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Review article

Clinical application of robots in dentistry: A scoping review

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Abstract

Purpose: The surge in digitalization and artificial intelligence has led to the wide application of robots in various fields, but their application in dentistry started relatively late. This scoping review aimed to comprehensively explore and map the current status of the clinical application of robots in dentistry.
Study selection: An iterative approach was used to gather as much evidence as possible from four online databases, including PubMed, the China National Knowledge Infrastructure, the Japan Science and Technology Information Aggregator, Electronic, and the Institute of Electrical and Electronics Engineers, from January 1980 to December 2022.
Results: A total of 113 eligible articles were selected from the search results, and it was found that most of the robots were developed and applied in the United States (n = 56; 50%). Robots were clinically applied in oral and maxillofacial surgery, oral implantology, prosthodontics, orthodontics, endodontics, and oral medicine. The development of robots in oral and maxillofacial surgery and oral implantology is relatively fast and comprehensive. About 51% (n = 58) of the systems had reached clinical application, while 49% (n = 55) were at the pre-clinical stage. Most of these are hard robots (90%; n = 103), and their invention and development were mainly focused on university research groups with long research periods and diverse components.
Conclusions: There are still limitations and gaps between research and application in dental robots. While robotics is threatening to replace clinical decision-making, combining it with dentistry to gain maximum benefit remains a challenge for the future.

Keywords: Dentistry, Robot, Clinical application, Scoping review

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1. Introduction

The term "robot" originates from the Slavic root "robot-", which means labor. The Czech writer Karel Čapek used the term to signify artificial human bodies without souls in his classic 1921 play Rossum's Universal Robots[1]. Along with other important discoveries and inventions, such as X-rays and quantum and relativity theories, the term "robot" became the cornerstone of the rise of modernism in the arts and sciences[2]. However, there is no unified definition of "robotics" in academic fields. People continue to endow it with more profound and broader meanings with the development of applications in various fields. In this review, we define robotics as a field of reprogrammable, multifunctional, multipurpose, and versatile systems intelligently linking sensing to action[3].

Generally, robots can be classified based on their level of autonomy into three categories: active, semi-active, and master-slave. They can also be classified based on the type of material into two categories: hard and soft. Active systems work autonomously and undertake pre-programmed tasks, while semi-active systems allow surgeons to provide guidance and assistance to these pre-programmed robotic systems, like telerobots. Master-slave systems lack pre-programming and depend entirely on the operations of surgeons. Examples of such systems are described later in the review[4]. In terms of material, traditional (i.e., hard) robots are made of rigid hard materials, while soft robots designed to imitate the biological system in nature are made of flexible soft materials, which allow for greater flexibility, adaptability, freedom, and stronger deformation ability. Their application in the medical field also makes the interaction between the robotic system and humans more secure[3].

While robots have been in the industry for several decades, their application in medicine only began in the 1990s. The first recorded medical application of a robot was in 1985 when it was used to place a needle for a brain biopsy under the guidance of computed tomography[5]. The first successful surgical robot to be applied clinically was developed in the United States[6]. Since robots are advantageous over humans in terms of accuracy, stability, safety, high dexterity, and reduction of doctors' fatigue, they have become widely used in many medical fields currently[7,8], especially in laparoscopic surgery in urology and cardiac surgery[9].

However, the application of robots in dentistry has been introduced much later compared to medicine. The introduction of new

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technologies such as digitalization and intellectualization in dentistry is critical to replacing manual operations and improving work efficiency. For example, with the increasing demand for dentures, there is a shortage of dental technicians, making the application of robots essential in prosthodontics[10]. While a few reviews on the applications of robots in dentistry have been published[11–13], to the best of our knowledge, there is no comprehensive review exploring and mapping the breadth, depth, and scope of the application of robots in dentistry. Therefore, this review aimed to identify the current status of the applications of robots in dentistry, reveal limitations and gaps, provide insights about future implementation and advancement, and explore ways to develop robotics more effectively.

2. Materials and Methods

Following a framework[14–16], we conducted a scoping review and prepared the report according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews[17].

2.1. Search strategy and article selection

We conducted a comprehensive literature search in four online databases such as PubMed, the China National Knowledge Infrastructure, the Japan Science and Technology Information Aggregator, Electronic, and the Institute of Electrical and Electronics Engineers from January 1980 to December 2022, using search terms like "robot," "robotics," "oral," "head and neck," "dental," "dentistry," and "stomatology," without limitations on language or article type (**Table S1**). Subsequently, additional articles were included through a manual search of relevant articles, web pages, and other sources.

We included articles on robots in the clinical treatment of dental diseases such as head and neck cancers, obstructive sleep apnea and hypopnea syndrome, dentition defects, and temporomandibular joint disorders. Reviews, articles that did not involve robots that were closely related to dentistry, such as dental education or basic research (e.g., chewing robots), articles that mentioned the same robot by the same authors or research team, or articles whose research purpose was not the robot itself, were excluded from the study.

2.2. Data charting

We retrieved data from the articles, including the year of publication, authors, dental specialty, name and country, development stage, function, company, type of material (hard or soft), level of autonomy, level of injection control, advantages, and limitations of robots. Additionally, we contacted the corresponding authors to clarify unclear data.

3. Results

The literature search identified 9,940 articles in the online databases, and 12 articles were added from references or other relevant articles. Finally, we included 113 articles in this review based on the article selection strategy (**Fig. S1 and Tables 1–4**). Of the 113 articles, 83% (n = 94) were published after 2009. The United States had the largest number of robots being researched and applied (n = 56; 49.6%), followed by China (n = 27; 23.9%), Japan (n = 12; 10.6%), and Germany (n = 7; 6.2%) (**Fig. 1**). Almost half of the articles were related to oral and maxillofacial surgery (OMS) (n = 62; 54.9%), followed by implantology (n = 12; 10.6%), orthodontics (n = 11; 9.7%), and prosthodontics (n = 6; 5.3%) (**Fig. 2**). Regarding the developmental stage, 51.3% (n = 58) of the systems had reached clinical application, and 48.7% (n = 55) were pre-clinical (research: n = 13, 11.5%; phantom experiment: n = 22; 19.5%; clinical validation: n = 20; 17.7%). By material properties, 9.7% (n = 11) are classified as soft robots; robots with the levels of autonomy of active, semi-active, and master-slave accounted for 37.2% (n = 42), 6.2% (n = 7), and 56.6% (n = 64), respectively; and 74.3% (n = 84) required the highest level of infection control sterilization.

3.1. OMS

The first active surgical robotic system in a clinical environment for maxillofacial surgery was presented in 1998[18]. Additionally, one of the earliest systems for robot-assisted maxillofacial surgery was developed in Germany in 1998, when Burghart *et al.*[19] introduced a complex expert system including a planner for generating treatment plans, infrared navigation for monitoring patients, robots and surgical tools, and a surgical robotic system to work on bones. Duan *et al.*[20] developed a cranio-maxillofacial-assisted surgical robotic system and detailed its preoperative planning, the mechanical configuration of the robot, and control and navigation systems. Ma *et al.*[21] proposed an autonomous surgical system to conduct OMS under the assistance and surveillance of surgeons. Recently, Zhang *et al.*[22] presented a novel single-arm stapling robot and introduced its mechanism and kinematics control.

In recent years, transoral robotic surgery has rapidly developed for head and neck surgery. It is defined as a robot-assisted surgery performed in the upper aerodigestive tract, accessed through the oral cavity. The most typical surgical system, which is the most widely used robotic surgical system in the world to date, accounts for more than half (56%) of the 62 studies we reviewed in the field of OMS. It is used only for soft tissue resection, and nearly half of them are used to remove head and neck cancers[23–43], with the rest used for gland resection[44–49], gland stone resection[50,51], tongue base resection for obstructive sleep apnea and hypopnea syndrome[52–55], and cleft lip and palate surgery[56,57]. Surgeons control the arm of the robotic surgical system to perform surgical operations such as cutting and suturing under three-dimensional (3D) vision. The first generation of this robotic surgical system was developed in 1999 and approved by the Food and Drug Administration (FDA) in July 2000 to operate general laparoscopic surgery, and its use was extended to head and neck surgery in 2005. Since then, it has led to the development of minimally invasive surgery in the 21st century. The second to fourth generations of this surgical system were developed successively from 2006 to 2018. As most patents on the technology expire in 2019, various surgical robots are expected to be developed. Furthermore, a single-port operator-controlled flexible endoscope adapted for minimally invasive transoral surgery of the oropharynx, hypopharynx, and larynx has been developed[58–60]. Fang *et al.*[61] proposed a magnetic resonance (MR)-safe soft robotic system for MR imaging-guided transoral laser microsurgery, which enables safe and dexterous operation under the electromagnetic interference of MR imaging.

Further, many other robot-assisted surgeries have been attempted in the various fields of OMS, especially for the treatment of head and neck cancers. Kawaguchi *et al.*[62] reported their experience using the CyberKnife system (Accuracy Inc., Sunnyvale, CA, USA) as a treatment option for an 88-year-old woman with synchronous cancer (oral squamous cell carcinoma and a malignant

Table 1. Robots in oral and maxillofacial surgery

Publication Year	1st Author	Country of robotics	Name of robotics or purpose	Development stage *	Hard/soft robot	Autonomy level **	Infection control level
Oral and Maxillofacial Surgery (OMFS)							
1998	Lueth TC[18]	Germany	OTTO	III	Hard	A	Sterilization
1998	Burghart CR [19]	Germany	a system for robot assisted maxillofacial surgery	I	Hard	C	Sterilization
2011	Duan XG[20]	China	a robot system for craniomaxillofacial surgery	III	Hard	C	Sterilization
2019	Ma Q[21]	Japan, China	an autonomous surgical system for OMFS	III	Hard	A	Sterilization
2022	Zhang JT[22]	China	a single-arm stapling robot for OMFS	II	Hard	C	Sterilization
Head and neck cancer							
2006	O'Malley BW Jr[23]	USA	da Vinci	IV	Hard	C	Sterilization
2009	Genden EM[24]	USA	da Vinci	IV	Hard	C	Sterilization
2011	Kim WS[25]	USA	da Vinci S	IV	Hard	C	Sterilization
2012	Borumandi F[26]	USA	da Vinci	IV	Hard	C	Sterilization
2012	De Virgilio A[27]	USA	da Vinci	IV	Hard	C	Sterilization
2012	Arshad H[28]	USA	da Vinci S	IV	Hard	C	Sterilization
2012	Shimizu A[29]	USA	da Vinci S	IV	Hard	C	Sterilization
2013	Kim CH[30]	USA	da Vinci	IV	Hard	C	Sterilization
2013	Bonawitz SC[31]	USA	da Vinci	IV	Hard	C	Sterilization
2013	Mercante G[32]	USA	da Vinci	IV	Hard	C	Sterilization
2013	Park YM[33]	USA	da Vinci	IV	Hard	C	Sterilization
2014	Kawaguchi K[62]	USA	CyberKnife	IV	Hard	A	Sterilization
2015	Chan JY[34]	USA	da Vinci	IV	Hard	C	Sterilization
2015	Lörincz BB[35]	USA	da Vinci Si	IV	Hard	C	Sterilization
2015	Mendelsohn AH[36]	USA	da Vinci Si	IV	Hard	C	Sterilization
2016	Kim DH[37]	USA	da Vinci Xi	IV	Hard	C	Sterilization
2016	Holsinger FC[38]	USA	da Vinci SP	IV	Soft	C	Sterilization
2017	Liu Q[39]	USA	da Vinci	IV	Hard	C	Sterilization
2017	Mattheis S[58]	USA	Flex Robotic System	IV	Soft	C	Sterilization
2017	Tay G[40]	USA	da Vinci	IV	Hard	C	Sterilization
2017	Duan XG[63]	China	a surgical robot for radioactive seed implantation of craniomaxillofacial tumors	I	Hard	C	Sterilization
2018	Chen YQ[41]	USA	da Vinci S/Xi/SP	IV	Hard/Soft	C	Sterilization
2018	Persky MJ[59]	USA	Flex Robotic System	IV	Soft	C	Sterilization
2020	Cammaroto G[42]	USA	da Vinci	IV	Hard	C	Sterilization
2020	Fanhao M[64]	China	Remebot surgical robot	IV	Hard	C	Sterilization
2020	Li CS[65]	Singapore	a flexible robotic system with variable-stiffness manipulators	II	Soft	C	Sterilization
2021	Barbara F[60]	USA	Flex Robotic System	IV	Soft	C	Sterilization
2021	Chillakuru Y[43]	USA	da Vinci	IV	Hard/Soft	C	Sterilization
2021	Fang G[61]	China	an MR-safe soft robotic system for MRI-guided transoral laser microsurgery	II	Soft	C	Sterilization
Gland resection							
2011	Walvekar PR[44]	USA	da Vinci Si	IV	Hard	C	Sterilization
2012	Prosser JD[45]	USA	da Vinci	IV	Hard	C	Sterilization
2013	Park YM[46]	USA	da Vinci	IV	Hard	C	Sterilization
2019	Lin X[47]	USA	da Vinci Si	IV	Hard	C	Sterilization
2019	Yang TL[48]	USA	da Vinci Si and Xi	IV	Hard	C	Sterilization
2020	Capaccio P[49]	USA	da Vinci Si	IV	Hard	C	Sterilization
Gland stone resection							
2010	Walvekar PR[50]	USA	da Vinci Si	IV	Hard	C	Sterilization
2019	Capaccio P[51]	USA	da Vinci Si	IV	Hard	C	Sterilization
Obstructive sleep apnea/hypopnea syndrome (OSAHS)							
2012	Vicini C[52]	USA	da Vinci	IV	Hard	C	Sterilization
2012	Friedman M[53]	USA	da Vinci	IV	Hard	C	Sterilization
2017	Montevecchi F[54]	USA	da Vinci	IV	Hard	C	Sterilization
2020	Lee JA[55]	USA	da Vinci	IV	Hard	C	Sterilization

Table 1. Continued

Publication Year	1st Author	Country of robotics	Name of robotics or purpose	Development stage *	Hard/soft robot	Autonomy level **	Infection control level
Cleft lip and palate							
2015	Khan K[56]	USA	da Vinci Si	III	Hard	C	Sterilization
2016	Nadjmi N[57]	USA	da Vinci	IV	Hard	C	Sterilization
Osteotomy							
2002	Engel D[66]	Germany	RobaCKa	I	Hard	C	Sterilization
2010	Burgner J[67]	Germany	a robot assisted laser bone ablation setup	II	Hard	A	Sterilization
2015	Baek KW[68]	Switzerland	an integrated, miniaturised laser system guided by a surgical robot	II	Hard	A	Sterilization
2015	Gui HJ[69]	China	a novel navigation-guided robotic system	II	Hard	A	Sterilization
2016	Zhu JH[70]	China	a parallel kinematics robotic system for mandibular reconstruction	II	Hard	A	Sterilization
2019	Zhang HY[71]	China	a robotic system for mandibular reconstruction surgery	II	Hard	C	Sterilization
2020	Iijima T[72]	Japan	a multi DOF haptic robot for dentistry and oral surgery	I	Hard	C	Sterilization
2020	Sun M[73]	China	a fully automated robot for OMFS	II	Hard	A	Sterilization
Orthognathic surgery							
2003	Theodossy T[74]	UK	a passive robot arm for orthognathic surgery planning	III	Hard	C	Sterilization
2016	Wang X[75]	China	an orthognathic assisted robot system	I	Hard	C	Sterilization
2017	Li Q[76]	China	a orthognathic assisted robot	III	Hard	C	Sterilization
2017	Woo SY[77]	Korea	a integrated robot-assisted orthognathic surgery system	II	Hard	A	Sterilization
2019	Hara K[78]	Japan	an orthognathic surgical robot with a workspace limitation mechanism	II	Hard	C	Sterilization
2020	Wu JY[79]	China	CMF robot system	III	Hard	A	Sterilization

* I: Research level (The robot is in the process of development, such as design and analysis of hardware or software.), II: Phantom experiments level (The preliminary development of the robot has been completed, and experiments and related improvements are being carried out on phantoms.), III: Clinical validation level (The robot has been developed and is in the clinical trial stage, but has not yet received national medical approval and marketed.), IV: Clinical application level (The robot is already on the market and has been used in treatments of dental diseases.). ** A: active, B: semi-active, C: master-slave.

lung tumor). Radioactive particle implantation has proven effective in the treatment of cranial and maxillofacial tumors[63]. Meng *et al.*[64] introduced a new multimodal, image-guided surgical robot, the Remebot surgical robot (Beijing Baihui Weikang Technology Co., Ltd.; Beijing, China), while performing interstitial brachytherapy for head and neck cancers. This represents the first attempt to use a robot for ^{125}I seed implantation in head and neck surgery. Li *et al.*[65] proposed a flexible robotic system with variable-stiffness manipulators for transoral surgery, and its feasibility was preclinically verified by performing a tonsillectomy on a cadaver.

For hard tissues, robotic systems for osteotomy, orthognathic surgery, and mandible reconstruction surgery are currently in the research and improvement stage and have not yet been approved for clinical application. In 2002, Engel *et al.*[66] introduced the RobaCKa robotic system developed by the Institute for Process Control and Robotics in Germany for assisting osteotomies in mouth, jaw, and facial surgery. The robotic arm used in this study was the FaroArm (FARO Technologies, Lake Mary, FL, USA), which is a highly accurate portable coordinate measurement device designed for engineering, manufacturing, and controlling dimensional quality. Burgner *et al.* established the first robot-assisted laser bone ablation setup, comprising a prototype carbon-dioxide laser system and a robot with six degrees of freedom (DOF)[67]. Baek *et al.*[68] demonstrated the clinical application of robot-guided contact-free laser osteotomy in cranio-maxillofacial surgery. Gui *et al.*[69] developed a robotic system to perform Le Fort I osteotomies. Zhu *et al.*[70] developed a parallel kinematics robotic system for mandible reconstruction and confirmed its efficacy and accuracy were better than manual operation. Zhang *et al.*[71] developed a robotic system for mandibular reconstruction with fibula grafts to help the surgeon hold and locate the free bone. Lijima *et al.*[72] developed a master-slave multi-DOF haptic robot for osteotomy. In 2020, the first report on robot-assisted automatic surgery in craniofacial surgery showed promising results for the automatic drilling procedure under the condition that there were no interferences like soft tissues[73]. In orthognathic surgery, Theodossy and Bamber[74] represented the first attempt to use a robotic system in the planning of orthognathic surgery. Wang[75] developed a robotic system that assists surgeons in completing maxillary repositioning. Qianqian *et al.*[76] proposed a specific system design for an orthognathic-assisted robot based on the image-guided automated surgical robot. Woo *et al.*[77] developed a robotic system to assist with orthognathic surgery and integrated it into the image-guided virtual planning system presented earlier to accurately transfer a preoperative virtual plan into the intraoperative phase of orthognathic surgery. Hara *et al.*[78] developed a compact and lightweight 6-DOF robot with a workspace limitation mechanism. Wu *et al.*[79] developed a surgical robotic system for craniomaxillofacial surgery, named the CMF robot system, which can effectively assist in orthognathic surgery with high accuracy and feasibility.

Table 2. Robots in oral implantology and prosthodontics

Publication Year	1st Author	Country of robotics	Name of robotics or purpose	Development stage	Hard/soft robot	Autonomy level**	Infection control level
Oral Implantology (dental implant surgery)							
2001	Boesecke R[80]	Germany	An assisting medical robot	II	Hard	C	Sterilization
2001	Dutreuil J[81]	France, Sweden	A robotic work plan for dental implantation	III	Hard	C	Sterilization
2011	Sun X[82]	USA	An image-guided robotic system for dental implantation	II	Hard	C	Sterilization
2012	Kasahara Y[83]	Japan	a telerobotic-assisted bone-drilling system	II	Hard	B	Sterilization
2014	Syed AA[84]	Pakistan, China	a dental implant tele-robotic system	II	Hard	B	Sterilization
2017	Haidar Z[88]	China	BLUE BOY	III	Hard	A	Sterilization
2018	Zhao YM[89]	China	BLUE BOY	IV	Hard	A	Sterilization
2020	Mozer PS[85]	USA	Yomi	IV	Hard	C	Sterilization
2020	Bolding SL[86]	USA	Yomi	IV	Hard	C	Sterilization
2021	Bolding SL[87]	USA	Yomi	IV	Hard	C	Sterilization
2021	Wu Y[90]	China	Remebot Dental Robot	IV	Hard	A	Sterilization
Oral Implantology (zygomatic implant surgery)							
2020	Cao Z[91]	China	a surgical robot system for zygomatic implant placement	II	Hard	B	Sterilization
Prosthodontics (tooth arrangement)							
2001	Zhang Y[92]	China	single manipulator tooth-arrangement robot system for complete denture	III	Hard	B	Disinfection
2010	Zhang Y[93]	China	a multi-manipulator tooth-arrangement robot	III	Hard	B	Disinfection
2013	Jiang JG[94]	China	a tooth-arrangement robot	I	Hard	B	Disinfection
Prosthodontics (tooth preparation)							
2015	Otani T[95]	USA	an automated robotic tooth preparation system for porcelain laminate veneers	II	Hard	A	Disinfection
2017	Yuan FS[96]	China	LaserBot (a miniature laser manipulation robotic device for tooth crown preparation)	III	Hard	A	Disinfection
2019	Yuan FS[97]	China	a miniature laser manipulation robotic device for tooth crown preparation	III	Hard	A	Disinfection

* I: Research level (The robot is in the process of development, such as design and analysis of hardware or software.), II: Phantom experiments level (The preliminary development of the robot has been completed, and experiments and related improvements are being carried out on phantoms.), III: Clinical validation level (The robot has been developed and is in the clinical trial stage, but has not yet received national medical approval and marketed.), IV: Clinical application level (The robot is already on the market and has been used in treatments of dental diseases.). ** A: active, B: semi-active, C: master-slave.

3.2. *Oral Implantology*

The first study on robot-assisted dental implant surgery was reported in 2001[80]. This system provides real-time visualization and can assist the surgeon during implant osteotomy site preparation by holding a drilling guide. Dutreuil *et al.*[81] introduced a 5-DOF robot for dental implant procedures to accurately drill splints. Sun *et al.*[82] developed an image-guided dental implant robotic system using the MELFA RV-3S robot. *In vitro* experiments showed an error of 1.42 ± 0.70 mm. However, tactile feedback is crucial in minimally invasive and implant surgery. Kasahara *et al.*[83] proposed a telerobotic-assisted drilling system for dental implant surgery that can transmit the cutting force to the surgeon using acceleration-based bilateral control. Syed *et al.*[84] developed a telerobotic system that provides virtual force feedback and allows surgeons to remotely control the surgical manipulator using handheld haptic devices.

The first commercial dental robotic system globally received FDA clearance in March 2017 and had been applied in over 1,800 dental implant surgeries by 2020[85–87]. It is a computerized navigational system that provides visual and physical guidance in both the planning (pre-operative) and surgical (intra-operative) phases of dental implant surgery. The system also provides haptic feedback and holds the drill in position, depth, and angulation.

The world's first autonomous dental implant robotic system was developed by a team at Beijing University and the Fourth Military Medical University in China[88]. It was approved for clinical application on September 16, 2017[89]. The system is composed of an image-guided platform, a commercial mechanical robot, an implantation platform, and Dental Navi software (the Fourth Military Medical University Hospital, China). It is highly autonomous and can execute surgical tasks directly without any apparent control by a surgeon.

In March 2021, the Remebot Dental Robot was approved for use in dentistry. Wu *et al.*[90] used the Remebot dental robot to perform dental implant surgery on 66 patients with dentition defects, proving its high positioning accuracy and satisfactory clinical results. Additionally, some researchers have tried to introduce robotics in zygomatic implant placement and have developed a novel, comprehensive surgical robotic system for it[91]. Preliminary results showed better accuracy and feasibility of the robotic system than that of surgeons. However, more cadaveric trials are needed for improvement before practical application.

Table 3. Robots in orthodontics

Publication Year	1st Author	Country of robotics	Name of robotics or purpose	Development stage	Hard/soft robot	Autonomy level**	Infection control level
Bending archwires							
1998	Fischer-Brandies H[98]	Germany	BAS(Bending Art System)	III	Hard	A	Disinfection
2004	Rigelsford J[99]	USA	SureSmile	IV	Hard	A	Disinfection
2007	Müller-Hartwich R[100]	USA	SureSmile	IV	Hard	A	Disinfection
2009	Scholz R[101]	USA	SureSmile	IV	Hard	A	Disinfection
2009	Zhang YD[103]	China	an archwire bending robot based on MOTO-MAN UP6	I	Hard	A	Disinfection
2011	Alford TJ[102]	USA	SureSmile	IV	Hard	A	Disinfection
2011	Gilbert A[104]	USA	LAMDA (Lingual Archwire Manufacturing and Design Aid)	III	Hard	A	Disinfection
2016	Xia Z[105]	China	a robotic system for orthodontic archwire bending	I	Hard	A	Disinfection
2016	Van der Meer WJ[106]	Germany	FMU 2.7	IV	Hard	A	Disinfection
Tooth movement							
2011	Kau CH[107]	USA	AcceleDent	IV	Hard	A	Sterilization
Reducing discomfort							
2016	Lobre WD[108]	USA	AcceleDent	IV	Hard	A	Sterilization

* I: Research level (The robot is in the process of development, such as design and analysis of hardware or software.), II: Phantom experiments level (The preliminary development of the robot has been completed, and experiments and related improvements are being carried out on phantoms.), III: Clinical validation level (The robot has been developed and is in the clinical trial stage, but has not yet received national medical approval and marketed.), IV: Clinical application level (The robot is already on the market and has been used in treatments of dental diseases.). ** A: active, B: semi-active, C: master-slave.

3.3. *Prosthodontics*

3.3.1. *Tooth arrangement*

Zhang *et al.*[92] developed a robotic system for tooth arrangement in complete dentures. The first robotic system was developed in 2001 using Visual C++ and RAPL robot languages and was based on the CRS-450 6-DOF robot, produced by CRS Robotics Corporation in Canada. It was used to achieve any position for the grasped teeth. In 2011, a multi-manipulator tooth-arrangement robot was developed for manufacturing complete dentures. The 84-DOF robotic system, consisting of 14 independent manipulators, can adjust each tooth's rotation by moving along its tail, and the repeated positioning accuracies are 0.07 and 0.10 mm for a single manipulator and the whole robotic system, respectively. Subsequent research was conducted on related parameters and technology, such as the dental arch generator, to improve its accuracy[93,94].

3.3.2. *Tooth preparation*

Otani *et al.*[95] evaluated the accuracy and precision of an automated robotic tooth preparation system for porcelain laminate veneers. In this system, tooth models were scanned using a 3D laser scanner, and the tooth preparation was designed on a 3D image, which improved safety and efficiency. In China, researchers developed an automatic robotic system for 3D tooth crown preparation using a picosecond laser and explored its appropriate parameters[96]. This system, called the Laser Bot[97], is comprised of various components such as a miniature robotic end-effector, tooth fixture, laser generator, laser transmission arm, laser scanner (3Shape D700, Denmark), and computer console. The robotic system was able to generate satisfactory tooth preparation; however, further tests are required to determine the ablation efficiencies for different layers of teeth like dentin, enamel, and other dental materials. In 2018, Laser Bot was contracted to Robotoo Robotics company (Isreal) and is currently being upgraded.

3.4. *Orthodontics*

The bending art system, one of the earliest machines for orthodontic archwire bending, was developed in the late 20th century[98]. It consists of an intraoral camera, a computer with software, and a bending machine. Butscher *et al.*[99–102] combined other medical equipment with an orthodontic archwire bending robot to perform the complete process, from data collection to 3D imaging and automatic archwire bending. This archwire-bending robot was developed in 1994.

Zhang *et al.*[103] developed an archwire-bending robotic system based on the movement pattern of the MOTOMAN UP6 robot and optimized some parameters later. In 2011, Gilbert[104] introduced a system called Lingual Archwire Manufacturing and Design Aid (LAMDA; Lancer Orthodontics, Inc., 2330 Cousteau Court, Vista, CA) to precisely design and bend archwires rapidly. It works only on the X and Y axes, making it relatively simple, compact, and inexpensive to manufacture. Xia *et al.*[105] developed a novel robotic system for automatic archwire bending, consisting of a modular and robot-operating system-integrated control system, and demonstrated that it could conduct automated and accurate orthodontic archwire preparation. To determine whether clinicians could use digital workflows to produce multicomponent dental appliances, Van der Meer *et al.*[106] used a robot called FMU 2.7 (Airedale Springs, West Yorkshire, UK), a machine for coiling and forming wire, for archwire bending.

Additionally, a robot called AcceleDent (OrthoAccel Technologies Inc., Bellaire, TX) was developed to aid orthodontic treatment. It is a novel micro pulse vibration robotic system that applies cyclic forces to move teeth faster through accelerated bone remodeling and can reduce the discomfort associated with orthodontics[107,108].

Table 4. Robots in endodontics, oral medicine, and other fields

Publication Year	1st Author	Country of robotics	Name of robotics or purpose	Function	Development stage *	Hard/soft robot	Autonomy level**	Infection control level
Endodontics								
2006	Dong J[109]	USA	an endodontic micro robot	root canal treatment	I	Hard	A	Disinfection
2010	Ortiz Simon JL[110]	Mexico	a mechatronic assistant system for dental drill handling	support and stability	II	Hard	A	Disinfection
2010	Gulrez T[111]	Pakistan	a visual guided robotic endodontic therapeutic system	root canal treatment	I	Hard	A	Disinfection
2012	Nelson CA[112]	USA	a 'vending machine' type tool supplier in robot-assisted endodontic surgery	endodontic surgery	II	Hard	A	Disinfection
2019	Hwang G[113]	Brazil, USA	catalytic antimicrobial robots (CARs)	fighting persistent biofilm infections	I	Soft	A	Disinfection
Oral Medicine								
1995	Ohtsuki K[114]	Japan	WY-1 (Waseda Yamanashi)	mouth opening/ closing training	IV	Hard	C	Sanitation
1997	Takanobu H[115]	Japan	WY-3	mouth opening/ closing training	IV	Hard	C	Sanitation
2001	Takanobu H[116]	Japan	WY-5R	mouth opening/ closing training	IV	Hard	B	Sanitation
2002	Ohtsuki K[117]	Japan	WY series	mouth opening/ closing training	IV	Hard	C	Sanitation
2009	Ariji Y[118]	Japan	WAO-1(Waseda-Asahi Oral-Rehabilitation Robot No. 1)	massage therapy	IV	Hard	C	Sanitation
2009	Solis J[119]	Japan	WAO-1R(Waseda-Asahi oral-rehabilitation robot No.1 Refined)	massage therapy	IV	Hard	C	Sanitation
2015	Yu H[120]	China	a soft oral interventional rehabilitation robot	mouth opening/ closing training	III	Soft	A	Sanitation
2020	P. Vela-Anton[121]	Peru	Borjibot	a soft robotic device to rehabilitate the sucking capacities of preterm neonates	II	Soft	C	Sterilization
Oral and Maxillofacial Radiology								
1991	Burdea GC[122]	USA	the robotic system for dental subtraction radiography	dental subtraction	I	Hard	A	Sterilization
1999	Burdea GC[123]	USA	the robot-based dental subtraction radiography system	dental subtraction	I	Hard	A	Sterilization
Dental Public Health								
2004	Toshikazu Y[124]	Japan	a simple robot for assisting tooth brushing guidance	brushing teeth	III	Hard	A	Sterilization
2016	Yasemin M[125]	Turkey	a human-robot interaction scenario	dental anxiety	III	Hard	A	Sterilization
2017	Sakaeda G[126]	Japan	an automatic teeth cleaning mouthpiece robot	cleaning teeth	III	Hard	A	Sterilization
2020	Kasimoglu Yv[128]	Turkey	a humanoid robot for the reduction of dental anxiety in children	dental anxiety in children	IV	Hard	A	Sterilization
2021	Sakaeda G[127]	Japan	an automatic teeth cleaning robot	cleaning teeth	III	Hard	A	Sterilization
Common								
2015	Zhang HZ[129]	China	an integrated robot system for oral and dental treatment	multiple dental treatment	III	Hard	A	Sterilization
2018	Zhao R[130]	China	a integrated dental robot system	diagnosis and maintenance care	III	Hard	A	Sterilization

* I: Research level (The robot is in the process of development, such as design and analysis of hardware or software.), II: Phantom experiments level (The preliminary development of the robot has been completed, and experiments and related improvements are being carried out on phantoms.), III: Clinical validation level (The robot has been developed and is in the clinical trial stage, but has not yet received national medical approval and marketed.), IV: Clinical application level (The robot is already on the market and has been used in treatments of dental diseases.). ** A: active, B: semi-active, C: master-slave.

3.5. *Endodontics*

In 2006, Dong *et al.*[109] proposed a microrobot for endodontic treatment that can be mounted on the tooth and controlled using a computer to perform automatic treatment procedures, including probing, drilling, cleaning, and filing. Simon *et al.*[110] developed the first mechatronic system to assist dentists in handling dental drills. This system allows the dentist to manipulate the appliances

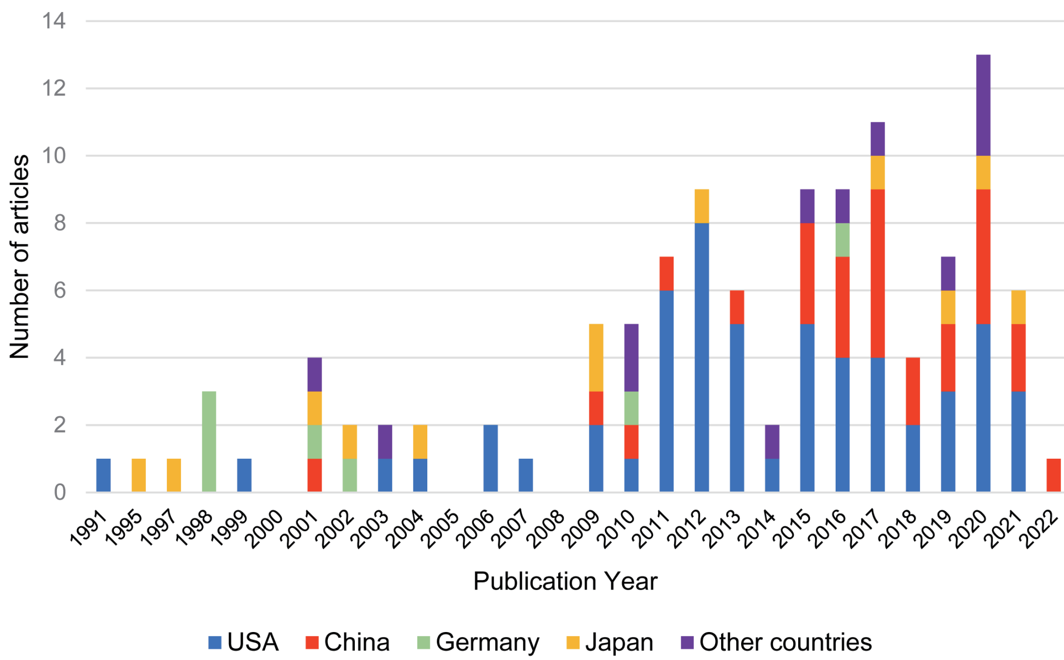

Fig. 1. Yearly trend of articles related to the development of applications of robots in dental treatment by countries

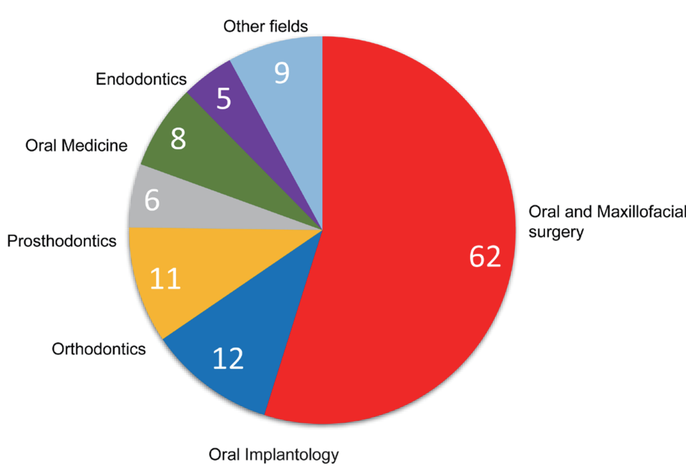

Fig. 2. Number of articles related to the applications of robots for treatments in different dental specialties

smoothly and accurately, thereby reducing the risk of iatrogenic injuries during cavity preparation. Gulrez *et al.*[111] assessed a visual-guided robotic endodontic therapeutic system and proposed a specially designed visual servo controller model for this system. Nelson *et al.*[112] introduced a novel tool vending machine for providing root canal instruments during surgery, which is preprogrammed to automatically select and deliver surgical instruments according to the surgeon's needs, thereby acting as a surgical assistant. A series of experiments showed that it can save up to 4.4% of the time required for conventional root canal treatment. Hwang *et al.*[113] designed catalytic antimicrobial robots that can kill, degrade, and remove biofilms precisely, efficiently, and controllably. These robots generate bactericidal free radicals, break down the biofilm exopolysaccharide matrix, and remove the fragmented biofilm debris *via* magnetic field-driven robotic assemblies with iron oxide nanoparticles. However, all the above-mentioned robots are still in the simulation and testing stages; there is no clinical precedent for using robots in root canal treatment.

3.6. *Oral medicine*

Oral medicine is concerned with the clinical diagnosis and non-surgical management of non-dental pathologies affecting the orofacial region (the mouth and the lower face). Examples include lichen planus, dry mouth conditions like Sjögren's syndrome, and non-dental chronic orofacial pain such as burning mouth syndrome, trigeminal neuralgia, and temporomandibular joint disorder. Some oral rehabilitation robots have been included in this study.

Takanishi *et al.* began to develop the Waseda Yamanashi (WY) series in the mid-1990s as a platform for treating masticatory dyskinesia and an instrument for oral rehabilitation training; it has undergone upgradation from WY-1 to WY-5R during 1995–1999[114–117]. Subsequently, the Waseda Asahi oral-rehabilitation robot was developed to provide appropriate massage therapy for maxillofacial disorders such as temporomandibular joint disorders and dry mouth, as well as for the elderly[118,119]. However, this robot was created to massage the bilateral masseter and temporal muscles; hence, the problem of massaging the painless muscles needs to be solved through future studies.

Additionally, Yu *et al.*[120] presented a force estimation algorithm based on masseter muscle surface electromyography signals to be used in the control of a developed soft oral rehabilitation robot. Vela-Anton *et al.*[121] presented the design and prototype of a soft robotic system to rehabilitate the sucking capacities of preterm neonates.

3.7. Other fields

In the field of oral and maxillofacial radiology, Burdea *et al.*[122,123] proposed a new repositioning system that uses a 6-DOF position sensor and a robotic arm with an X-ray source to improve accuracy and repeatability by overcoming the low accuracy caused by mechanical alignment and the time consumption caused by post-processing registration.

In dental public health, in 2004, a robot using Lego Mindstorms was designed to guide elementary school students to brush their teeth correctly[124]. Yasemin *et al.*[125] developed a human-robot interaction scenario for children aged 4 to 10 to improve their experience in a clinical environment by minimizing pain and anxiety during dental treatments. Sakaeda *et al.*[126] developed an automatic teeth-cleaning mouthpiece robot consisting of an eccentric cam, a wiper with sponges, and a rounded guide railto aid the elderly and handicapped in brushing their teeth. The robot has been improved to achieve a higher plaque removal rate[127]. Kasimoglu *et al.*[128] introduced a humanoid robot that can reduce anxiety in children during dental treatments and improve their behaviors.

In 2015, Zhang[129] proposed an integrated system for dental treatments that consists of a console, robot, chair device, and navigation system. Dentists can control the robotic arm at the console to perform various oral and dental treatments with the help of the navigation system. The team later proposed a novel self-service robotic system for the early diagnosis of oral diseases and routine maintenance of oral hygiene[130].

4. Discussion

This scoping review provides an overview of the current state of robotics in dentistry, with articles that are not directly related to dentistry being excluded from the review. The development of dental robots is mainly focused on by university research groups[19–22,61,63,67–84,88–98,103–105,109–123,129,130], which have diverse components and require a long research period. Most advanced dental robotic systems are based on commercial industrial mechanical arms, such as Flex Robotic System[58–60], CyberKnife[62], RobaCKa[66], LAMDA[104], and FMU 2.7[106]. However, due to the large number of potential publications, early-stage technologies without any published studies involving real users were not considered in this review.

Of the studies included in the review, 54.9%[18–79] were related to OMS, with the surgical robotic system approved by the FDA in 2009 accounting for half of them[23–57]. This is not surprising, as it is the most widely used medical robot and has been in clinical use for over 20 years. The surge in the number of studies since its approval in 2009 further supports this observation. Furthermore, the development of robots in OMS and oral implantology[80–91] is relatively fast and comprehensive, likely due to the development of medical-surgical robots. In contrast, other fields such as prosthodontics[92–97] and orthodontics[98–108] have a large number of studies focused on a single type of system. However, their development is stagnant at the parameter research or validation stages, which highlights the need for future collaboration between researchers and clinicians worldwide.

Regarding the development stage, 40% of studies are included in the clinical application stage. If those commercial industrial robotic arms are excluded, only a small proportion of robots have been applied in clinical practice[64,85–90,99–102,107,108,114–119]. This indicates that the number of studies with lower levels of technical development is fewer than those with higher levels of technical development, which is not conducive to long-term progress. Therefore, the government should encourage more scientific research and urge dentists to pay more attention to the development of digitalization and artificial intelligence[131,132].

Additionally, the level of automation and infection is closely related to the characteristics of different dental disciplines, although there is a serious tendency. For example, the robotic systems approved by the FDA earlier and widely used in the world, such as the master-slave system, account for a large proportion. There are also varying infection control requirements for *in vivo* surgery and *in vitro* orthodontic archwire bending. Soft robots, with the improvement of technology, have gained developers' attention since 2015 and may become a more mainstream trend in the future considering their high strength and durability combined with the characteristics of hard or traditional robots.

Due to the characteristics of dental treatment, such as the need for high accuracy, a narrow field of vision, and discomfort caused by time-consuming procedures, there are many advantages to the application of robots in dental treatment. First, the use of transoral robotic surgery offers a variety of concealed incisions, reduces postoperative scarring, and improves aesthetic outcomes[23–61]. Second, planning can be carried out using data collected and analyzed before surgery as well as real-time intraoperative navigation information, which allows for accurate positioning and a transparent process, thereby improving the safety, accuracy, and success rate of surgery[19,20,69]. Third, there is reduced trauma to adjacent tissues due to the minimal amount of tissue resected, which results in a clear surgical field and contributes to the postoperative recovery of patients. Fourth, the clamping stability of the mechanical arm is good, and the risk caused by the doctor's fatigue is avoided. Fifth, remote guidance and teaching are possible due to network connections[83,84]. Lastly, advanced diagnosis and treatment modalities improve the patient experience and reduce unnecessary panic and anxiety[129,130].

There are also limitations to robots in dentistry. First, they require expensive infrastructure, including purchase, machine maintenance, and operation costs[85–87]. Second, many robots are complex in structure and large in size, making them difficult to master[110,112]. Unskilled use could prolong surgical times and even cause unnecessary risks. Third, most robots lack tactile feedback, which may increase surgical time and become a bottleneck restricting the development of robotic surgery. Lastly, robots have low levels of intelligence and a limited range of functions, which means they cannot deal with complex and dynamic oral diseases. Diagnosis and treatment robots cannot completely free clinicians from the heavy clinical load. However, these problems could be solved with continuous developments in artificial intelligence and other technologies in the future.

5. Conclusions

This review highlights the wide range of applications of robots in dentistry. With the increasing demand for dental treatments and the advancements in digitalization and artificial intelligence, robotics has great potential in this field. However, there are still gaps in the research and application of robotics in dentistry. While advanced technologies are threatening to replace clinical decision-making, combining robotics with dentistry at a better and deeper level in the future remains a challenge.

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Conflicts of interest statement

The authors declare that they have no conflicts of interest.

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