Robotics Application in Dentistry: A Review

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***Abstract*—Digital dentistry and afterwards intelligent dentistry have been considered a trend in the development of both dental research and clinical practice. Robotics enhances precision and efficiency in medicine. In particular, robotics in dentistry is revolutionizing patient care with advanced technological integration, minimally invasive procedures, and improved outcomes and patient experiences. This review presents an in-depth concept of robots in digital dentistry, highlighting major contributions and impact in clinical scenarios. We first present the motivation behind dental robots and then will discuss the limitations and gaps between the research and applications of dental robots in different fields of dentistry. These robots are clinically involved in oral and maxillofacial surgery, dental implants, prosthodontics, orthognathic surgery, endodontics, and dental education treatments. The literature suggest that these robots are efficient, making quick decision, and maximize the benefit of digital dentistry. It fully automate the surgical procedure for diagnostic and treatment system. By integrating Artificial Intelligence (AI) to these robots eliminates the clinical decision making approach for predictive analysis for early detection and prevention. Finally, the key technologies and potential developments in robotics across various fields of dentistry were demonstrated. It is also discussed carefully how aspects such as mechanical design, recognition sensors, manipulation planning, and state monitoring can significantly influence the future impact of dental robots. These components play a crucial role in enhancing the functionality and efficiency of dental robotics, paving the way for advanced dental care. This review paper will enable researchers to gain better understanding of current status, challenges and future directions of dental robots.**

Manuscript received 14 January 2024; revised 22 March 2024; accepted 12 April 2024. Date of publication 3 June 2024; date of current version 5 August 2024. This article was recommended for publication by Associate Editor T. Haidegger and Editor P. Dario upon evaluation of the reviewers' comments. This work was supported in part by the National Natural Science Foundation of China under Grant U2013205 and Grant 62073309; in part by the Guangdong Basic and Applied Basic Research Foundation under Grant 2022B1515020042; and in part by the Shenzhen Science and Technology Program under Grant JCYJ20210324115606018. *(Corresponding authors: Zeyang Xia; Jing Xiong.)*

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Digital Object Identifier 10.1109/TMRB.2024.3408321

***Index Terms*—Medical robotics, dental robot, dentistry, precision dentistry.**

I. Introduction

MEDICINE has revolutionized the healthcare industry by combining cutting-edge technologies, such as remote sensing, image processing, automation and artificial intelligence (AI), to assist healthcare professionals in various medical fields. These state-of-the-art technologies, combined with sensors and precision instruments to fabricate medical robots, influence surgical procedures, rehabilitation processes, diagnostics, and patient care. With their ability to enhance accuracy, improve efficiency, and provide remote assistance, medical robots are crucial in improving patient outcomes and transforming healthcare delivery. With the development of advanced technology, the potential for medical robots to revolutionize healthcare and expand their applications is seemingly limitless [1]. Typically, there are three types of medical robots: (a) surgical robots, one of which is famous as Da Vinci systems, (b) medical assistant robots which are widely used in guiding, disinfection, diagnosis, drug dispensing, nursing, and delivery, (c) artificial body parts robots which are used to fabricate prostheses, mechanical organs or other implants. These varied medical robots are famous for general surgery and are able to be used in dentistry areas. And the application of medical robots in surgical and healthcare industries are shown in Fig. 1 [2], [3], [4], [5], [6], [7], [8]. According to the World Health Organization, oral diseases affect nearly 3.5 billion people worldwide. Furthermore, oral treatment is expensive and needs access to primary oral health services in most countries due to the unequal distribution of oral health professionals and a lack of health facilities [9]. Moreover, the substantial patient demand coupled with persistently low dentist-patient ratios underscores the urgent need to mitigate dental care challenges and ensure equitable access to comprehensive oral healthcare services.

Conventional clinical dentistry generally relies on manual procedure, which is highly laborious, costly and in accurate. For instance, in clinical orthodontics, all the procedures start by following a traditional treatment plan by discussing the necessary plan with the patient: (a) fill an impression tray with an alginate material and place it in the patient's mouth to produce a mold of teeth. After that, a patient usually needs to wait several days for the next visit; (b) a plaster cast is built based on previously collected mold; (c) the teeth can be separated, rearranged, and implanted using the paraffin wax to produce a mold of teeth. After that, a patient usually

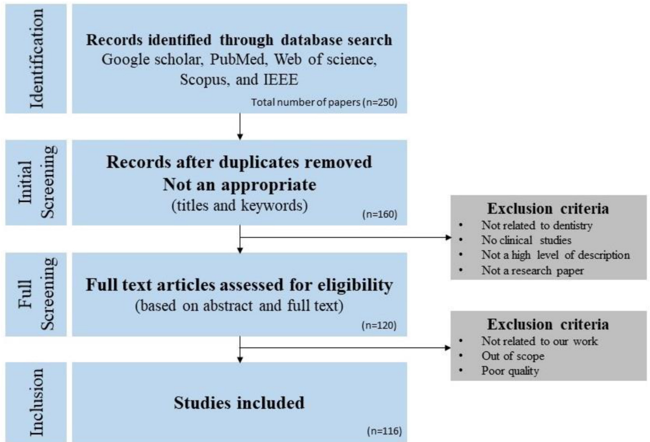

Fig. 1. PRISMA flow chart showing inclusion and exclusion criteria used for the search.

needs to wait several days for the next visit; (b) a plaster cast is built based on previously collected mold; (c) the teeth can be separated, rearranged, and implanted using the paraffin wax to generate a new plaster cast model; From (b) and (c), in conventional practical uses, plaster molds used in dental surgery are not match the patient's teeth very precisely which may cause inaccurate operation compared to automation solutions. (d) design a customized appliance; (e) make it using orthodontic pliers. From steps (b-e) are done in a clinical operation room. Finally, the treatment coordinator can arrange a new appointment: (f) to place a metal ring; (g) brackets for orthodontic treatment; (h) load the first designed appliance into the bracket slots. In total, the patient requires a regular visit for at least the next two years (i, j) to adjust wires to ensure that the repositioning of teeth continues throughout the process for at least two years [10]. Above all, there are a large amount of manual works, and the cost of time and money is very high. In recent years, computer-aided-based methods [11], [12] have been proposed to automate dental procedures. However, manual surgical procedures remain the fundamental task, which is an emergency problem need to be solved.

Advancing sustainable robotics necessitates a comprehensive multidisciplinary strategy to grasp the complex interrelation of sustainability, technology, and societal issues [13]. The robotic-based solution initially originated from science fiction-based literature for medical procedure [14]. In order to reduce labor cost and time waste in dental surgery, robots in dental secretaries map the societal drivers to research motivations. Therefore, researchers and practitioners are trying to develop different dental robots called "Dentrobots." The first step towards incorporating robotics in dentistry was taken in the 1980s. Researchers began exploring the uses of robotic systems for tasks such as cavity preparation, tooth polishing, and orthodontic bracket placement. These early robotic systems were primarily experimental practices and lacked the sophistication and widespread adoption seen today. It is briefly categorized that these robots based on dentrobots as dentist robots, nurse robots and dental patient robots. They perform two types of tasks which are chairside treatments and preoperative or postoperative operations. The main difference between these two tasks is whether the robots make contact with patients. These interdisciplinary fields integrate all engineering aspects, such as design, construction, manipulation, control of dentrobots and advanced diagnostic techniques, for instance, AI, image processing, and deep learning [9]. The ultimate goal of dentrobots is to provide patients with accurate and timely diagnosis, effective treatment and improved outcomes, more specifically, to alleviate the current imbalance of the dentist-patient ratio, reduce labor intensity, and optimize the limited medical resources [2]. Recently, there have been a few surveys [3], [4], [5], which either concentrate on reporting the general progress of the filed or application in one specific dentistry department. However, very few of them aim at identifying challenges and presenting potential research directions by analyzing the key technologies of dentrobots.

In this review, a literature review is demonstrated the development of the state-of-the-art dentrobots based on different types of robotics applications in dentistry at each sub-dental field. After that, the challenges and key technologies from an aspect of robot development are addressed in this review. Finally, the preliminary observations are summarized and comments on the future research tendency between cutting-edge robotic technologies and clinical applications are demonstrated. Fig. 1 presents an array of medical robots, each tailored for specific healthcare applications, demonstrating the diverse roles robotics play in modern medicine. It highlights how these sophisticated robots are deployed for surgeries, rehabilitation, diagnostics, and patient care.

We performed the protocols established by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [15] guidelines as shown in Fig. 1.

Robot-assisted dental treatment papers published up to, 2023 were searched on Google Scholar, PubMed, Web of Science, Scopous, and IEEE Xplorer. The purpose of this search was to map the overall research activity in which the robot plays a role in dentistry. The above search was iterated upon using narrower searches in different field of dentistry. These narrower searches were also used to test whether the results were consistent with our goal of including potentially impactful papers. The union of all the results from the different searches engines total set of included papers 110.

II. Application of Robotics in Different Field of Dentistry Dental Fields

Dental robots are an emerging technological advancement in dentistry, designed to enhance precision, consistency and efficiency in various procedures from assisting in surgical procedures like dental implants to applying orthodontic and prosthodontics appliances fabricated by Computer Numerical Control (CNC) machines and addictive manufacturing equipment (3D printers), these robots aim to reduce personal error and expedite treatments. While they promise transformative potential, challenges such as high costs, the need for

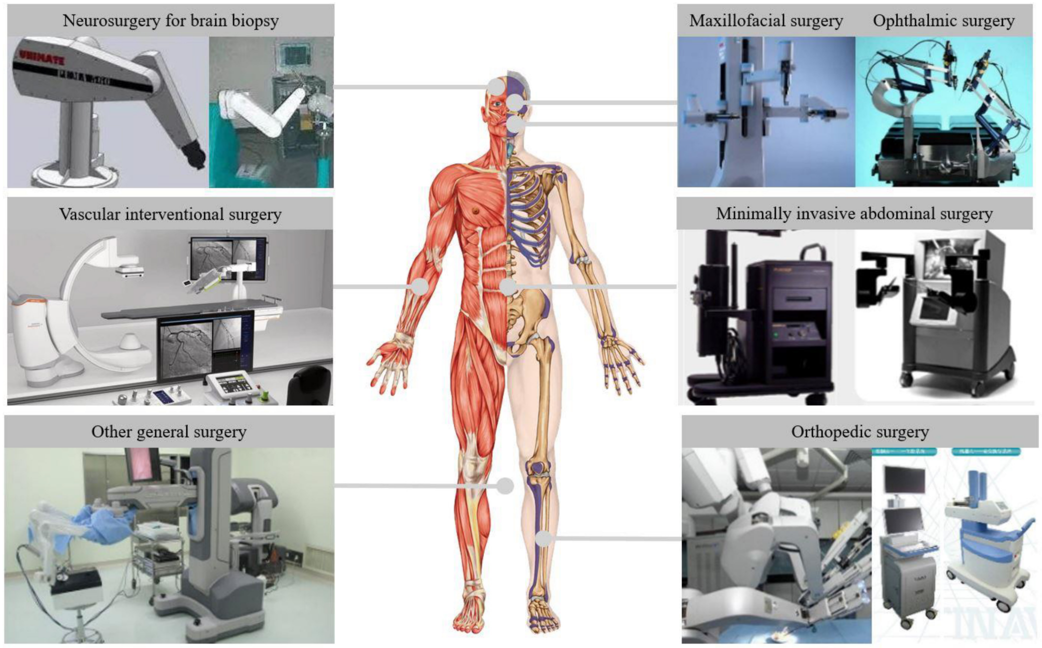

Fig. 2. Robotics application in general medical and healthcare fields, including neurosurgery for brain biopsy [2], vascular interventional surgery [3], orthopedic surgery [4], maxillofacial surgery [5], ophthalmic surgery [6], minimally invasive abdominal surgery [7], and other general surgery [8].

specialized training, technical reliability and patient acceptance can impact their widespread adoption in dental practices.

In this review, the unified artificial division and the dental health care setting in China is used as a standard. For instance, the stomatological hospital consists of different departments, including oral surgery, oral medicine, prosthodontics, and orthodontics. These departments have sub-departments, which include oral and maxillofacial surgery and dental implantology. Similarly, endodontics and periodontics are different from the oral medicine. Since the clinical cases and treatment operations vary from department to department and require different robotic systems. Fig. 2 shows robots used in different field of dentistry [6], [7], [8], [16], [17], [18], [19], [20], [21], [22], [23] which are discussed in Sections II-A–II-F carefully.

A. Application of Robotics in Oral and Maxillofacial Surgery

Oral and maxillofacial surgical robots concentrate on surgical treatment that deals with injuries and defects involving the face, mouth and jaws to restore normal function or aesthetic appearance [25]. Typical oral and maxillofacial surgeries include oral cancer resection, facial injury treatment, trauma surgery, corrective jaw surgery, and facial cosmetic surgery [26], [27], [28], [29]. Typically, there are two types of studies: resection of neoplasms and cranio- maxillofacial surgery.

Head and neck cancers are a group of neoplasms that develop in or around the throat, larynx, nose, sinuses, and mouth, constituting the sixth most common malignancy worldwide [30]. Clinically, treatment for head and neck cancer may involve surgery, radiation therapy, chemotherapy, targeted therapy, immunotherapy or a combination of these modalities [31]. With the development of robotics technologies, robots play an important role in head and neck cancers surgery, particularly during radiation therapy or when utilizing dental robots as the primary treatment method to remove cancerous tumors from healthy tissue [32]. Compared to robotic surgery treatment, conventional minimally invasive approaches have certain physical limitations, primarily due to limited visualization of vital structures and a restricted range of effective instrumentation [20]. In contrast, transoral robotic surgery (TORS), conducted through the mouth and throat, offers surgeons an enhanced view and the ability to operate in tight spaces with deeper access, all without the need for large open incision [33]. This approach can result in quicker recovery times and fewer complications which cannot be realized by conventional approaches.

The first study of a robotic system in maxillofacial surgery was reported in 2003 [34] for the resection of the submandibular gland in animals. McLeod and Melder [35] reported the first Da Vinci surgical system for laryngeal surgery in 2009 for its applications in TORS. Several studies on various neoplasm cases were subsequently reported, such as the resection of base of tongue neoplasm resection [36], radical tonsillectomy [37], malignant melanoma [38], and pleomorphic adenoma [39]. Duan et al. [40] developed acranio maxillofacial surgical robot system to achieve precise positioning of the puncture needle for an automated surgical procedure. They proposed a master-slave control system and a hybrid automatic motion control-based navigation system to enhance needle positioning accuracy. Zhang et al. [41] designed a single-arm stapling robot for oral and maxillofacial surgery, utilizing magnesium alloy staples to efficiently perform stapling operation.

Compared to neoplasm resection surgeries that involve the removal of soft tissues, cranio-maxillofacial (CMF) surgeries addresses surgical and therapeutic interventions for congenital and acquired conditions affecting the head, face and jaws,

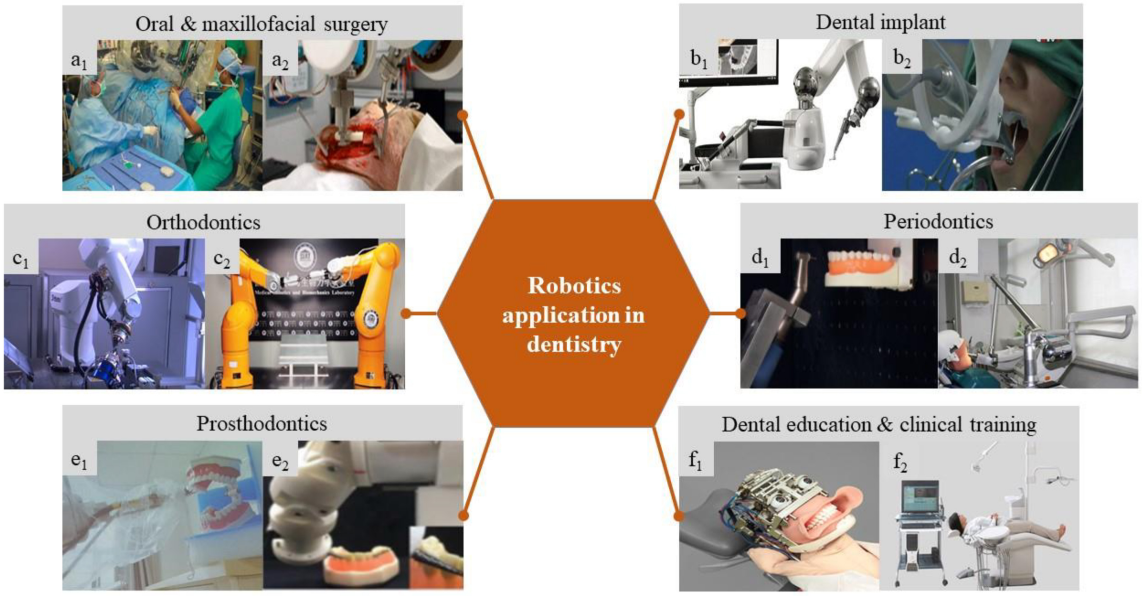

Fig. 3. Applications of robots in different field of dentistry: (a) oral & maxillofacial surgery: (a1) radical tonsillectomy [6], (a2) mandible reconstruction [7]. (b) dental implant: (b1) Yomi robot, guided dental implantation systems [8], (b2) autonomous dental implant robot [17]. (c) orthodontic: (c1) SureSmile wire bending robot [18], (c2) dual-arm wire bending robot [19]. (d) periodontics: (d1) tooth preparation systems for PLV [20], (d2) full crown tooth preparation [21]. (e) prosthodontics: (e1) teeth cleaning [22], (e2) automatic teeth cleaning [23]. (f) dental education & clinical training: (f1) dentaroid [16], (f2) simroid [24].

and also involve soft tissues, such as reconstructive surgery following tumor resection [42]. CMF surgery, also known as orthognathic surgery [43], is designed for orthodontic surgical procedures, such as the removal of impacted or displaced teeth. Advanced methods come up to correct or reshape physical deformities of the jaw and lower face that may result from congenital deformities or accidental injuries for improving the performance of CMF surgery [44]. Typically, the mandibular reconstruction includes mandible resection, implant placement and bone graft application as an example of CMF surgery. Since the movement of the jaw is three-dimensional (3D), the success of CMF surgery relies not only on accurate deformity diagnosis, skeleton modeling, and pre-surgical planning but also on precise surgical operations. However, conventional surgery is usually performed manually by surgeons and can take more than 8 hours. Currently, due to the lack of accurate methods, the preoperative treatment plan cannot be effectively implemented. In recent years, with the rapid development of computer-aided technologies, methods for image-based diagnosis [45], virtual surgical planning [46], and intraoperative guidance [47] have been introduced to enhance the physical abilities of surgeons, thereby the positioning accuracy and repeatability features of surgical robots.

An integrated drilling system for the planning and execution of CMF surgery. A surgical delta-kinematics robot system for maxillofacial surgery was developed in 1998 [48]. Burghart et al. [49] developed a computer-aided method using a 6-degree of freedom (DoF) surgical robot (RX-90) to control the surgeon's cutting movements. Model surgery was performed with the aid of a passive robot arm, which significantly enhanced the accuracy of anteroposterior and vertical directions compared to manual model surgery [50]. Chen et al. [51] reported on a theoretical system that used a 6-DoF industrial arm and an optical tracking navigation system to perform bone cutting and drilling operations for orthognathic surgery. Kong et al. [52] designed a three-arm surgical robot to perform bone graft placement under optical navigation guidance for mandibular reconstruction. Ma et al. [53] proposed an autonomous surgical robot that automatically performs surgery according to a preoperative plan with the assistance of a surgeon. The robot adopted a parallel mechanism to control the 3-DoF linear movement and a remote center of motion mechanism to control the 3-DoF rotational movement. Iijima et al. [54] proposed a master-slave dentistry and oral surgery-assisting robot. By implementing acceleration-based bilateral control, haptic information can be communicated. To prioritize safety in surgical procedures, it is of paramount importance to prevent any direct physical engagement between surgical instruments and essential vessels or nerves. Zhou et al. [55] developed an advanced robotic system underpinned by augmented reality. This innovative system aims to augment accuracy and ensure the safety of bone drilling procedures, as shown in Fig. 3, specifically in the context of mandibular angle split osteotomy. The utility of this system underscores the potential of technology in enhancing surgical precision and patient safety. Xu et al. [56] proposed a master-slave CMF surgical robot system based on force feedback. Woo et al. [57] reported their work on improving and evaluating the maxillary repositioning accuracy for a 6-DoF image-guided robot system in orthognathic surgery.

B. Application of Robotics in Dental Implant

Dental implant surgery is a procedure that plants a special designed screw like implant into the jawbone or skull to physically support a dental prosthesis or act as an anchor [58].

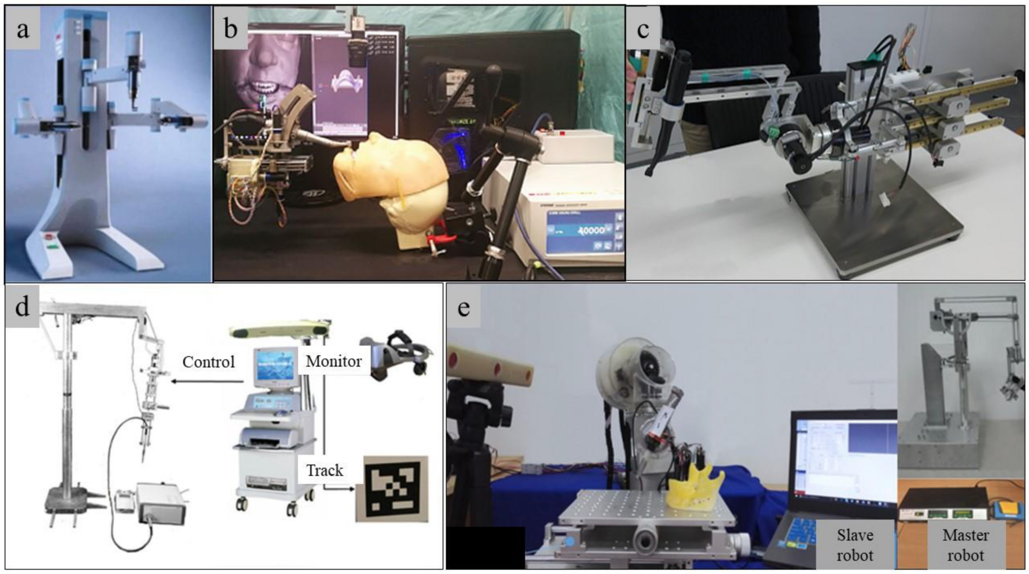

Fig. 4. Drilling robot systems for CMF surgeries: (a) three-arm robot [51], (b) remote center of motion mechanism [53], (c) master-slave surgical robot [53], (d) augmented reality-based robotic system [54], (e) master-slave surgical robot [56].

The most common case in dental implantology is to replace damaged or missing tooth with an artificial tooth that can look and function as are alone as shown in Fig. 4(a). The standard dental implant surgery involves several procedures, but compared to the previous surgeries mentioned in the current review, it is usually an outpatient surgery. To plant the artificial teeth into the jawbone, damaged tooth removal and healing and implant placement and bone growth, in which the patient gum is cut to expose the jawbone for drilling, are required as shown in Fig. 4(b). Then a dental implant will be placed inside the hole, and after that, patient waits several months for bone growth and healing. The following step is abutment placement and gum healing, where the gum is cut and reopened to expose the implant for abutment attaching. Finally, artificial crown placement is conducted. Among these procedures, the accuracy of implant hole drilling is the most important factor influencing the effect of dental implant treatment. In the current clinical scenario, surgeons try to reduce the errors by using a template guidance to control the drilling position, orientation and depth, however, the results are often constrained due to the limited operation space and angle of view. Also, due to the high temperature generated by drilling that can damage bone cells permanently. The solution is usually to flush the tooth implant site during the drilling process, which makes it more difficult for surgeons to sense the exact states of drilling [59].

Robotic dental implant surgery offers significant benefits, including sustained precision and stability, which are crucial for intricate procedures. The system's inherent capability for accurate state sensing and perception throughout the operation provides surgeons with real-time feedback, thereby enhancing the accuracy and safety of the implantation process. Additionally, the simplification and repeatability afforded by robotic assistance ensure that complex surgeries can be performed with consistency and efficiency. Boesecke et al. [60] proposed a theoretical studies of robot assisted dental implant, in which a robot system was designed to hold a drilling template and guide the operation of surgeon according to the preoperative planning, as from Fig. 4(c). Goulette et al. [61] proposed a 5-DoF robot that can drill a jaw splint from preoperative planning results, as shown in Fig. 4(d). However, the two applications utilized robots just for assistance and their drilling operations were still performed by surgeons. Chiarelli et al. [62], designed a 5-DoF robot to reproduce planned milling vectors for the common implants, as from Fig. 4(e). Sun et al. [63], implement the 6-DoF robot that was used for natural-root-formation during implants with single or double roots, as shown in Fig. 4(f).

In 2017, a robotic system named Yomi received the a premarket submission from Food and Drug Administration (FDA) 510(k) in USA, clearance for both the preoperative and intraoperative guidance for dental implant procedures [64], as shown in Fig. 4(g). During the same period, an autonomous dental implant robotic system was reported [65], which could actively adjust to the slight movement of patient in intraoperative procedures and execute implant surgery without guidance control from a surgeon, as shown in Fig. 4(h). Introducing AI to these robots enhancing precision, personalizing treatments, and increase success rates [66], [67].

C. Application of Robotics in Prosthodontics

Robotics in prosthodontics is revolutionizing the field by introducing advanced precision and efficiency in the creation and fitting of dental prosthetics. Through the use of computer-aided design and manufacturing (CAD/CAM) technology, robotics assists in the design and manufacturing process, enabling the production of customized dental restorations with exceptional fit and function. Prosthodontics, the dental specialty pertaining to the design, manufacture, and fitting of artificial replacements for teeth and other parts of the mouth, has achieved significant advancements with the integration of

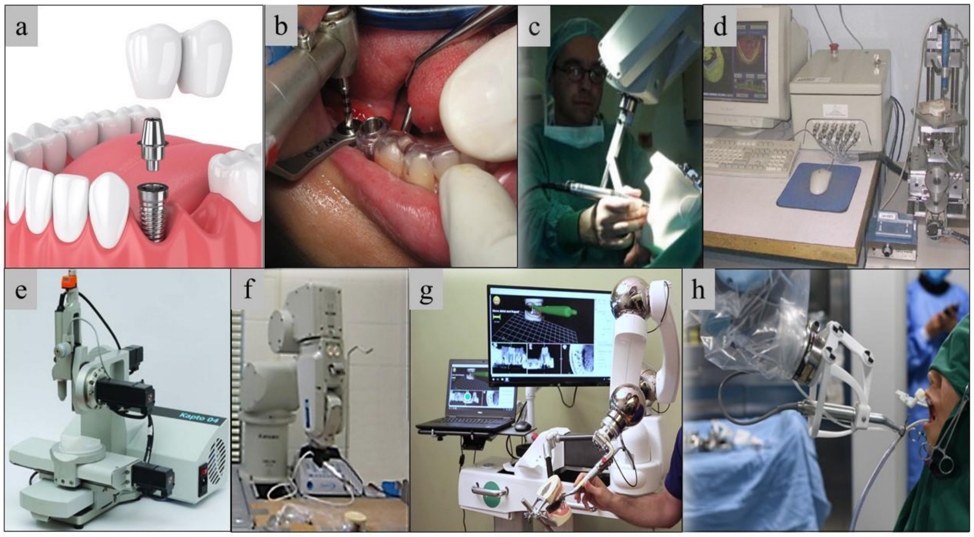

Fig. 5. Traditional robot systems for dental implant: (a) artificial implant component, (b) procedure for drilling a screw-access hole in the patient jawbone, (c) robot-assisted by holding a drill template [60], (d) 5-DoF robot system for splint drilling [61], (e) 5-DoF robot system for positioning titanium guides [62], (f) 6-DoF robot with dental drill-bit for milling of natural-root-formed implants [63], (g) Yomi robotic system for guidance of dental implant procedures [64], (h) autonomous dental implant robotic system [65].

robotics. AI significantly enhances prosthodontics by enabling automated diagnostics, predictive analytics, and classification tools [68].

Dental restoration is a clinical procedure to restore integrity and inherent function of damaged teeth from caries or external trauma using specific materials in order to keep natural tissues [69]. The significant difference from a dental implant is that the teeth to be restored generally have available roots. Usually restoring a tooth requires two steps, including the tooth preparation and materials placement, where the process of preparation involves drilling or grinding the tooth with a rotary dental hand-piece or laser to remove the dental decay or portions [70]. Moreover, the restoration is fabricated, inside or outside of the patient's mouth, the restorative techniques can be classified into two types, the direct and indirect restorations. After the tooth preparation, the direct technique involves placing photo curable resin into the prepared holes and setting it hard using light to restore the natural tooth shape [71], while in the indirect technique, finished restoration such as a porcelain laminate veneer (PLV). Finally, the bone is permanently prepared for tooth using dental cement.

In these two types of dental restoration, tooth preparation is a key operation referring to removing the hard tooth tissue and forming an expected tooth shape [71]. Currently, the inaccurate manual grind operated by a dentist using the turbine-driven drill may generate micro cracks in enamel due to the mechanical and thermal stress, resulting in further new carious. The latest laser ablation is considered to reduce this drawback, but the manual manipulation pattern still limited the treatment accuracy due to the natural hand trembling and lack of real-time feedback.

Ma et al. [72] developed two miniature laser manipulation robotic end-effectors. Three miniature voice-coil motors with optical grating rulers are utilized to drive the 2D pitch/yaw rotation of a vibration mirror and 1D translation of a protruding optical lens, as shown in Fig. 5 (a) and (b). Another study utilized 2-DoF scanning system consists of a vibrating mirror X and a vibrating mirror Y [73]. After that, the developed robot control uses ultrashort pulse laser system. Finally, the charge-coupled device (CCD) on camera is integrated with the scanning system [21], [74]. Currently, a robotic arm is used to position the whole laser robotic end-effectors [75]. Otani et al. [20] proposed a robotic tooth preparation system for porcelain laminate veneers. The accuracy and precision at the finish line is better than the conventional freehand tooth preparation. Jiang et al. [76] developed a robot-assisted tooth preparation system based on the Dobot Magician robot.

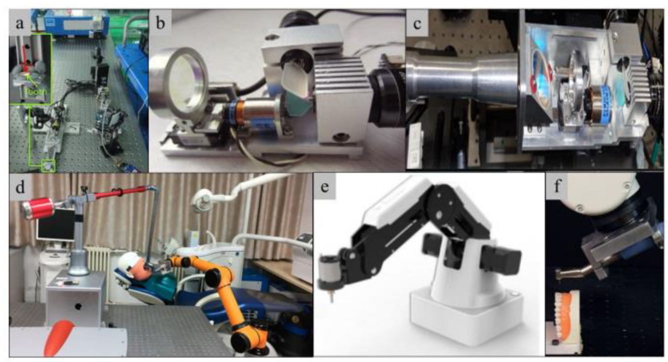

Fig. 6. Teeth preparation robots: (a) laser type I [71], (b) laser type II [72], (c) laser type III [73], (d) laser type IV [74], (e) tooth preparation [76], (f) typodont [20].

Denture robotic systems used for the creation, adjustment, and fitting of dentures. These robotic systems can be designed to automate, which can improve the precision of denture and assist in the fitting, adjustment of dentures for patients and other tasks related to prosthetic dentistry. This technology

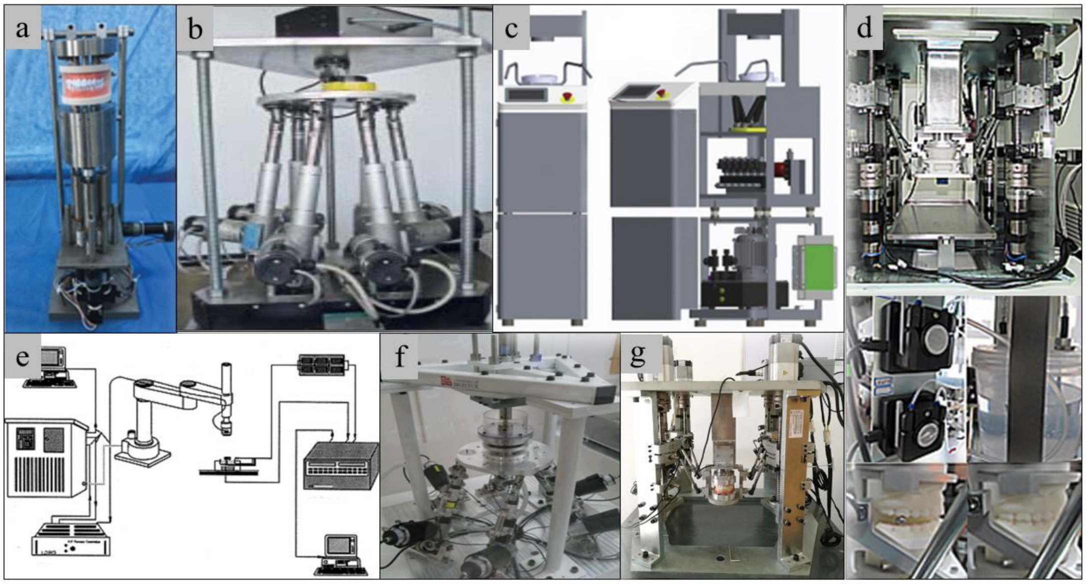

Fig. 7. Denture testing robots. (a) 5-DoF IDR [78], (b) Conserva et al. [79], (c) Tahir et al. [81] , (d) DUT-2 [83] , (e) measurement system for mastication force [86], (f) Waseda-Yamanashi [87], (g) redundantly actuated parallel manipulator (RAPM) prototype [88].

aims to enhance accuracy, efficiency, and patient outcomes in dental prosthetics. The performance of the denture, such as the fracture strength, and success rate is evaluated after being design and fabricated the denture robot. The in-vitro evaluation method is an important evaluation method, which integrated with the finite element (FE) and clinical methods, respectively. Traditional denture testing device consist of 1-DoF universal testing machine, and 2-DoF chewing simulator. The loading movement is constrained in a plane. However, these devices could not simulate the 3D realistic mandibular motion, and the lack of sufficient DoFs enables them only to replicate the sliding motion of a single occlusal contact point by neglecting rotational movements and the motion along one Cartesian axis.

Wang et al. [77] proposed a 4-DoF robotic system for testing dental implant. The simulated mandibular movements and occlusal contact forces are designs and process through testing and evaluation. Ren et al. [78] developed a commercially serial intelligent dental robot for the artificial denture verification and testing in order to drive five Maxon motors to provide the driving force for the intelligent dental robots (IDR). Conserva et al. [79] designed a six-axis parallel dental robot for dental materials testing on a sensor-equipped with implant setup. A sensor- equipped setup is placed on the moving platform of the robot used for mandible and records the degree of force being transmitted through the 3 axes. Raabe et al. [80] proposed a six-axis wear chewing robot integrating hybrid control of biological feature that combined the force/position in dental material testing. Tahir et al. [81] developed a robotic mastication simulator for interactive load testing of dental implants and the mandible. The six-axis robotic chewing simulator suppling six-axis chewing motion, high occlusal force and saliva environment [82]. Similarly, the bionic robotic mechanism combines with six parallel driving chain and two point-contact higher pair, mimicking the biting muscles and temporal-mandibular joints [83]. These innovative robotic systems for dental implant testing offer unique features like multi-degree-of-freedom movement, occlusal force simulation, and advanced control mechanisms to mimic human jaw movements and conditions for accurate dental material evaluation. The denture fabrication process typically involves with an initial consultation, where a dentist assesses the patient's oral health and takes detailed dental impressions using special materials. This is followed by bite registration to ensure proper jaw alignment. Then wax models are created from these impressions for trial fittings, allowing for adjustments in fit, color, and shape. Once the wax model is approved, the final denture is crafted using materials like acrylic or resin, often in a dental lab. The final product is then fitted in the patient's mouth, with any necessary adjustments made for comfort and functionality. Follow-up visits may be scheduled to ensure a perfect fit and to provide care instructions for the new dentures. This process may vary slightly depending on the specific type of dentures robots used. Meanwhile, the use of auxiliary design and manufacturing technologies such as CAD/CAM and addictive manufacturing has also improved the precision and efficiency of denture fabrication.

Denture fabrication process of different prosthesis type is different. The most common part is the robotic fabrication of the complete removable denture. The traditional technique is to acquiring the dental arch curve form of the complete denture is based on manual operation, which will randomly bring numerous errors caused by human factors. The key technology of the tooth arrangement robot is how to grasp and position the teeth.

A serial robotic system automatically implanted artificial teeth of the complete denture [80]. However, it is difficult to grasp a tooth accurately using ordinary grippers due to the complicated tooth shapes. Zhang et al. [84] proposed a robotic tooth arrangement method using conjugate tooth-caps instead of teeth to be grasped by the robot. The most successful teeth arrangement robot is the small multi-manipulator type with the

Fig. 8. Tooth arrangement robots (a) serial robot with normal grasper [89], (b) serial robot with tooth-caps [84], (c) multi-manipulators [90].

tooth-caps [85], each tooth is directly connected with a 3-DoF manipulator. The teeth arch is bended by four controlling bars and derived by 2-DoF system. The corresponding teeth arch curve and the positions of the teeth is designed using CAD system.

Teeth cleaning robots represent a novel advancement in dental hygiene technology, designed to automate and enhance the effectiveness of oral cleaning. These robotic systems utilize advanced tools like 3D imaging, AI algorithms and sensitive sensors to accurately map and clean the mouth, targeting unattainable areas with precision. They offer consistent, efficient cleaning, potentially surpassing manual techniques, and are particularly beneficial for individuals with limited manual dexterity. Their ability to efficiently and thoroughly clean all areas of the teeth, including hard-to-reach spots, enhances overall dental health. Particularly beneficial for individuals with limited dexterity, these robots ensure efficient plaque and tartar removal, which is crucial for preventing dental diseases. Additionally, the potential for customization allows for tailored dental care, catering to specific oral health needs. This innovative approach to teeth cleaning represents a leap forward in ensuring effective and accessible dental hygiene. While still in development and not widely available, these robots hold promise for transforming dental care routines by integrating cleaning with oral health monitoring, appealing to both individual users and professional dental practices for their potential to streamline dental hygiene and improve oral health outcomes. Dental teeth cleaning is a procedure cleaning the odontolith and dental plaque attached on the tooth surface. The procedure includes cleaning step using ultrasonic teeth cleaner and polishing step, which can increase the cleaning performance.

Yuan et al. [21] designed another type of teeth cleaning robot known as automatic toothbrush. The robot removes the dental plaque which is planted in the mouthpiece, and powered by small motors which moves in an up-down, side- to-side direction along with the teeth. Villa et al. [91] designed a chemical micro-robot as self-propelled micro-brushes against dental biofilm. Such micro-robots use low concentrations of fuel for their propulsion, and they achieve an efficient dental biofilm disruption within 5 min of treatment. Moreover, these micro-robots are biocompatible with epidermal and organ cells and may stimulate the immune system to fight against microbial infection. Ajani and Assal [92] combined the cooperative robot and automatic toothbrush as a teleoperation robot. The end-effector of the robot is assembled with the ultrasonic teeth cleaner. The camera and the force sensor are integrated to record the intra-oral environment and the contact force.

D. Application of Robotics in Orthodontics

Robotics in orthodontics is a relatively new and evolving field that integrates robotic systems into orthodontic diagnosis, treatment planning and procedures. Robotic technologies can enhance precision in tooth movements, create more efficient and effective treatment plans, and even assist in customizing orthodontic appliances. Robotics can also contribute to automating certain orthodontic laboratory processes like bending wires for braces. The application of robotics in orthodontics aims to improve patient outcomes, reduce treatment times, and potentially decrease the overall cost of orthodontic care. As the application of robotic orthodontic is an emerging area, ongoing research and development are expanding its potential applications within orthodontic practice. These robots play a crucial role in customizing brace fittings and automating wire bending, ensuring each adjustment is meticulously tailored to individual patient needs. Advanced 3D imaging with AI capabilities integrated with these robotic systems aid in detailed treatment planning, allowing for more personalized and effective orthodontic strategies [93].

Orthodontic archwire preparation is a procedure that bends a standard archwire to form different curves and loops to generate desired loading units on the tooth. The manual bending performance relies on the dentist's experience, which can lead to time wasting and inaccuracy. The archwire-bending robot can overcome these issues due to its high and stable operational accuracy. According to the robot mechanism feature, the bending robots can be divided into two categories, including Cartesian bending robots and articulated robots.

Fischer-Brandies et al. [94] proposed a Cartesian bending robots based on traditional bending machine. Bending art system (BAS) is the earliest research report on automatic bending of archwire [100]. This system makes it possible to make personalized bending of archwire. The bending head consists of an outer bending cone and a guiding cone. Relative movement of the bending cone achieves bending. Jin-gang et al. [95] proposed a Cartesian bending robots with 5-DoF to improve the flexibility. Hamid and Ito [96] design a 3-DoF bending robot integrating computer numerical control (CNC) wire bending technology into dental archwire, offering a novel CAD/CAM-based workflow with an automated program for converting coordinates into bending parameters. Gilbert [97] design Lingual archwire manufacturing and design aid (LAMDA) robot, a gantry-like robot, working only on the X- and Y-axes to overcome the challenges caused by irregular lingual anatomy and manual bending difficulties. The articulated bending robots are closed to the industrial robot. SureSmile bending robot was first developed by OraMetrix company to commercialize the product [96]. The robot system has a joint bending robot and a fixing device, and have two grippers to assist the bending of the fix archwire. Jin-gang et al. [95], and Xia et al. [19] proposed a similar single-arm robot, but the main difference lie in the design of the gripper.

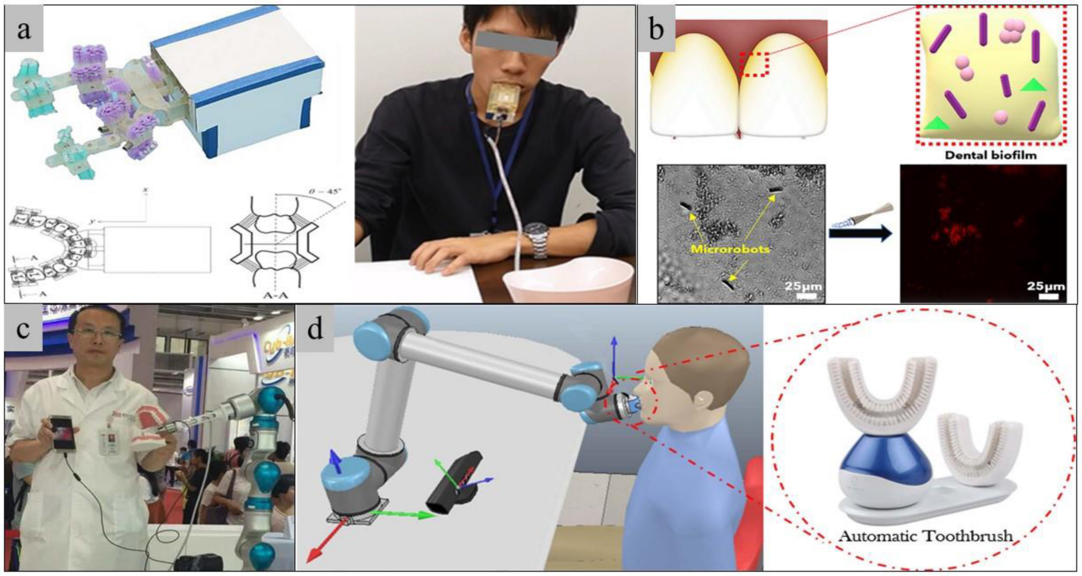

Fig. 9. Dental teeth cleaning robots. (a) automatic toothbrush [21], (b) chemical micro-robots [91], (c) cooperative robots (d) robotic system setup for tooth brushing [92].

E. Application in Endodontics

Robotics in endodontics involves the integration of advanced robotic systems to enhance precision and efficacy in root canal treatments. These robotic technologies can assist endodontists in canal preparation, cleaning, and filling, with greater accuracy and consistency compared to conventional methods. Robotics may also offer improved navigation within the intricate canal system of teeth, potentially leading to better treatment outcomes and patient satisfaction. This field is still in the early stages, with ongoing research focused on developing and refining robotic endodontic systems.

Dong et al. [99], [101] proposed two design concept for a Cartesian robot mainly on the row of teeth in which the tooth undergoing treatment is located. The robot has 5-DoFs, for instance, X-axis translational and rotational motion are controlled by two rods. The independent control of each rod would control the rotational degree of tilt needed to angle the end effector towards the tooth canal opening, similarly, Y-axis motion is the same. The Z-axis would be controlled by a rack-and-pinion design that would raise and lower the end effector into the tooth cavity. There is another rotational motion provided for the spindle, which is more compact. A quick tool change mechanism is added to change the tool. Sample tools need to be changed include bur for opening the crown, file for shaping the root canal, filling needle for filling materials into the root canal, and probes used to sense the inner situation of the root canal. This tool vending machine combining automation and cleaning processes, proposed by Nelson et al. [102], which is not only useful for saving space in the treatment room but also enhancing the overall efficiency of dental surgery. In addition, advancements in simulation and measurement systems assisted with robots have significantly enhanced the application of dental robots in scientific researches. The robots consist of sensors; a maxillary model and a control system can simulate orthodontic tooth movement and measure the dynamic course of forces and moments, proposed by Dotzer et al. [103].

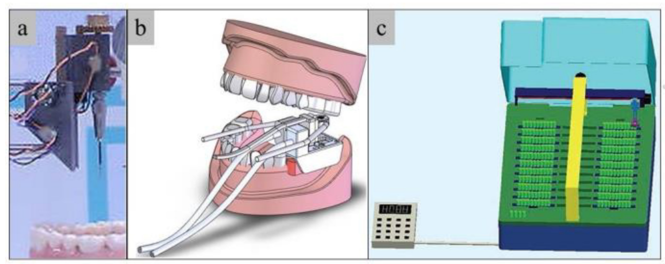

Fig. 10. Endodontic micro-robot: (a) first version micro-robot [99], (b) second version micro-robot [101], (c) model of the canal vending machine [102].

F. Dental Education and Clinical Training Robots

Robots in dental education and clinical training are used to simulate real-life scenarios for students, providing practical experience without the risk to patient life. These robots can mimic various dental conditions, offering a consistent training platform and enabling students to practice procedures, develop their skills, and gain confidence in a controlled environment. They are becoming increasingly important in dental curricula as they can help bridge the gap between theoretical knowledge and practical proficiency. Dental education is related to almost every dental field. It could assist to improve the therapy quality by enhancing the dentist's technology. Traditional device has simple head model, which is not able to simulate the real clinical environment, proper communication, autonomously movement and effective feedback. The major difference between the real-time and simulation environment lead to the limited training effectiveness of the treatment ability.

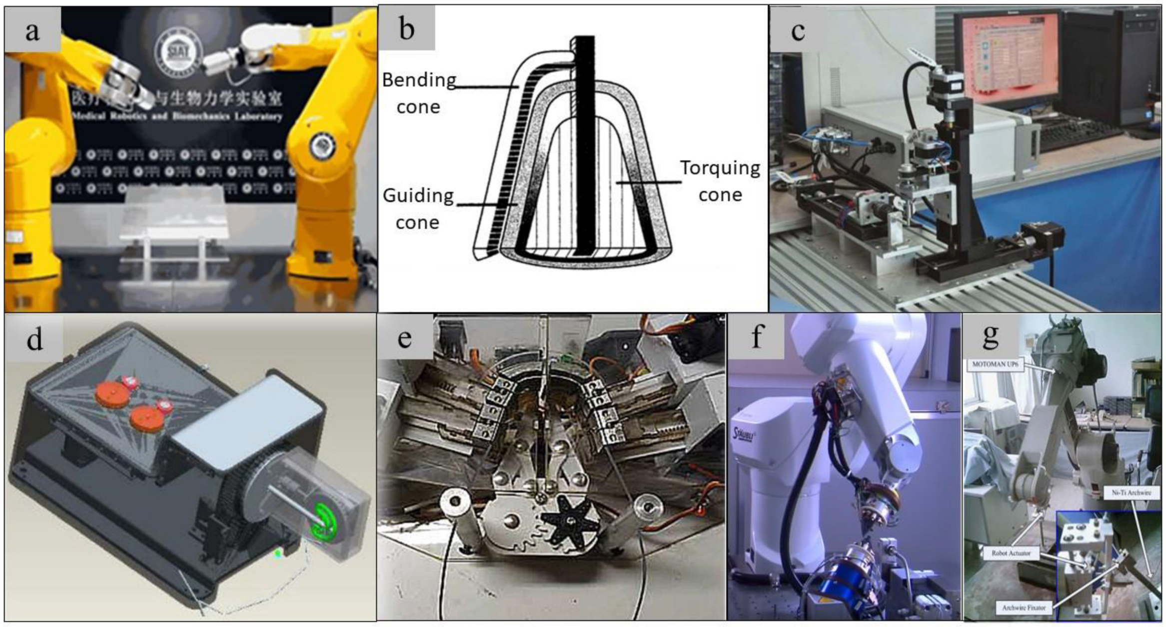

Fig. 11. Cartesian bending robots. (a) multi-arm robot [19], (b) BAS [94], (c) 5-DoF bending system [95], (d) 3-DoF bending system [96], (e) LAMDA [97], (f) SureSmile [98], (g) single-arm robot [99].

Takanobu et al. [107] was the first to develop the dental patient robot. The patient robot was designed for dental therapy training using humanoid robotic technology. A dental patient simulator, developed by Nissin, knows over 20 patterns of automatic dialogues, equipped with about 10 different reaction movements, and have an easy to use control panel [108]. A dental patient simulator, DENTAROID, is developed by tmsuk Inc. [109]. Featuring voice recognition robot which can open its mouth according to the doctor's instructions, changing the direction of its face, and perform actions such as unexpected movements, such as coughing. It can also realistically reproduce complex actions, such as jaw closing and vomiting reflex. The robot patient is useful in dental education for medical emergency training and assessment not only for situation management but also for differential diagnosis [24].

Table I presents a detailed overview of robotic applications in various dental specializations, underscoring significant technological advancements and their clinical implications. In oral and maxillofacial surgery, robotic systems like transoral and cranio-facial surgery robots offer minimally invasive, and aid in complex surgical planning, thus enhancing patient outcomes. Dental implant procedures have been revolutionized by CT-guided and 3D planning systems, leading to more precise implant placements. Prosthodontics has seen advancements with robotic end- effectors and mastication simulators, improving accuracy in tooth preparation and understanding material stresses in dental prosthetics. In orthodontics, innovations such as the archwire bending art system and CNC wire bending robots have refined the process of orthodontic wire manipulation, offering greater precision. Endodontics has benefitted from the development of micro robots for root canal treatments, presenting less invasive and more efficient methodologies. These advancements across various dental fields illustrate the transformation of robotics in dentistry by enhancing both the accuracy and efficacy of dental treatments and paving the way for more innovative and patient-centric dental care practices

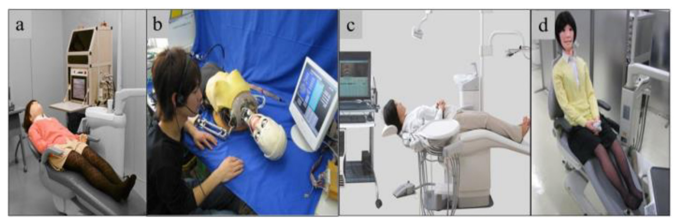

Fig. 12. Dental education robots: (a) DENTAROID by Nissin Inc. [108], (b) Takanobu et al. [110], (c) DENTAROID by Tmsuk Inc. [109], (d) SIMROID by Morita Inc. [111].

III. Key Technologies of Dental Robots

Dental robotics research is a multidisciplinary endeavor that encompasses the precise. In summary, the common technologies mainly include 1) mechanical construction and modular integration of robotic systems, cutting-edge control techniques, 2) advanced recognition and sensory capabilities for environmental interaction, 3) sophisticated manipulation strategies for procedure-specific tasks, and 4) comprehensive monitoring systems for real-time status assessment and responsive error correction during dental procedures. The comprehensive overview of dental robotics systems is shown in Fig. 12 including components and functionalities for enhanced clinical practice. Sections III-A–III-D discuss the key technologies of dental robots carefully.

A. *Mechanical Design and Modular Integration*

Mechanical design and modular integration in dental robots involve designing a physical structure that allows for precise

TABLE I
ROBOTICS IN DIFFERENT FIELD OF DENTISTRY

Field	Robotics system	Findings	Reference
Oral and maxillofacial surgery	Head and neck surgery	Robotic surgery reduces invasion, complications, and enhances patient outcomes.	[27], [29]–[31]
	Transoral robotic surgery	Minimally invasive approaches in robotic surgery in otolaryngology evolves, influenced by technology, safety, and cost.	[11], [33]
	Cranio-facial surgery	System aids surgeons in preoperative planning and intraoperative execution management.	[49]
	Robot Assisted Maxillofacial Surgery	A planner, infrared navigation, and surgical robot system for bone work.	[26],[39],[42],[46], [51],[102],[103]
	Drilling of 3D-printed mandible	Practical solution to decrease the human-related factors on the OMS.	[105]
	Robot for craniomaxillofacial tumor treatment.	CyberKnife radiosurgery and S-1 chemotherapy effectively treated.	[49], [56]
Dental implant	CT guided precise implant placement	CT-guided dental robot-based implant surgery enhances patient outcomes.	[58]
	3D plan for dental implant inserting	Surgical robot efficiency hinges on referencing, software optimization, and practicality.	[60]
	3D approach for oral implant planning	Correct position, orientation and depth of the planned implants are easily computed and transferred to the surgical phase	[62]
	Image-guided dental implantation robot	Phantom experiments confirm feasibility and accuracy of dental implantation robots.	[63]
Prosthodontics	Miniature robotic end-effector	The LaserBot strategy improves tooth preparation accuracy by stabilizing scanning speed	[72]
	3D tooth crown preparation	Improved robotic system to manipulate the laser beam to achieve safe and accurate 3D tooth ablation	[74]
	Robot-assisted trajectory planning for tooth preparation	Augmented reality enhances tooth preparation efficiency and accuracy, reducing manual strain.	[76]
	Mechanical chewing simulator to reproduce mandibular movements in 3D	Elastic moduli of materials affect stress at bone-implant interfaces during mastication.	[79]
	Robotic mastication simulator	The system facilitated the teeth-replacement procedure involving 6 degrees of freedom, enabling any translation and rotation in sagittal, horizontal, and vertical planes.	[81]
Orthodontic	Arcwire bending art system	The bent pieces of wire were analyzed in a 3D-coordinate gauging system.	[94]
	Springback mechanism model for orthodontic archwire	Springback mechanism model of the orthodontic archwire is analyzed and compensated based on the characteristics of the robot structure.	[95]
	CNC wire bending robot	The feasibility shown through bend planning, coordinate extraction, and B-code generation.	[96]
	Lingual archwire system	LAMDA system have the ability to move an end effector (the device or tool at the end of a robotic arm) in multiple planes of space with great precision, though with limited degrees of freedom.	[97]
	Orthodontic wires bend robot	The dichotomy is adopted to search the ratio of chord length to arc length and the area surrounded by the chord and arc of adjacent key points	[106]
Endodontics	Mechanical design of robot for endodontic root canal treatment	Endodontic micro robot is less invasive method using automated access and canal preparation during endodontic therapy.	[99]
	Micro robot for root canal shaping and cleaning	Intelligent micro robot system will overcome the problems encountered in current treatment practice and increase the treatment accuracy and efficiency.	[101]
	Vending robot for root canal treatment	The design of the vending robot takes into account both the requirements of dentists and the product's entire life cycle.	[102]
	Human-patient robotic system	Dental therapy training as one of the practical applications of the humanoid robot technology.	[107]

movements and interactions within the confined space of the oral cavity, and the modular integration allows for flexibility in the robot's functions, enabling it to perform a variety of dental procedures with different tools or end- effectors that can be swapped out or reconfigured as needed. This approach to design and integration is crucial for the adaptability and effectiveness of dental robots in clinical settings.

Dental robots feature an advanced manipulator configuration that provides precise and flexible movement, optimized for the complexities of oral surgeries and procedures. The manipulator design typically includes multi-DoF robotic arms and end-effectors, such as specialized dental tools or imaging devices that mimic the dexterity of a human hand [112]. The configuration leverages haptic feedback and 3D vision technology to ensure the accuracy of robot movements, adjusting to the patient's anatomy with real-time feedback. Coupled with artificial intelligence algorithms, this configuration allows the dental robot to execute intricate tasks, such as, implant placement or tooth drilling, with high precision, thereby reducing human error and enhancing patient safety.

End-effectors for dental robots are intricately designed to mimic the dexterity and precision of a dentist's hand, ensuring they can perform complex tasks within the confined space of a patient's oral cavity with high precision. These

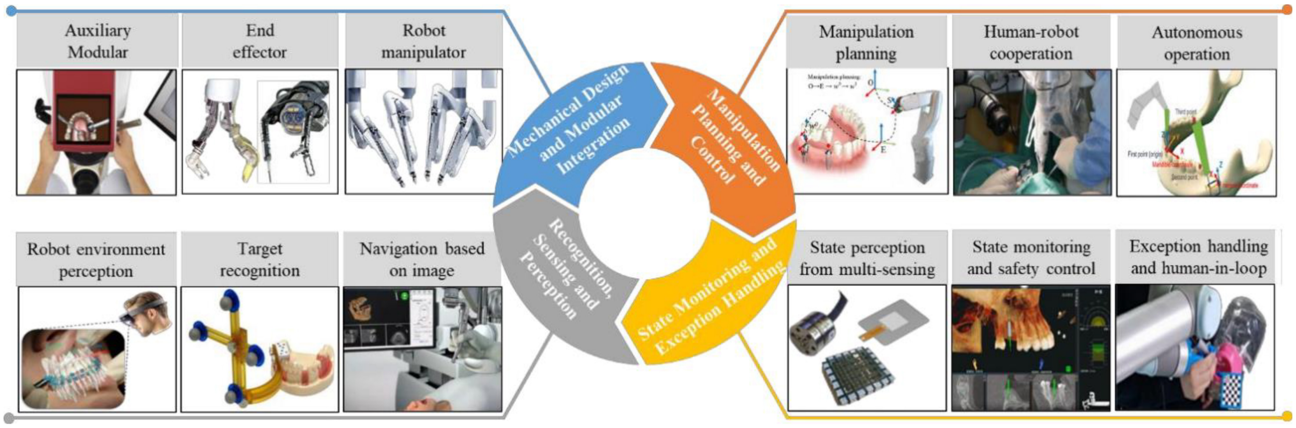

Fig. 13. Comprehensive overview of integrated dental robotic systems: components and functionalities for enhanced clinical practice.

end-effectors could be specialized dental tools, such as drills or implant placement devices, designed for specific procedures like cavity preparation or implant surgery. Some designs incorporate advanced sensor technologies to provide real-time feedback, enabling the robot to adjust its operations according to the patient's unique anatomy [112] and to carry out complex procedures with greater accuracy and consistency in automated or semi-automated robotic systems. Additionally, some designs might use haptic or force-feedback systems, allowing the dentist to remotely control the robot with a sense of touch. Incorporating machine-learning algorithms and imaging technology, these end- effectors can perform tasks autonomously or semi-autonomously, while maintaining a high level of precision and minimizing human error.

Auxiliary modular integration in dental robots refers to the addition of complementary units or modules that enhance the functionality and efficiency of the robot in the dental care setting. These modules can include advanced imaging systems, such as intraoral scanners and 3D imaging units, which facilitate accurate diagnosis and precise procedural planning. Other modules might include sterilization units for tools, material handling systems for dental prosthetics, and patient monitoring systems that track vital signs during procedures. The integration of these modules helps create a cohesive, streamlined workflow, where tasks from diagnosis to treatment execution can be performed seamlessly. Moreover, the modular design allows for easy updates and customizations, adapting to the evolving needs of dental practices and the advancements in dental technology.

B. Recognition, Sensing and Perception

Recognition, sensing, and perception in dental robots involve the integration of advanced technologies to enable the robot to interpret and interact with its environment effectively. The dental robot includes the use of sensors, cameras and other imaging tools to capture detailed visual and physical data within the oral cavity. Through further processing of these data, the dental robot is able to recognize various structures such as teeth, gums and dental tools. Therefore, these sensory inputs are the fundamental and crucial information for the robot to make informed decisions, navigate complex spaces, and perform precise dental procedures.

For the dental robot, the purpose of image-based navigation is to display the deviation between the current position and the planned path to guide the dentist's operation and expand the visual range to ensure the success rate of oral surgeries, reduce the risk of possible iatrogenic complications. The navigation system includes the localization and tracking system, computerized image processing and control monitoring system. The medical image data used for navigation include X-rays, computed tomography (CT) and magnetic resonance imaging (MRI). In the process of image-based navigation, it is crucial to perform image segmentation, image enhancement and other processing based on the characteristics of this image in order to extract the region of interest (RoI) and perform the trajectory planning of dental robot and real-time status update according to the purpose of diagnosis and treatment. Furthermore, 3D model navigation techniques based on the reconstruction of these 2D images can intuitively visualize the 3D anatomical structure of the RoI. These technologies assist dentist to overcome these issues, such as distortion, noise and artifacts in 2D images. When compared to mechanical and electromagnetic localization and tracking methods, optical localization and tracking technique is more commonly used in maxillofacial oral surgery due to its higher accuracy [113].

Target recognition and localization in dental robots involve advanced algorithms and sensory systems to accurately identify and pinpoint specific areas for treatment within the complex structure of the oral cavity. Utilizing a combination of 3D imaging and machine vision, these robots can differentiate between various dental tissues and structures, such as teeth, gums and cavities. The precise localization of the targets is critical for performing intricate dental procedures, based on the precise localization information, the position and attitude of the dental robot and the dentist and robot could confirm patient, which in turn assists the dentist in making appropriate surgical decisions and the robot in surgical process sensing and trajectory planning. This technology relies heavily on data processing and real-time feedback, integrating information from multiple sensors to guide the robot's movements with exceptional accuracy. In dentistry, robot environment perception is pivotal for precise and safe operations, which involves the use of advanced sensors and imaging technologies, such as 3D scanners, intraoral cameras and haptic feedback systems. These tools allow the robot to accurately map the oral cavity's unique topography, identifying structures like teeth, gums and nerves with high precision. Combined with sophisticated algorithms, the robot interprets this data to understand spatial relationships and movement constraints within the mouth. The real-time environmental perception is crucial for the robot to adapt its actions dynamically, ensuring effective and minimally invasive dental treatments. Visual information perception technology, utilizing camera devices, enhances a dentist's ability to observe dental conditions intuitively and clearly. This technology facilitates more effective interaction between the dentist, the dental robot and surgical instruments, ensuring precise engagement with oral tissues and the patient. The integration of visual technology into dental robotics not only aids in diagnosis but also improves the accuracy and efficiency of treatments. In addition, virtual reality (VR) and augmented reality (AR) technology can superimpose virtual images onto the objective world [113], which is increasingly used in visual guidance of dental surgery. The tactile information is mainly obtained through the sensor force information, and then feedback to the operator, so that the dentist can obtain accurate and clear tactile feelings, ensure the tactile presence of the medical robot and improve the practicality of the medical robot.

C. Manipulation Planning and Control

Manipulation planning and control within the context of dental robotics involve the creation of state-of-the-art algorithms that enable a robot to execute precise movements required for dental procedures. This computational process involves the formulation of a movement strategy, taking the constraints imposed by the oral anatomy and the desired outcome of the procedure into account. Control systems then implement these plans through real-time adjustments, which can maintain accuracy regardless of dynamic oral conditions. The control system requires a high level of coordination between sensory inputs and actuator outputs, ensuring that manipulative actions such as drilling, filling, or scanning are carried out with minimal error and optimal results. The integration of these elements is critical for the successful application of robotics in dentistry, where the margin for error is exceedingly small. In addition, manipulation planning and control in dental operation are challenging due to the complex and narrow space in mouth. At the same time, the collaborative relationship between doctors-patient robots also makes the operating environment dynamic.

Manipulation and planning in dentistry refer to the strategic movements and procedural steps that dentists or the dental robots undertake to perform treatments. The manipulation and planning involve careful consideration of the patient's oral anatomy, the goals of the treatment and the sequence of actions which are needed to achieve these goals effectively. In the context of robotics, the manipulation planning would translate into programming the dental robot to perform complex tasks, such as preparing a cavity or placing an implant, with precision and care, ensuring the safety and comfort of the patient while optimizing the treatment outcomes.

Considering the unique constraints of the semi-enclosed oral cavity, it is crucial to ensures the end-effector follows an optimal manipulation planning in dental robotics, ensuring that the robotic arm moves precisely to achieve the desired posture for surgical procedures without causing harm. Furthermore, the emergence of soft robots, with their flexible material properties, has revolutionized this domain. The soft robots can navigate the confined spaces of the mouth more safely, adjusting their posture without risking damage to the patient's oral cavity. Consequently, the development and application of manipulation planning technologies in soft robotics hold significant potential and promise for enhancing dental treatments.

In contemporary dental practice, human-robot cooperation epitomizes an advanced interdisciplinary approach, integrating the dexterity and cognitive capabilities of human practitioners with the precision and repeatability of robotic systems. This collaborative model is instrumental in executing intricate dental procedures, where the robotic mechanism complements human skill with its ability to perform micro-movements and maintain unwavering accuracy. The dentist, leveraging this technological adjunct, can refine surgical interventions, enhancing both the accuracy and predictability of clinical outcomes. This amalgamation not only optimizes procedural efficiency but also minimizes human error.

In the realm of dental treatments, human-robot cooperation must be safety, accuracy, and reliability, and leveraging the strengths of both entities. In the process, efficient communication channels are essential, enabling robots to interpret human commands through methods like master-slave systems, hand gestures, speech, and gaze. Additionally, advanced collision detection ensures safety and security [114]. Critical to this synergy is the technology facilitating human-robot information transfer, ensuring that robots accurately interpret and execute human intentions. The human operator retains control throughout, aided by sensors providing real-time feedback on the robot's environmental interactions, thus enhancing system performance and ensuring robust safety measures.

In dentistry, the autonomous operation from perception is rapidly gaining traction, signifying a leap forward in dental robotic systems capabilities. These technological advantages intricate sensor arrays and state-of-the-art imaging techniques to meticulously map the oral cavity, enabling the robotic systems to independently execute a variety of dental procedures, which include intricate tasks like precise drilling and accurate filling, predicated on the system's real-time analysis and interpretation of the dental environment. This paradigm shift towards autonomous dental robotics not only exemplifies the intersection of technology and healthcare but also promises enhanced precision, reduced manual intervention, and potentially superior patient outcomes, contingent upon the reliability and accuracy of the underlying algorithms and sensory inputs. The process of autonomous operation involves integrating sensory data about the robot's position, patient's position, end-effector force, and working environment to generate appropriate motion trajectories for autonomous operation [115]. Real-time updates and corrections of this information, guided by control strategies, are crucial to prevent injuries from unintended movements. Additionally, incorporating voice reminders and other interactive modules enhances patient engagement, sets robust safety controls, and ensures the smooth execution of dental surgeries.

D. State Monitoring and Exception Handling

State monitoring and exception handling in dental robots involve continuously tracking the robot's operational status and responding appropriately to any irregularities or deviations from the expected performance. State monitoring ensures the robot is functioning correctly, adhering to predefined parameters, and safely interacting with the patient. Exception handling refers to the robot's ability to detect and manage unexpected situations or errors, such as deviations in movement or unforeseen obstacles, which is crucial for maintaining patient safety and ensuring the effectiveness of dental procedures. It is essential that these technologies work in automating complex dental tasks and provide both reliability and efficiency.

Advancements in sensor technology and artificial intelligence have significantly enhanced the autonomy of dental robots [116]. The robots rely on sensory data for external perception, implementing sophisticated multi-sensor information processing strategies to safely and effectively perform dental tasks. In dental robotics, visual sensors are fundamental for environment recognition and facilitating human-robot interaction, while tactile sensors play a vital role in external environment engagement. The deployment of multi-sensor systems, combined with multi-source information fusion strategies, allows for the alignment and integration of diverse data sources. This process amplifies the reliability and stability of the perceptual information and minimizes interference, providing accurate data essential for trajectory planning and ensuring the successful execution of dental procedures.

In the domain of dental robotics, safety is paramount, and therefore a comprehensive safety control program encompassing both the robot's functionality and its interaction with the patient is necessitated throughout the operation of the robot. State monitoring plays a critical role in this context, involving two key aspects: the real-time detection of the robot's sensor status to confirm its proper functioning and the vigilant monitoring of the patient's status. The second part includes tracking the position and posture of the robot's end effector during contact with human tissues, enabling the implementation of tailored control schemes to ensure the safety and reliability of the entire surgical process.

In the intricate and high-stakes realm of dental robotics, exception handling is pivotal for the safety and security of operations within the confined oral spaces [117]. Dental robots must be adept at detecting and addressing a spectrum of anomalies ranging from hardware malfunctions and sensor failures to communication breakdowns. Implementing stratified exception handling strategies, prioritized by their impact on critical tasks, is crucial. In addition, integrating human-in-the-loop interactions leveraging the dentist's expertise for exception assessment and response. This synergistic approach, particularly vital in invasive procedures like bone drilling, not only refines safety protocols but also aids in developing robust predictive models, ensuring the highest levels of operational safety.

IV. Conclusion

In conclusion, the manuscript has provided a thorough exploration of the role and advancements of robotics in various dental fields. The transformative impact of robotic technologies in enhancing the precision, efficiency, and outcomes of dental procedures is intensively highlight, from oral and maxillofacial surgery to dental implant, prosthodontics, orthodontics, and endodontics, and the integration of robotics has marked a significant leap in dental care.

The advancements in digitalization, AI, and AR have not amplified the role of robotics in dental procedures but have also opened door for more precise, efficient and personalized care. However, it is imperative to recognize the current limitations and challenges in the full-scale application of robotics in dentistry. Making dental robots fully independent is a difficult challenge because it requires advanced algorithms and safety measures. In addition, it is important to make these robots compatible with the current dental tools and systems, and they should be user friendly to dentists. Furthermore, it is discussed that the key technologies driving these advancements in 3D imaging, and minimally invasive tools, which collectively contribute to the evolution of dental robot practices. Additionally, it is also addressed that the challenges and potential future directions in dental robotics, emphasizing the importance of continued innovation and research in this field. The insights provided in this manuscript underscore the importance of robotics in modern dentistry and its potential to redefine dental care, making it more patient-centric, efficient, and effective. As dental robotics continue to evolve, they hold the promise of further enhancing the quality of care and patient experiences in digital dentistry.

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