REVIEW ARTICLE

BOT GUIDED PROSTHODONTICS : A REVIEW

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ABSTRACT

Application of robots for reducing the manual effort and increasing the accuracy of procedures are gaining momentum in various medical fields including dentistry. This article reviews the applications and progress thus far of the use of robots in prosthodontics. Robotic interventions in prosthodontics are mainly for designing and manufacturing of complete dentures and for assisting in dental implantology surgical procedures. In both cases, great progress has been achieved, helping to obtain higher level of accuracy in the procedures with high success rates. The time required tocomplete each procedure are considerably reduced with the use of robots. But such sophisticated and specially made robots for various prosthodontic treatments have to be used under the strict supervision of an expert dentist. There's no substitute for expert skill and clinical judgment.

Keywords: robots, dental implants, implant surgery, complete denture, tooth preparation.

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INTRODUCTION

Robots are innovations by humans to attenuate manual efforts in hazardous working environments, to extend the accuracy and precision of the work being administered, and to attenuate manual labour. Robotics deals with the planning, development, operation, and use of robots, also as computer systems for his or her control, sensory feedback, and Inter disciplinary branch of engineering and science that has applied science, engineering science, computer science, and others.[1]

Various sorts of robots are already a part of our lifestyle, they support production in industrial applications, cut our grass and clean our floors.[2] The present generation of human-safe robots is finally ready to work directly with human co-workers, assist them and relieve them of tedious and laborious routine tasks.[3]

Robotic systems aren't intended as replacements for human doctors, but rather as smart surgical tools. They assist to extend the precision, quality and safety of surgical procedures.[1.]

In dentistry, Robotics remains in its infancy, although all the required technologies have already been developed and will easily be adapted. In prosthodontics, the appliance of robots is restricted mainly to the tooth arrangement in partial and complete dentures, tooth preparation in fixed partial dentures and in dental implantology.[4]

BACKGROUND ON DEVELOPMENTS IN ROBOTICS

Robotic systems aren't intended as replacements for human doctors, but rather as smart surgical tools. They help to increase the precision, quality and safety of surgical procedures. Their most valuable function may be their capacity to create an information link from pre-operative surgical plans to the surgical arena (Chart 1).[1]

HUMAN–ROBOT INTERACTION

The understanding, designing, and evaluation of robotic systems for use by or with humans is

CHART: 1 BACKGROUND ON DEVELOPMENTS IN ROBOTICS

In 1985, Programmable Universal Manipulation Arm (PUMA 560) robotic system was used in a neurosurgical biopsy.5

In 1988, the same PUMA system was used to perform a robotic surgery - transurethral resection.5

In 1994, the Automated Endoscopic System for Optimal Positioning (AESOP) robotic system became the first system approved by the Food and Drug Administration (FDA) for its endoscopic surgical procedure. AESOP was designed to manoeuvre an endoscope inside the patient's body during the surgery. The camera moves based on voice commands of the surgeon or through computer commands. 6

In 1994, ZEUS surgical system was a successor of AESOP system, designed to assist in the control of blunt dissectors, retractors, graspers, and stabilizers during laparoscopic and thoracoscopy surgeries. 7,8

The Da Vinchi Surgical (DVS) system, which was approved by FDA in 2000. 9,10 This system was designed to facilitate complex surgery using a minimally invasive approach, and is controlled by a surgeon from a console.

The DVS system is currently used for a variety of surgical interventions: general, thoracic, cardiac, colorectal, gynaecology, urological, etc. 8

referred to as human-robot interaction. There are various modes of interaction between humans and robots.[11]

Physical human-robot interaction (PHRI)[12] has become increasingly relevant in modern robotics and will also play an important role in Dentronics applications. A former review article found haptics to be one of the key elements for robotics in dentistry.[13] Safe phri requires collaborative and sensitive robots and suitable compliant behaviour made possible by appropriate controllers.[14] An example for physical communication between humans and robots are haptic gestures. They allow the human to relay context-dependent intentions to the robot by touching it.[15] In a broader context, button interfaces are also related to physical interaction, especially if they are mounted on the robot in order to form an integrated direct control as for example on the Franka Emika Panda arm or the Baxter platform.[16]

Another rather basic form of contact-based interaction are graphical interfaces such as where it is important to not overwhelm the user with information but focus on the current context. However, these methods may not be as intuitive as direct physical interaction with the robot.[17]

Contact-free interaction modalities like visual interaction based on RGB-D camera systems or similar technologies such as infrared have been researched for many years. Especially, in dental scenarios this would be a great benefit as the dentist most of the time cannot move around freely to interact with a robot directly. In order to establish such type of communication, visually recognizable gestures like waving, hand opening/closing or pointing are utilized.[18,19] Visual communication is under the assumption that the dentist can move hands but cannot move around to directly touch the robot and after short auditory/visual cues for commands the dentist has hands free while the robot does its work autonomously. Furthermore, voice recognition and foot-pedal controlled commands are possible.[20]

More advanced techniques involve motion tracking of humans or face recognition. Its advantages are that no direct contact with the robot is necessary and a certain degree of comfort for the human user is created since they do not have to alter their respective location. Despite major advantages over the last years, the systems are still sensitive to factors such as different lighting, obstacles and still require substantial computational resources.[21]

Auditory interaction includes verbal communication and general sound signals to relay information between humans and robots.[22] Simple sound signals are often employed to support other means of communication e.g. A confirmation sound when pressing buttons or performing a haptic gesture. Verbal communication requires much more advanced algorithms and still is prone to errors in practice. While text to speech (TTS) is comparatively widespread and easy to implement, general speech recognition is a difficult problem especially in a quite unstructured scenario such as a dental office. By leveraging large amounts of data, neural networks have proven to be a promising approach.[23]

PROGRAMMING & MACHINE LEARNING

Before the emergence of collaborative and soft robots in the last decade most platforms - required a tedious and time-consuming process in order to be programmed even for the simplest tasks. Today's technological level allows for much more intuitive and efficient programming schemes.[24]

The term machine learning (ML) summarizes different methods for making use of possibly large amounts of data to learn and self-improve from own experience.[25]

Kinesthetic Teaching (KT) & Teleoperation (TO) are 2 methods for machine learning (Figure 1). In KT, the teacher physically manoeuvres the robot (Figure 2) while in TO it is performed with the help of Sensable's Phantom Omni R which

Fig. 1 : Types of programming

Fig.2: Kinesthetic teaching

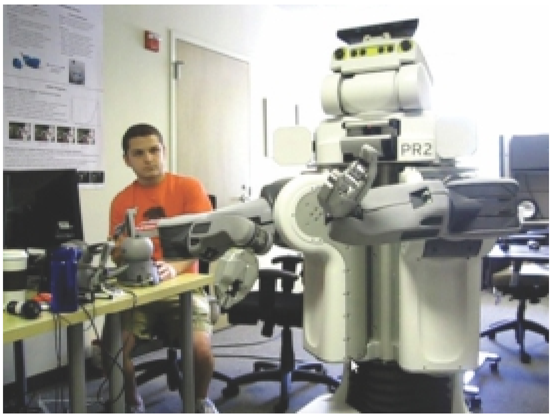

Fig.3: Teleoperation

is a haptic device having 6-degree of freedom positional sensing (Figure 3).[26]

CONTROL OF A ROBOT

The controller of a robot determines how its joints are actuated depending on sensory input and is therefore directly related to the way it is explicitly or implicitly interacting with the environment. The application of robotic systems in a dental scenario requires the capability of sensitive physical interaction without causing any form of harm to the environment or the system itself. In robotics, impedance control[27] became an essential framework that still serves as the basis for many modern control systems fulfilling this requirement. It enables robots to safely interact with the environment in a similar manner as humans do by mimicking the compliant human motor control behaviour. This stands in vast contrast to classical position-controlled industrial robots used at assembly lines and in segregated workspaces from humans.[28]

ARTIFICIAL INTELLIGENCE

In the context of robotics, the field of autonomous task planning comprises methods from classical artificial intelligence such as tree-search algorithms and symbolic task planning that are used to autonomously plan a sequence of actions in order to achieve a desired goal. Most of these methods originate from works that are unrelated to robotics yet very much applicable.[29] Generally, autonomous robots depend on a knowledge base in order to reliably perform their assigned tasks. Examples for stored knowledge are taxonomies of skills, i.e. The capabilities of the robot, 3D-maps of the surroundings or general information about the robot. Furthermore, they have to be able to reason about current events and new information in order to adapt to new situations.[30,31]

SAFETY

Human safety is among the most important aspects in a human-robot co-working scenario. Especially in the last decade there has been extensive research about this topic in order to determine requirements of safe robots and studies regarding injuries which resulted in the development of novel design paradigms that aim to make modern robots inherently safe.[32]

In particular, some works address safety issues and led to new safety standards such as ISO 13482-3 (safety of machinery - functional safety of safety-related electrical, electronic and programmable electronic control systems).[14] Within the soft robotics paradigm joint torque sensors with suitable disturbance observers are used for human-robot contact handling and, more general, for unified collision handling and reflex reaction.[33]

To prevent injuries of human co-workers in unintended collisions, safe motion control methods were developed[34], determining the maximum allowed velocity for ensuring human safety by means of an injury database and the current robot configuration, an essential component to let humans and robots share physical spaces and seamlessly interact.[35]

Beyond considering the isolated robot alone also its workplace in its entirety shall be considered when designing a safe work environment.[36] Within the European Economic Area, a robot system has to be provided with a CE marking which confirms the safety, health and environmental protection standards for products.[37]

ROBOTICS IN DENTISTRY

MAXILLOFACIAL SURGERY

Applications of digitalization in maxillofacial surgery with a special emphasis on the combination of implant dentistry and prosthodontics or on the positive effects of robot-assisted surgery in head and neck cancer.

The development of computer-assisted implant surgery based on the concept of prosthetic-driven implantology and CT-scan analysis have been reviewed. Although advances in technological readiness have been made, issues such as high costs and inherent complexity of the techniques and hardware utilized are still to be overcome.[38]

Orthognathic surgery was performed in a preliminary experiment with a jawbone skull phantom. However, Woo et al. Found that before automated orthognathic surgery can be tested in human studies the available software needs to be optimized and safety of the hardware augmented.[39]

A pilot phantom study concluded that implant placement with a six-axis robotic arm can improve accuracy of the operation in zygomatic implant placement. A surgical robotic application which has made it to reality is an invasive robotic assistant for dental implantology. It was permitted for operative use by the FDA (Food and Drug Administration) in March 2017.[40]

Human-related factors (such as reduced concentration, trembling, distraction or reduced vision) affect the accuracy and safety in maxillofacial surgery. A study proposed an autonomous surgical system aiming to conduct maxillofacial surgeries under the assistance and surveillance of the surgeon. A navigation module and a robot were seamlessly integrated into this system and a drilling experiment was conducted on five 3D printed mandible models to test the pose detecting capability and evaluate the operational performance. The experiment showed that this system was able to successfully guide the robot finishing the operation regardless of the mandible position.[41]

ROOT CANAL TREATMENT AND PLAQUE REMOVAL

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 during root canal treatment. The so-called “vending machine” was supposed to supply the dentist with the necessary root canal instruments during treatment in order to reduce deflection from the operating site. 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. Furthermore, the authors discussed the use of these systems for other applications such as prevention of tooth decay or peri-implant infection.[42,43]

ORTHODONTICS AND JAW MOVEMENT

A novel system that generates the dental arch form has been developed. The system can be used to bend orthodontic wires.[44] Edinger described a robot for the dental office for the first time in 1991, later he described a robotic system to reproduce condylar movements.[45,46] Virtual articulators are one of the technological bases necessary to fully rethink and digitalize dental workflows. 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.[47]

X-RAY IMAGING RADIOGRAPHY

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.[48,49] 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.[50]

MATERIAL TESTING

Robotic dental wear and mastication simulators are proposed to test tooth filling materials[51] or dental implant materials.[52] One of the systems was driven by a robot with 6 dof robotic arm.[53] In another study dental impression materials were tested with the help of a robotic arm.[54]

TESTING OF TOOTHBRUSHES

The efficiency of toothbrushes and their abrasiveness towards enamel may be tested with highest repeatability and comparability by using robotic systems. For example, an in vitro study with a six-axis robot compared the efficiency of two different tooth brushes with clinical hand brushing and in vitro robotic brushing. Results showed that robotic brushing of teeth is an alternative for plaque removal studies and may even replace clinical studies.[55]

ROBOT ASSISTANT

The possibility of active robotic support during treatments by handling of instruments via a multi-modal communication framework that aims at dentists as users. It comprises of bilateral physical human–robot interaction, touch display input, speech input and visual gestures. In their approach they used a state of-the-art safe collaborative and sensitive 7dof robot and conducted a user-study to explore the feasibility of different human-robot interaction modalities in dentistry.[56]

ROBOTIC EDUCATION

The idea of a dental training robot was first described in 1969.[57] The application of a humanoid in dental education was tested in 2017. A humanoid, a full-body patient simulation system (SIMROID), was tested during a study among dental students to seek out whether a robotic patient was more realistic for the scholars to familiarize with real patients[58] than the usually used dummies. “Hanako”, the SIMROID is standing 165 cm tall. It comes with a metal skeleton and vinyl chloride-based gum pattern of skin. “Hanako” is a stimulating contribution to education in dentistry because the SIMROID is imitating a person's in its actions and expressions. It can verbally express pain, roll its eyes, blink, shake its head in pain, perform movements of jaw, tongue, elbow and wrist. Furthermore, it can even simulate a vomiting reflex with a uvula sensor, and also simulate functions to induce bleeding and saliva flow.[59]

Tanzawa et al. Introduced a medical emergency robot with the aim to assist dental students to urge conversant in emergency situations.[60] Another robotic educational equipment described within the literature is that the ROBOTUTOR. This tool was developed as an alternate to a clinician to demonstrate tooth-cleaning techniques to patients. It's a robotic device to coach and show brushing techniques. Additionally, a study investigated the training experience of pre-clinical dental students using 3D printed teeth designed with realistic pulp cavities and simulated caries decays.[61]

ROBOTICS IN PROSTHODONTICS

TOOTH ARRANGEMENT FOR COMPLETE DENTURES

The traditional way of complete denture manufacturing is manual, and therefore the key step of the procedure is to implant artificial teeth into a tooth pad in their correct positions and orientations. Only speciality dentists and skilled technicians can do that work well. This traditional approach is now replaced with the utilization of robots to manufacture denture systems. Complete dentures vary considerably in tooth size, the relative position and orientation of every tooth, and therefore the shape of the teeth arch curve. The advantage of a robot is

Fig.4:
Robotic arm of the typical CRS robot system

its operational flexibility, and may be adapted for handling the manufacture of complete dentures.[62,63]

CRS Robotics Corporation (Figure 4), Canada, produced one manipulator robotic system with 6 dofs. This technique was then adapted for the manufacture of complete dentures. The most components of the system[64] are: (1) CRS robot, (2) electromagnetic gripper, (3) a computer, (4) a central system with tooth-arrangement and robot control software for tooth-arrangement, motion planning and control, (5) denture base, (6) light device, and (7) light-sensitive glue.

The three-dimensional virtual tooth-arrangement software of the robotic system helps to make medical record files of a patient, draw a jaw arch and dental arch curves by expert's experience consistent with the jaw arch parameters of the patient, and adjust the dental arch curve. It then displays the three-dimensional virtual dentitions on the screen, provide a virtual observation environment for designed dentitions, and interactively modify each tooth posture. The calibration of the tooth arrangement, initial positioning of the robot, creating control data for tooth arrangement and therefore the overall control of the robot is done by the robot control software. The utmost loads this robot system can handle is 3 Kg, the utmost line velocity is 4.35 m/s, and therefore the repeated positioning accuracy is ±0.05 mm. This technique was then adapted for the manufacture of an entire denture system for patients. The system relies on the utilization of a special light sensitive material that hardens under lighting. During this system, a robot grasps selected standard teeth and implants them in fixed positions. However, it had been found that the system had difficulty in grasping and manipulating the synthetic teeth accurately. This led to the event of more improved robotic systems with more number of dofs.[65]

Further research led to the planning of a complicated 84 DOF system with 14 independent tooth manipulators on the dental arch curve. So as to regulate the tooth's position on the dental arch, the manipulators were designed to maneuverer along its tail in both directions. There was a tooth arrangement helper within the system with 6 dofs (three rotations and three movements) to regulate the tooth for its position along X, Y, Z, lingual, rotation and near-far-medium directions. This robotic system is in a position to understand any posture within the artificial teeth space, and solved many problems of the only robotic system. But one major disadvantage of this technique is that it's driven by [84] independent motors and hence difficult to regulate it which reduced the efficiency. A way 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.[66] Dental arch generator creates the dental arch curve and matches with the one from the patient's mouth. The slipway mechanism is employed to regulate the dental arch generator. As within the 84 DOF robotic system, the 14 independent manipulators are ready to move along its own tail to regulate for every tooth's rotation. Each of those manipulators had 3 dofs (two rotations and one movement) to regulate each tooth for its position along Z, lingual and near-far-medium directions. The extra 3 dofs for adjusting the tooth within the X, Y and rotation are achieved by two parallel and rotatable vertical bars placed under every single manipulator. This type of adjustment helped to decrease the amount of motors required to drive the system to 50, thus increasing the efficiency of the system. Compared to previous generation systems, this 50 DOF tooth arrangement robotic system is straightforward and straightforward to regulate and takes only half-hour for the manufacture of an entire denture. The repeated positioning accuracy of the system is ± 0.07 mm for single manipulator and ±0.1 mm for the entire robotic system. Though there are tremendous progress in improving the efficiency of the entire denture manufacturing robotic system, the procedure still remains mostly a manual operation. The high cost and lack of operational knowledge of the system are the most hindrance for the wide spread use of the system.[67]

TOOTH PREPARATION

Preparation of a tooth for crowns and bridges is a routine task for the dentist, although even after years of practical experience it is still challenging. The challenge is to reduce the tooth sufficiently to create space for the prosthetic rehabilitation with a minimum of damage to sound tooth structure. The idea of a robotic arm used for tooth preparation or preparation support for the dentist seems tempting and sensible. A mechatronic system to support the dentist in drilling has been tested in vitro and showed good results, however, it has not yet been validated in a clinical setting. The dentist 's position accuracy was 53% better with the mechatronic system than without it.[68] Yuan et al. Described a robotic tooth preparation system[69] with the following hardware components: (1) an intraoral 3D scanner 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 dof robot 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. Moreover, other tooth preparation devices were tested for their accuracy. 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.[70,71] Another tooth preparation system for veneers with a rotating diamond instrument mounted on a robotic arm was compared to human hand crown preparation & showed better results than the tooth preparation carried out by the dentist.[73]

DENTAL IMPLANTOLOGY ROBOT

Applications of computer assisted preoperative procedures like CAD/CAM are followed in dental implantology for long. But the utilization of robots for the surgery is comparatively new. Applications of robots for the implant surgery was a search theme in many of the research and medical centres over the recent period. They're considered as a breakthrough in utilizing the applications of computer assisted pre- surgical getting to the usage of robots within the surgical phase.[74]

The general features of those systems were a robotic arm with drilling tools, a knowledge acquisition board, strain gauges for stress/strain evaluation, and a force/torque sensor (equipped with accelerometers) placed on the robot wrist.[13] This technique can realize drilling and implant insertion. The robot is programmed to perform the implant drilling operation with the assistance of a dental drilling tool and also to use pressure on the assembled implants to simulate the mastication process. The system software consists of robot calibration module, drill plan module, load plan module, drill execution module, and acquisition data module. The optimal number of implants and their placement/orientation is studied through the implant force, and therefore the stress/strain analysis of jaw bone tissue with the various drilling posture.

Fig. 5
Yomi dental implantology robotic system

The first commercially available and state of the art robotic system for dental implantology, named as Yomi (Figure 5) was developed by Neocis Inc, USA and approved by FDA in 2017 (U.S. Food and Drug Administration, 2017). Yomi may be a computerized system intended to supply assistance in both the design (pre-operative) and therefore the surgical (intra-operative) phases of dental implantation surgery. The system provides software to preoperatively plan dental implantation procedures and provides navigational guidance of the surgical instruments. Yomi delivers physical guidance through the utilization of haptic robotic technology, which constrains the hammer in position, orientation, and depth. This assistive technology leaves the surgeon on top of things in the least times. Unlike plastic surgical guides, Yomi allows for clear visualization of the surgical site and enables the surgeon to dynamically change the plan.[75]

ADVANTAGES AND DISADVANTAGES

Dental robots have several advantages and disadvantages. They are:

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.

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.

CONCLUSION

Dentistry is moving forward towards a new era of data-driven and robot-assisted medicine. Robotic assistance in prosthodontic applications will remain an intensively discussed topic in the coming years. Tremendous progress has been achieved in the utilizing the positive aspects of robotics for various applications of dentistry. In prosthodontics, incorporation of robots is mainly in the design and manufacture of complete dentures, tooth preparation & in implantology. Use of sophisticated and specially made robots helps to improve the accuracy and precision of various prosthodontic treatments under the supervision of an expert dentist. But the human interventions cannot be completely ruled out. There's no substitute for expert skill and clinical judgment.

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