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DOI
10.1016/j.dental.2021.06.002

Publication date
2021

Document Version
Final published version

Published in
Dental Materials

Citation (APA)
van Riet, T. C. T., Chin Jen Sem, K. T. H., Ho, J. P. T. F., Spijker, R., Kober, J., & de Lange, J. (2021). Robot technology in dentistry, part two of a systematic review: an overview of initiatives. *Dental Materials*, *37*(8), 1227-1236. https://doi.org/10.1016/j.dental.2021.06.002

DENTAL MATERIALS 37 (2021) 1227–1236

Available online at www.sciencedirect.com

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journal homepage: www.intl.elsevierhealth.com/journals/dema

Robot technology in dentistry, part two of a systematic review: an overview of initiatives

Tom C.T. van Riet[a,b,d,*], *Kevin T.H. Chin Jen Sem*[b], *Jean-Pierre T.F. Ho*[a,b], *René Spijker*[c], *Jens Kober*[d], *Jan de Lange*[a,b]

[a] *Amsterdam University Medical Center (AUMC), Dept. of Oral and Maxillofacial Surgery, University of Amsterdam, The Netherlands*
[b] *Academic Center for Dentistry Amsterdam (ACTA), University of Amsterdam, The Netherlands*
[c] *Medical Library, Amsterdam University Medical Center, University of Amsterdam, The Netherlands*
[d] *Mechanical, Maritime and Materials Engineering (3ME), Dept. of Cognitive Robotics, Delft University of Technology, The Netherlands*

ARTICLE INFO

Article history:
Received 15 December 2020
Received in revised form
27 May 2021
Accepted 2 June 2021

Keywords:
Robot
Technology
Dentistry
Automatic
Yomi
Suresmile
Automated

ABSTRACT

Objectives. To provide dental practitioners and researchers with a comprehensive and transparent evidence-based overview of physical robot initiatives in all fields of dentistry.
Data. Articles published since 1985 concerning primary data on physical robot technology in dentistry were selected. Characteristics of the papers were extracted such as the respective field of dentistry, year of publication as well as a description of its usage.
Sources. Bibliographic databases PubMed, Embase, and Scopus were searched. A hand search through reference lists of all included articles was performed.
Study selection. The search timeline was between January 1985 and October 2020. All types of scientific literature in all languages were included concerning fields of dentistry ranging from student training to implantology. Robot technology solely for the purpose of research and maxillofacial surgery were excluded. In total, 94 articles were included in this systematic review.
Conclusions. This study provides a systematic overview of initiatives using robot technology in dentistry since its very beginning. While there were many interesting robot initiatives reported, the overall quality of the literature, in terms of clinical validation, is low. Scientific evidence regarding the benefits, results and cost-efficiency of commercially available robotic solutions in dentistry is lacking. The rise in availability of open source control systems, compliant robot systems and the design of dentistry-specific robot technology might facilitate the process of technological development in the near future. The authors are confident that robotics will provide useful solutions in the future but, strongly, encourage an evidence-based approach when adapting to new (robot) technology.

* *Corresponding author at*: Department of Oral and Maxillofacial Surgery, Amsterdam University Medical Center, University of Amsterdam, 1105 AZ, Amsterdam, The Netherlands.
E-mail address: t.c.vanriet@amsterdamumc.nl (T.C.T. van Riet).
https://doi.org/10.1016/j.dental.2021.06.002

Contents

1. Introduction 1228
2. Materials and methods 1228
   2.1. Information sources and search strategy 1228
   2.2. Eligibility criteria 1229
   2.3. Study selection 1229
   2.4. Data charting process and data items 1229
3. Results 1229
   3.1. Study selection 1229
   3.2. Results per field of dentistry 1229
      3.2.1. Orthodontics 1229
      3.2.2. Implantology and surgery 1230
      3.2.3. Prosthodontics 1231
      3.2.4. Restorative dentistry 1231
      3.2.5. Gnathology 1231
      3.2.6. Education of students 1231
      3.2.7. General practice 1232
      3.2.8. Education of patients 1232
      3.2.9. Endodontics 1232
      3.2.10. Dental radiology 1233
4. Discussion 1233
   4.1. Summary of the evidence 1233
   4.2. Limitations 1233
5. Conclusion 1233
   Funding 1233
   References 1234

1. Introduction

In the field of medical surgery, different types of robotic systems are already widely in use. The “Da Vinci” robot (Intuitive Surgery, Inc., Sunnyvale, CA, USA) is one of the most well-known examples. According to data provided by Intuitive in 2019, over 5500 systems are in clinical use worldwide and over 7 million surgical cases have been performed [1]. The robot is a master-slave system, in which hand movements of a surgeon are transmitted to the robot and reproduced on a smaller scale, usually in difficult to reach locations. Whilst the Da Vinci robot is most commonly used in the field of Urology and Gynecology, it is also used by Head and Neck surgeons in, for example, transoral robotic surgery and neck dissections [2,3].

In dentistry one of the most well-known robots is the archwire bending robot of the Suresmile orthodontic system (OraMetrix, Inc., Richardson, TX, USA), first described in 2001 [4]. Since then, robot technology has been described in many other fields of dentistry such as for example, in restorative dentistry [5]. Some of these systems have become commercially available for use in the general dentist practice, such as the implantology robot ‘Yomi’ (Neocis, Miami, Florida, USA).

In part one of this systematic review, it was shown that over 80% of the first authors of articles concerning robot technology in dentistry have a technological background. Therefore, it might be difficult for the general dentist to keep track of these technological developments and their scientific standing. Robot technology itself is a rapidly developing scientific field. With a recent shift towards the development of more compliant robots, which facilitates human-robot interaction, it might be expected that new initiatives of robot technology in dentistry will be introduced. For robot technology in oral and maxillofacial surgery an extensive systematic review of literature exists [3] but a systematic overview of initiatives in dentistry is, to the authors best of knowledge, missing.

After discussing the characteristics of literature and technological readiness in part one of this systematic review, the primary aim of this second part was to construct a comprehensive overview of the usage of different robot technology initiatives in all fields of dentistry.

2. Materials and methods

2.1. *Information sources and search strategy*

This review followed both Preferred Reporting Items for Systematic Reviews and Meta-Analyses and Joanna Briggs Institute guidelines to structure the report [6,7]. A systematic search of the electronic databases Medline (through PubMed), Embase and Scopus was performed on 30 October 2020. In addition, the reference lists of included full text and excluded reviews were hand searched for additional articles. Search strategies were defined together with a medical librarian (RS). The search strategy for all three databases can be found in Tables 1–3.

Table 1 – PubMed search strategy. Number of articles found = 314.

	PubMed search terms
#1	Robotic Surgical Procedures[MeSH] OR robot*[tiab] OR yomi[tiab] OR suresmile[tiab]
#2	Dentistry[MeSH] OR Education, Dental[MeSH] OR Health Education, Dental[MeSH] OR Students, Dental[MeSH] OR Dental Materials[MeSH]) OR (dentistry[tiab] OR dental [tiab] OR denture[tiab] OR dentist[tiab] OR dentine[tiab] OR enamel[tiab] OR tooth[tiab] OR teeth[tiab] OR molar* [tiab] OR gingiva[tiab] OR periodontal[tiab] OR Prosthodontic[tiab] OR Periodontic[tiab] OR Endodontic [tiab] OR Implantology[tiab] OR Orthodontic[tiab] OR Dentistry/surgery[MeSH]
#3	#1 AND #2

Table 2 – Scopus search strategy. Number of articles found = 568.

	Scopus search terms
#1	(TITLE-ABS-KEY (robot* OR yomi OR suresmile))
#2	(TITLE-ABS-KEY (dentistry OR dental OR denture OR dentist OR dentine OR enamel OR molar* OR gingiva OR periodontal OR prosthodontic OR periodontic OR endodontic OR implantology OR orthodontic))
#3	#1 AND #2

Table 3 – Embase search strategy. Number of articles found = 247.

	Embase search terms
#1	((exp robot assisted surgery/) or (robot* or yomi or suresmile).ti,ab,KW)
#2	((exp "Dentistry"/or dental education/or dental health education/or dental student/or exp dental material/) OR (dentistry OR dental OR denture OR dentist OR dentine OR enamel OR tooth OR teeth OR molar* OR gingiva OR periodontal OR Prosthodontic OR Periodontic OR Endodontic OR Implantology OR Orthodontic).ti,ab,kw)
#3	#1 AND #2

2.2. *Eligibility criteria*

To cope with the difficult definition of a robot, when authors used the term robot for the described technology, it was considered as such. The search timeline started in 1985 and no language restrictions were applied. Articles not containing any primary data such as reviews were excluded as well as patents, presentation slides, posters and video content. Robots used for research purposes only or articles concerning oral and maxillofacial surgery were excluded.

2.3. *Study selection*

For title and abstract screening, articles were imported into a web application for systematic reviews (Rayyan, Qatar Computing Research Institute, Doha, Qatar) [8]. Duplicates were removed using an inhouse application before uploading to Rayyan in which two independent reviewers screened titles and abstracts for relevance (TR, KC). Results were compared afterwards and in case of any discrepancies, a discussion was held to reach an agreement. A third reviewer was consulted to act as a referee (JH), when required.

2.4. *Data charting process and data items*

Full texts of all included articles were collected and a customized data extraction form was used for data extraction in duplicate by two authors (TR, KC). Relevant data items collected were the corresponding field of dentistry as well as a summary of the performed study, the robot usage and its technological readiness level (TRL). For data registration and analysis, Microsoft's Office Excel (version 2019, Microsoft Corporation, USA) was used.

3. Results

3.1. *Study selection*

The search in all three databases combined resulted in 1253 articles of which 363 duplicates were excluded. During screening of title and abstracts another 751 articles were excluded because they did not match the inclusion criteria for this review. In total 137 articles were deemed eligible for inclusion but 71 articles had to be removed with reasons as summarized in Fig. 1. In total 94 articles were included in this systematic review for qualitative synthesis (Fig. 1).

3.2. *Results per field of dentistry*

3.2.1. *Orthodontics*

With 21 included articles, orthodontics has a higher number of articles concerning robot technology compared to any other fields in this study. It also contained most articles describing commercially available technology (Fig. 2). The oldest included study in this field is the only one not concerning the bending process of orthodontic wires. It described the automatic deposit and cure of the acrylic part of a maxillary orthodontic appliance [9]. With eight articles 'Suresmile' (OraMetrix, Richardson, Tex) was the most frequently described robot in this review. Suresmile is a computer-aided design and computer-aided manufacturing system for customized archwire bending. Treatment outcomes and treatment time have been compared to the conventional method (manual bending) in observational epidemiological studies [10–12]. Other articles evaluated the accuracy and effectiveness of tooth positioning [13–15]. In two articles, 'Suresmile' users described their opinions of its use in their practices [16,17]. No prospective interventional studies were found. Other bending robot initiatives outside Suresmile were mostly originating from Eastern Asia and also focused on (improving) the design of archwire bending robots. Clinical studies have, to the authors best of knowledge, not yet been performed [18–27]. One group of researchers, developed an orthodontic archwire bending robot based on Robot Operating System (ROS), an open-source control system [18,26]. Next to the more traditional buccal orthodontic appliances, also the technique of automated manufacturing of lingual appliances has been described in detail together with clinical results of five cases [28]. Another initiative on lingual archwire bending was described called

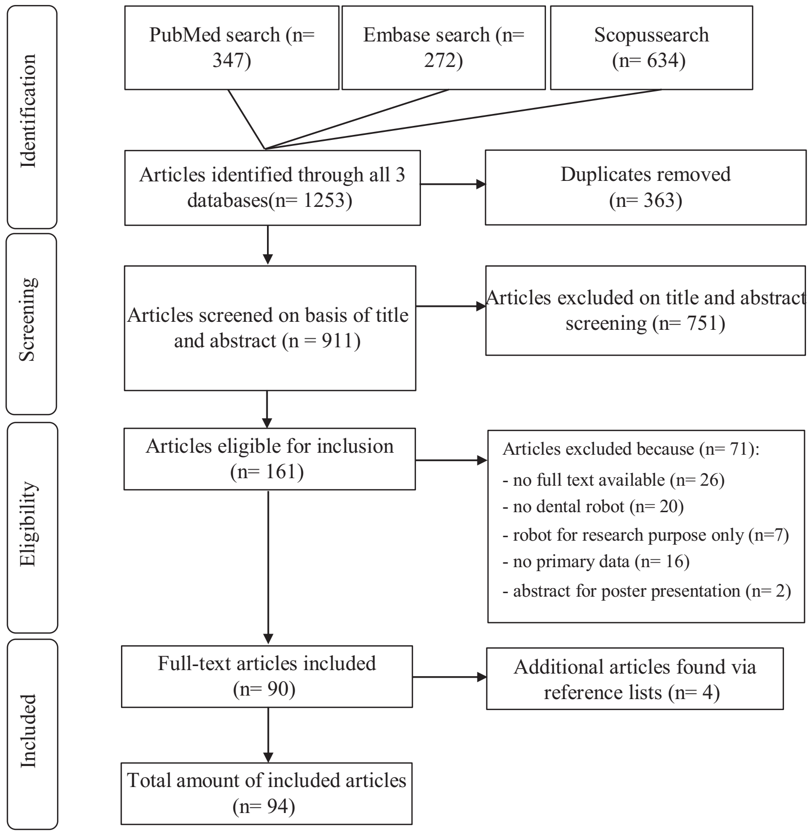

Fig. 1 – Diagram of the search process and results.

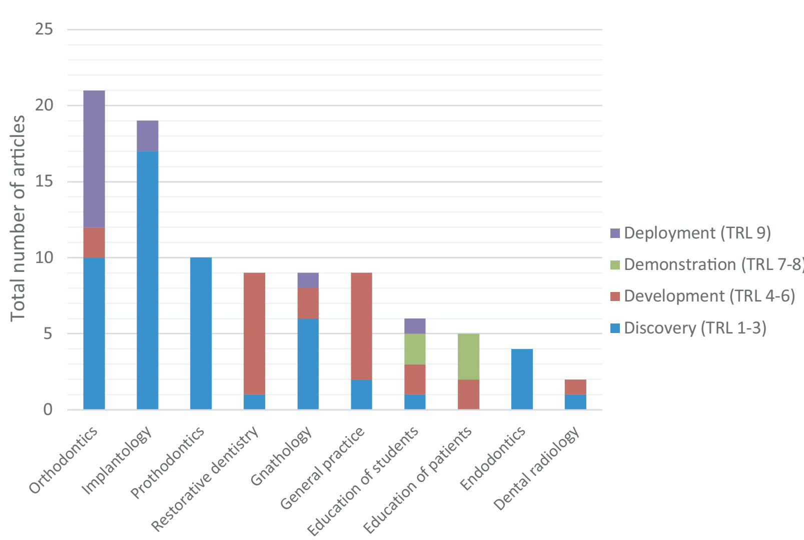

Fig. 2 – Included articles per field of dentistry including the respective technological readiness levels (TRL) ranging from lowest (Discovery, TRL 1–3) to commercially available systems (Deployment, TRL 9).

Lingual Archwire Manufacturing and Design Aid (LAMDA). A limited experiment was conducted to compare manually bent wires with this technique [29].

3.2.2. *Implantology and surgery*

Seventeen articles addressed the field of implantology and two the field of dental surgery, making it the second largest group of articles concerning robot technology in dentistry. Except for two articles, describing a commercially available robot, all included articles were categorized into the basic research group [30,31]. In contrast to other fields the application of robot technology in implantology is heterogeneous. A few studies were categorized as being theoretical research only and proposed designs for different parts of an implantology robot

[32–35]. Some papers propose different methods of how robot technology can be used for transferring a treatment plan to the patient. One method is an indirect technique where the robot assists in creating drill guides for a surgeon to use during implant treatment [30,36–38], whereas other initiatives let the robot guide the drill directly towards the proposed location. The latter has been performed by using a separate coordinate measuring machine attached to both robot and jaw [39,40] or directly with the aid of computer vision [41–43]. Two articles focused on tele-robotic systems where haptic feedback was studied during implant drilling [44,45]. The development of an ultra-short pulse laser robot-controlled system for preparation of implant sites [46] was described by the same research group involved in using the robot and laser combination for restorative dentistry purposes [5]. Despite being commercially available, only one case report was included describing the use of Yomi [31]. Other reviews often mention the system, but refer to other reviews or grey literature when discussing its capabilities [47–49].

Most articles concerning implantology and dental surgery are aimed towards hard tissue surgery. A recent paper by a Russian research group developed a prototype of a probe determining soft tissue contact, necessary for (diode) laser surgery to the soft tissue [50]. Another study described a robot as part of a measurement setup to enable an in depth analysis of movements during tooth removal procedures. Data is used to model the procedure for both scientific as well as educational purposes [51].

3.2.3. *Prosthodontics*

All ten articles concerning prosthodontics originated in China. No article had a technology readiness level exceeding the level of proof of concept (level 3) and all were categorized into basic research. Nine articles described the developmental process of an automatic tooth arrangement robot for dentures by researchers from the same research institutes in Eastern China. Four of these originated between 2000 and 2002 [52–55], five between 2010 and 2013 (Fig. 3) [56–60]. Its goal was to automatically place artificial teeth into a dental arch to manufacture complete dentures based upon the patient's arch size. Limited experiments in a laboratory setting were performed. To the authors best of knowledge no clinical studies to evaluate the functional or esthetic outcomes were undertaken. Another research group more recently reported the design and test results of an 'intelligent dental robot' for the purpose of testing full dentures [61]. Its goal was to replicate human's masticatory movements and perform stress and wear test on artificial dentures. Experiments were performed in a laboratory setting.

3.2.4. *Restorative dentistry*

Robotics in the field of restorative dentistry is relatively new with all included articles published after 2013 (Fig. 3). All articles were categorized into basic applied research, and experiments were mostly conducted on cadavers. Eight out of the nine articles originated from China. In a series of eight articles a research group from Beijing reported the development of an automatic full-crown tooth preparation robot using ultrashort pulse lasers [5,62–68]. The most recent version of the robot consisted of computer-aided design and manufacturing system (CAD/CAM), a tooth positioning system and a 6-DoF robotic arm controlling the position of a laser system [5]. Preparation of a full-crown was done with layer-by-layer laser ablation of the tooth and experiments took place on extracted human teeth inside a phantom model to show its clinical potential. Another group also evaluated an automated tooth preparation system but used a high-speed handpiece attached to the robot instead of a laser [69]. The reduction for porcelain laminate veneers with a robot were compared to conventional freehand preparation. Experiments took place in a laboratory setting.

3.2.5. *Gnathology*

Seven out of nine included articles concerning gnathology originated from Japan. All articles were categorized into basic research, except for one recent article describing commercially available technology [70]. Four articles published between 1999 and 2003 looked at a mouth opening-and-closing rehabilitation robot [71–74]. A master-slave system was developed, called Waseda Yamanashi (WY). The goal of this robot was to facilitate mouth opening training. Limited experiments were performed. Four articles looked at robotic articulators to reproduce jaw movements either with or without the use of jaw movement tracking devices [70,75–77]. An experiment on a single patient's working cast was performed for the fabrication of a full veneer crown using a robotic articulator [75]. The most recent paper in this group describes a case study of a commercially available robot, called the 'Bionic Jaw Motion' (Bionic Technology, Vercelli, Italy) to reproduce mandibular kinematics with a combination of a movement analyzer (high-speed camera) and a robot articulator [70]. A validation of the technique is, to the authors best of knowledge, not reported. Finally, a Japanese article published in 2018 described the development of a motorized robotic denture for healthy elderly people to assist with chewing and swallowing [78]. Experiments were performed in a laboratory setting.

3.2.6. *Education of students*

All six articles concerning the education of students originate from Japan and were published between 2006 and 2018. Technological readiness levels in this category were relatively high and subjects for these performed studies were mostly human. Although most papers fell into the observational epidemiological research category, study design was mostly limited to unvalidated questionnaires with dental students or their trainers regarding their subjective perception of usefulness as results. In two articles a humanoid (human-like) robot was developed for dental training purposes [79,80]. It came with different 'effects' such as performing hand movement, tongue movements, saliva production, effusion of bleeding, pain-sensors for drilling with too much force, and voice recognition. The robot was used to practice dental restorations. A questionnaire was completed by trainers and trainees showing their satisfaction with the system. Recent research showed a more extensive version of a humanoid training robot which was developed by members of the same group together with a commercial robot manufacturer (Tmusk Co., Ltd. Fukuoka, Japan) [81]. This robot is capable of moving its head, to have a conversation with students, perform unexpected (but intended) movements, create vomiting reflexes and produce saliva. The

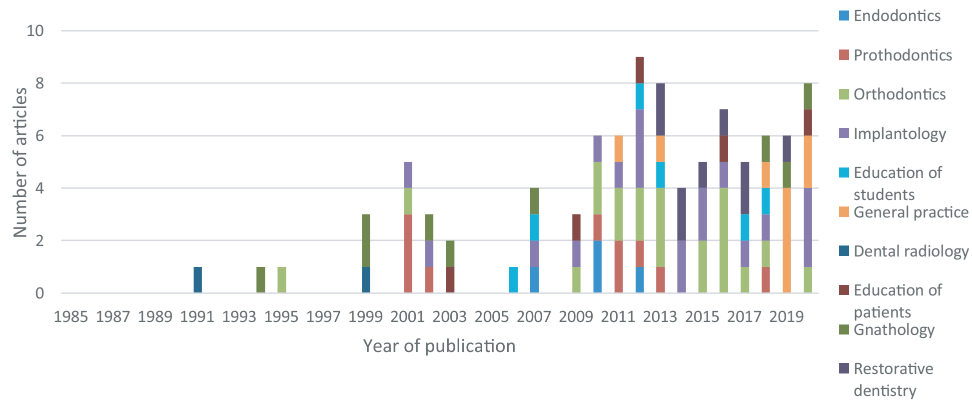

Fig. 3 – Included articles per field of dentistry and their respective year of publication.

same robot, after adjustments, was later used for the practice of medical emergencies [82]. In both studies a questionnaire was used to evaluate the student's opinion about education using a robot patient. In another article of a parallel group, a robot (Simroid, Morita Group, Japan) with similar functions was compared to a mannequin phantom model with jaw movement reproducibility [83]. Dental students performed preparations for restorative treatments and were given questionnaires to evaluate the use of robot patients for educational purposes. One article looked at a haptic robotic drilling system for training of implant surgery [84]. The goal was to simulate realistic cutting-force responses during implant procedures for dental students. An experiment was conducted on pinewood to test the force response in relation to the actual forces.

3.2.7. *General practice*

Five recent articles by the same research group from Hong Kong describe the development a compact robotic manipulator specially designed for dentistry [85–89]. By using a tendon-driven mechanism, the dimension of the manipulator was kept within limits. Motion scaling is an additional feature of the system. Experiments in a laboratory setting and under different circumstances where performed to validate the system. Two other groups designed systems supporting the dentist in its movements. One group designed a system in which a handpiece is both guided by dentist and robot to actively support its movements. Limited experiments were performed showing results in terms of accuracy and tremor reduction [90]. Another group designed a master-slave system in which the robot copies movement made by the dentists and haptic feedback is given to the dentist. Laboratory experiments were performed to validate the setup [91]. Other projects include a system to identify and position dental instruments automatically [92] and a basic 'service robot' to be used for delivering messages between patients in a waiting room and their dentist [93]. Limited experiments were performed.

3.2.8. *Education of patients*

Four out of the five included articles concerning the education of patients described technology tested in its relevant environment, leading to technology readiness levels higher than five [94–96]. Robots in this field could interact with humans whilst avoiding necessity for physical contact. Two articles derived from the same research group described the effect of 'The Smiling Robot' in a Brazilian population of school children [94,95]. 'The Smiling Robot' is a humanoid android, whose movements and sound are remotely controlled by an operator. It emits previously recorded messages with a metallic voice with instructions on oral hygiene. Epidemiological observational research conducted on children exposed to different learning methods evaluated their effect on a plaque index after 30 days compared to a group of children who did not receive any education at all. A comparable initiative is the 'Robotutor' brushing robot designed for educating the 'Bass brushing method' [97]. It consisted of a toothbrush which is moved by a robot arm alongside dental plaster models and an audio tape with instructions. A questionnaire was used to evaluate its effectiveness. Another initiative in this field was described in a Turkish paper on the effect of a humanoid robot as a distraction method during dental treatment [96]. The same group published the only prospective interventional study found in this review comparing dental anxiety in children with and without distraction by a customized commercially available robot (iRobiQ, Yujin Robot Co., Ltd. Incheon, Korea) [98].

3.2.9. *Endodontics*

Four articles were included concerning endodontology, published in the years between 2007 and 2012. None of these articles exceeded level two when it comes to technological readiness. Two articles derived from the same research group looked at an endodontic microrobot, with a tool changer to hold or switch instruments [99,100]. A theoretical model was proposed for the design of a part of a (micro) robot, called an actuator, to enable reliable drilling in the axis of the tooth. To the authors best of knowledge no prototype has been build. In another study, a preliminary visual-guided robot to reduce procedural errors during endodontic treatments was described. Based on image data a robotic-file was controlled in two axes and a single experiment in a laboratory setting was performed showing preliminary results of the system [101]. In the most recent study of this group a design is proposed for an automatic 'tool vending machine' to increase work efficiency and to reduce the amount of space needed during treatment [102]. Its goal was to provide dentists automatically with the correct endodontic tools and had the capability of cleaning the tools as well. No working prototype has been described.

3.2.10. Dental radiology

Only two articles were included concerning dental radiology, published in 1991 and 1999 [103,104]. Both articles derived from the same research group and looked at the possibility of automatic alignment of a robot containing the X-ray source to the patient for the purpose of digital radiographic subtraction. The goal was to replace free-hand alignment with non-contact positioning of the X-ray source. Experiments were performed with an industrial robot to compare alignment errors between mechanical and robotic alignment.

4. Discussion

4.1. Summary of the evidence

The primary aim of this systematic review was to construct a comprehensive overview of the different robot technology initiatives in all fields of dentistry.

A recent review of literature was published by Grischke et al. including 49 articles on a broader field of dental robotics. The review included robot technology in the field of oral and maxillofacial surgery as well as cognitive robotics technology such as machine learning [105]. In contrast to their work, this study has provided a more systematic approach in addition to a narrower search field in order to provide a more thorough overview of all literature concerning physical robotic technology specifically relevant to the general dentist. A broad timeframe (starting in 1985) was used and, besides Medline and Embase, also the Scopus database was included in the search. Despite the narrower scope of this review, the number of included articles were almost twice as compared to Grischke et al., emphasizing the thoroughness of this review.

Robot technology in dentistry is, compared to general medicine, in its relative infancy. Although articles on this topic started to appear around 20 years ago and initiatives can be found in every field dentistry, the initiatives that made it into practice are scarce. This is interesting since robots can be particularly useful in difficult to reach areas and are known for their accurate performances in a reliable and reproducible manner. This review showed that most research in this field has been limited to those situations where physical contact with a human can be avoided, i.e., education or manipulation of dental materials such as orthodontic wires. As discussed in a recent review by Grischke et al. this might be caused by the limited availability and accessibility of robot systems for dental researchers. Where in earliest experiments industrial robots where used for experiments [103] in recent literature a shift towards widely available, human-compliant robots or even robots specifically designed for dentistry has occurred [85]. Next to that, the use of open-source control software (ROS) for robot control has been described in this review [18,26,51]. Together with robot technology improving on a wider scale and generally becoming less expensive, these developments might help to facilitate the progression of initiatives to higher levels of technology readiness more easily.

Despite the important limitations found in literature, as also described in part one of this review, there are commercialized systems using robot technology available on the market, mainly in orthodontics and to a lesser extend in implantology and education of students. The implantology robot 'Yomi' (Neocis, Miami, Florida, USA) is marketed as being the first and only Food and Drug Administration approved robot device for dental surgery, including implantology. Its capabilities have been described in other reviews, referring to either grey literature or non-scientific papers [47,48,105]. The present search resulted in one article matching the inclusion criteria and concerned a case report on its usage. Strong scientific data supporting the functionality of commercially available robotic systems in dentistry seems limited in clinical terms but also in terms of cost-effectiveness. Therefore, the authors would strongly encourage the publication of well-designed research supporting the use of these innovative and state of the art examples of robot technology in dentistry.

4.2. Limitations

This study was designed to give an overview of scientific literature on robot technology in dentistry. This approach led to the exclusion of, amongst others, grey literature and patents. Following this decision, some initiatives that could be relevant were not included in this review and might have led to an underestimation of the hereby-presented results. The authors nevertheless believe to have established a transparent and thorough review of relevant literature which is meaningful for the general dentists.

5. Conclusion

This extensive literature review gives an overview of robot initiatives in all fields of dentistry. The overall quality of the literature, especially in terms of clinical validation, should be considered as low. In cases where technology reaches the level of commercial availability, articles supporting their value in clinical or economical terms is largely absent or very limited. The rise in availability of open source control systems, compliant robot systems that enable human-robot interaction and the design of dentistry-specific robot technology might facilitate the process of technological development in the near future. The authors are confident that robotics will provide useful solutions in the future but, strongly, encourage an evidence-based approach when adapting to new (robot) technology in dentistry.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors. There are no conflicts of interest to report.

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