arch curve differ significantly amongst complete dentures.

The advantage of a robot is its operational flexibility, and can be adapted for handling the manufacture of complete dentures.[9]

Robotic assistance may also be helpful in supporting the dental technician. A novel system that generates the dental arch has been developed. The system can be used to fabricate full dentures. A study on this tooth-arrangement robot showed that it was very accurate. [12]

For the fabrication of a complete denture, Canadian scientists developed a single manipulator robotic system utilizing a 6-DOF CRS robot.[1]This system was then adapted for the manufacture of complete dentures (Zhang et al. 2001, Song et al. 2001). A single-manipulator robotic system for tooth arrangement of complete dentures is composed of the following parts:
(a) Light-sensitive glue (Wang and Li. 2001)
(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
(h) 6-DOF CRS robot

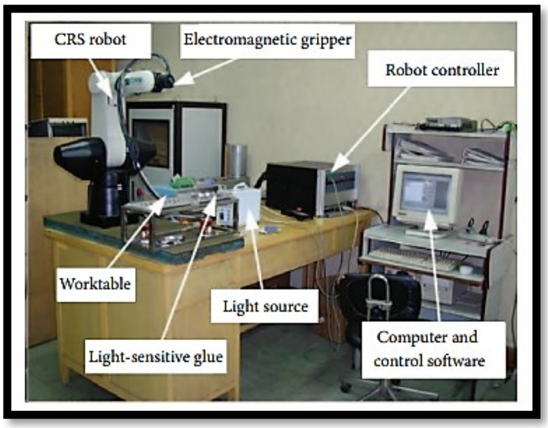

Figure 5a: Single manipulator tooth-arrangement robot system for complete denture.[8]

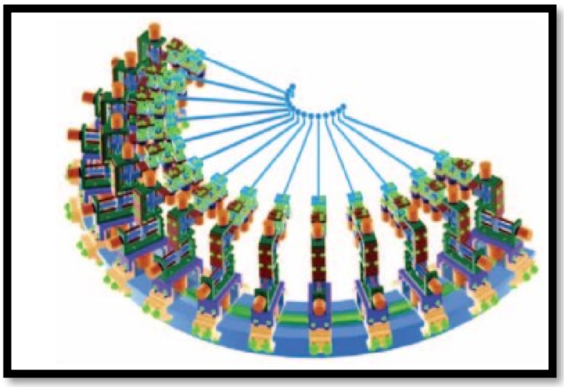

Figure 5 b: Structure of the 84DOF multi-manipulator tooth-arrangement robot. **Figure 5 c**: Complete denture made by the 50DOF multi-manipulator tooth-arrangement robot system.[8]

A much improved 50 DOF tooth arrangement robotic system was then designed with 14 independent manipulators, a dental arch generator and a slipway mechanism as its components (Zhang et al. 2011, Zhang et al. 2010). Dental arch generator create the dental arch curve and matches with the one from the patient's oral cavity. The slipway mechanism is used to control the dental arch generator.[9]

3. Role in maxillofacial prosthesis

Oral & Maxillofacial Prostheses

The bionic eye, developed in the United States, has already been tested in a dozen patients with vision damages. Without the need for surgery, these devices can benefit the people in attaining vision with the help of artificial intelligence.[5]

Due to amputation of limbs, patients can lose the sensory capacity in those areas. Artificial skin developed by researchers from the California institute of technology (USA) and the federal polytechnic school of Zurich (Switzerland) is changing this scenario.[5]

Artificial olfaction plays a crucial role in robotics by mimicking the human olfactory structure that can identify different smells that compare to a range of fields, together with environmental monitoring, disease diagnosis, public security affairs, agricultural production and food industry.[15]

Malignant lesions of the oropharynx are not always readily accessible, and conventional treatment must often resort to radiotherapy and/or chemotherapy. Salvage surgery is usually conducted through mandibulotomy with mandibular displacement and lip split. However, robotic oral and maxillofacial surgery has become an attractive possibility, especially in the treatment of oropharyngeal carcinoma.[9] In 2009, the US-FDA approved the da Vinci system for transoral treatment of selected malignant diseases and all non-malignant lesions of the oropharynx, even when located at the base of the larynx and the tongue.[1]

In 2010, Vicini et al. first proposed transoral robotic surgery for treating obstructive sleep apnoea. They reported that robot-assisted surgery resulted in minimal morbidity and was well-tolerated by the patients. Moreover, the apnoea-hypopnea index was significantly improved in all participants.[16]

A 6-DOF robotic arm was proposed as a surgeon aid during orthognathic surgery. Established on 3D information obtained from a CT, positioning must be performed by the surgeon before surgery.[17] A jawbone skull phantom was used to perform preliminary experiments for the orthognathic surgery. According to Woo and colleagues, the available software needs to be upgraded and hardware safety improved before automated orthognathic surgery being investigated in human trials.[1]

4. Miscellaneous

Robotic System for Bending Orthodontic Arch-Wire

Sure-Smile Orthodontic Arch-Wire (OAW) bending robot involves of a robot installed on to table or base support surface.[18] Sure-Smile utilizes contemporary 3D computer and imaging techniques to diagnose and plan treatment and employs the robotic system to personalize fixed orthodontic appliances. Detailed treatment planning can be done by simulating the treatment in anticipation.[1,8]

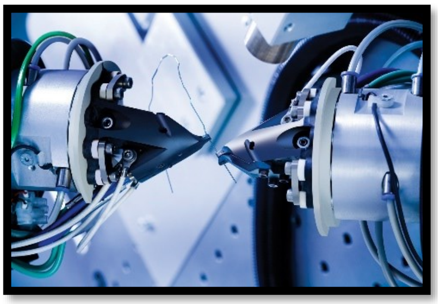

Figure 6: Sure-Smile OAW bending robot.

Jaw movement

Edinger described a robot for the dental office for the first time in 1991, later he described a robotic system to reproduce condylar movements.[19,20] Virtual articulators are one of the technological bases necessary to fully rethink and digitalize dental workflows.[21] They enable simulation of occlusal changes in the digital world and may be strongly empowered by AI in the future to e.g. simulate use of dental materials patient-individually or simulate treatment outcomes of implant placement or maxilla-facial surgeries.[9]

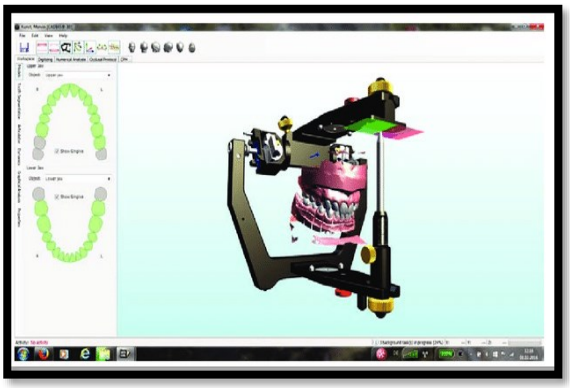

Figure7: The digital models in the virtual articulator.

Endodontics

Root canal treatment is a procedure which is based on high accuracy. Usually, a dentist specialized in endodontics works using magnification to assure adequate view of the root canal. Nelson et al. published the idea of a robotic system for assistance (i.e. vending machine) during root canal treatment.[9,1] The primary function of the "vending machine", as proposed by the authors, was to provide the clinician with the required root canal therapy instruments during the procedure.[22]

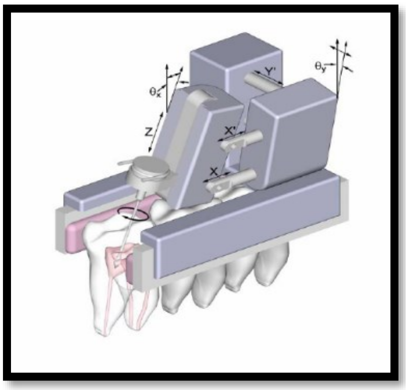

Figure 8: Multi-purpose micro-machine for automatic endodontic treatment.

Oral Radiology

Positioning of the film/sensor and the X-ray source was proposed to be executed by a 6 DOF robotic arm and was found to have no adverse effects. Results showed that the robotic system was superior to the mechanical alignment approach, due to its excellent accuracy and repeatability.[23] Another application presented in the literature is a robot equipped with a skull to investigate the influence of head movement to the accuracy of 3D imaging.[9,1]

Dental Hygiene Applications

Ernst et al. [24] developed a robot system that simulated 3D brushing movements as a function of time. The in vitro results revealed the capability of the robotic system to exhibit reproducible significant differences in the cleaning efficacies of powered toothbrushes.A recent study proposed the application of micro-robots with catalytic-ability to destroy biofilms within the root canal and tested the system In vitro.[1]

Dental Education

The idea of a dental training robot was first described in 1969. The application of a humanoid in dental education was tested in 2017. A humanoid, a full-body patient simulation system (SIMROID).[25] "Hanako", the SIMROID is standing 165 cm tall. It comes with a metal skeleton and vinyl chloride-based gum pattern of skin.

Figure 9: SIMROID-Patient Simulation System for Dental Education.

Tanzawa et al.[26] introduced a medical emergency robot with the aim to help dental students to get familiar with emergency situations. Another robotic educational equipment described in the literature is the ROBOTUTOR.[27] This tool was developed as an alternative to a clinician to demonstrate tooth-cleaning techniques to patients. It is a robotic device to train and show brushing techniques.[9]Gaengler et al. developed a clinically validated robot toothbrushing program for reproducible and fast in vitro testing of tooth cleaning.[1]

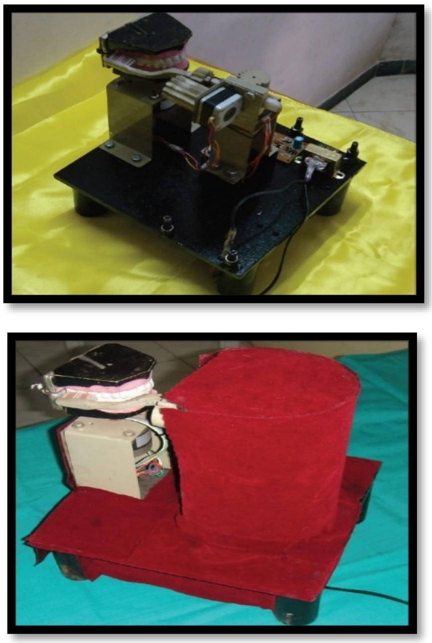

Figure 10: ROBOTUTOR model.

Virtual reality (VR) laboratories with haptic devices become more and more part of the regular curriculum in dental education and have been found to improve student's learning efficiency and effect. Ernst et al. developed a robot system that simulated 3D brushing movements as a function of time.[1]

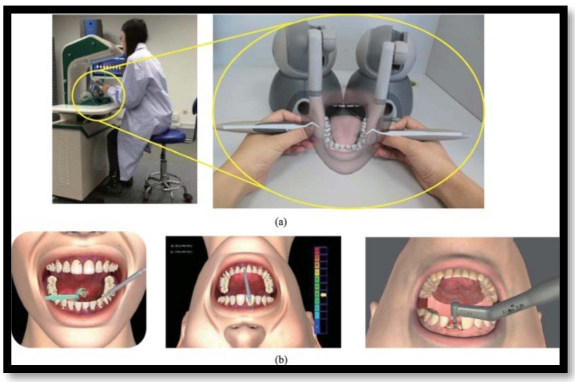

Figure 11: Dental surgical simulator with bi-manual haptic feedback. (a) Visio-haptic collocated hardware platform; (b) Typical surgical scenarios, including dental inspection, periodontal depth probing, and implant surgery.

Dental Assistance and Dental Materials

The robotics finds application to standardize simple endoral radiographs to analyse the CBCT and compare the bone volumes to match the bone pre-and post- augmentation procedure. A study examined the probability of active robot assistance during dental procedures by exchanging instruments through a multi-nodal communication model designed for clinicians as consumers. It consists of visual gestures, speech input, touch display input, bilateral physical robot-human communication. In this study, the researchers utilized a state-of-the-art sensitive, collaborative, and safe 7-DOF robotic system and performed a user study to investigate the possibility of varying robot-human communication dental procedures.

Robotic mastication or dental wear simulators are suggested to analyse dental implant materials or tooth filling materials.[9] A 6-DOF robot drove one of the systems. Another report described the testing of dental impression material utilizing a robotic arm.[1,28]

Figure 12: 6-DOF robot arm.

Advantages And Disadvantages [6]

A. ADVANTAGES

- Extremely high accuracy and precision
- Stable and untiring, and hence can be used repeatedly without rest
- Able to accurately process and judge quantitative information fed into the system

B. DISADVANTAGES

- No judgment of the situation and hence unable to use any qualitative information
- Continuous monitoring of an experienced dentist is always required
- These devices still remain very expensive and out of reach of the common man

Limitations

In theory, there are no restrictions on how AI can be used in prosthodontics. However, in many situations, it is monetary factors that drive the development and widespread adoption of new AI technologies in the most commercially lucrative areas- and tend to restrict interesting dental applications since a market appears to be limited for the dental sector.

Nevertheless, future developments and research on AI can be eagerly awaited.[3]

AI was heavily dependent on datasets. These datasets should be appropriately classified and filtered for excellent model training. The drawback is that most data are in paper format and due to lack of awareness in follow up treatment, data consolidation was not done correctly. In present scenario, the medical sector had started digitalizing the diagnosis and reports but still a long way to go for accurate data that can be used in model training.

Furthermore, robotic systems are complex and require expertise for their proper operation and function. Another vital aspect might be the unknown patient acceptance and compliance among dentists. The point regarding the input of data is very critical.

Presently, in dentistry, two main facets can be seen —those that are performed very well via meticulous preoperative planning and implementation, and those carried out very inefficiently by the inexperienced and uninformed personnel resulting in unfavourable results. The results would only be as good as the personnel incorporating the data into the robotic system.

Future scope

The use of AI in dentistry is said to increase precision, repeatability, and reliability throughout the literature; yet, the volume of robotic dentistry research is constrained by the absence of readily available systems. Additionally, there is a lack of proficiency to program and regulate robotic systems. Therefore, research in this area depends on effective collaboration between dentists and engineers. This might alter shortly since the robotics community investigates innovative communication strategies and programming paradigms.

Majority of the interdisciplinary research merging dentistry and engineering in robotic dentistry is focused on dental implantology, though the invasive nature of this technology might undermine the acceptance of this application among dentists and patients. Thus, these invasive technologies are less appropriate as forerunners. Hence, research in the domain of assistive robotic dentistry appears to be more potential to support the presentation of this contemporary robotic-enabled era.

Moreover, research on dental educational robotics in university setup appears to be a potential propagator to introduce robotic dentistry and removing the hindrance of acceptance of robotic system among future dentists.

Conclusion

The application of AI in healthcare held promise for the future since it would decentralise the treatment process. AI lets medical workers deliver remote care more effectively. Future illness diagnosis will be more accurate thanks to artificial intelligence (AI), which will be able to forecast outcomes and combine them with human diagnoses to increase the likelihood of accurate identification.

All robot applications described in this article from teeth arrangement for complete dentures to dental material testing or tooth preparation have an innate potential to progress dentistry into a new era where digitalization supports the management of our real world. Overall, the level of technological readiness is still less, and more research is required to be performed to produce a worth of robotic dentistry, hence the pace of research in this domain should increase over the next years.[1]

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