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Robot technology in dentistry, part one of a systematic review: literature characteristics

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ABSTRACT

Objectives. To provide dental practitioners and researchers with a comprehensive and transparent evidence-based overview of the characteristics of literature regarding initiatives of robot technology in dentistry.
Data. All articles in which robot technology in dentistry is described, except for non-scientific articles and articles containing secondary data (reviews). Amongst others, the following data were extracted: type of study, level of technological readiness, authors' professional background and the subject of interaction with the robot.
Sources. Bibliographic databases PubMed, Embase, and Scopus were surveyed. A reference search was conducted. The search timeline was between January 1985 and October 2020.
Study selection. A total of 911 articles were screened on title and abstract of which 161 deemed eligible for inclusion. Another 71 articles were excluded mainly because of unavailability of full texts or the sole use of secondary data (reviews). Four articles were included after hand searching the reference lists. In total, 94 articles were included for analysis.
Conclusions. Since 2013 an average of six articles per year concern robot initiatives in dentistry, mostly originating from East Asia (57%). The vast majority of research was categorized as either basic theoretical or basic applied research (80%). Technology readiness levels did not reach higher than three (proof of concept) in 55% of all articles. In 84%, the first author of the included articles had a technical background and in 36%, none of the authors had a dental or medical background. The overall quality of literature, especially in terms of clinical validation, should be considered as low.

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Contents

1. Introduction

The first generally recognized digitally operated and programmable robot was an industrial robot called 'Unimate' (Unimation, Inc., USA) that was used in the automotive industry in 1961 [1]. The Programmable Universal Machine for Assembly 200 (PUMA 200, Westinghouse Electric, Pittsburg, PA, USA) was the first robot to be used in medicine over 25 years later (1988). Its purpose was to align a needle during neurosurgical biopsies [2].

Since then, experiments with robot technology in many fields of dentistry have been described, for example in implantology, restorative dentistry and education [3,4]. Some robotic solutions have become commercially available in recent years and are marketed for use in the general dentist practice, such as the implantology robot 'Yomi' (Neocis, Miami, Florida, USA). For the general dentist, it might be difficult to keep track of these initiatives and their level of (scientific) development. Furthermore, in 'grey literature' the capabilities of robots when it comes to their functionality and stage of development might be difficult to interpret and can be easily overestimated [5].

Most reviews on this topic have a narrow scope, i.e., describing robot technology in a specific field. A recent review by Grischke et al. explained more about the possibilities of robotics on a broader scale in dentistry, including cognitive robotics, but as with other reviews concerning robot technology in dentistry, it lacked a clear systematic approach [6–8]. To the authors best of knowledge, a strong systematic overview of available evidence in dental robotics and how this evidence is synthesized, is missing.

In this first part of a systematic review, the primary aim is to provide dental practitioners and researchers with a comprehensive, transparent and evidence-based overview of the characteristics of the literature and level of development of robot initiatives in dentistry. In a second part of this systematic review an overview of the usage of robot technology in all fields of dentistry since its very beginning is provided.

2. Materials and methods

2.1. *Information sources and search strategy*

Guidelines from both the Preferred Reporting Items for Systematic Reviews (PRISMA) as well as the Joanna Briggs Institute (JBI) were used to structure this review [9,10]. The bibliographic databases Medline (through PubMed), Embase and Scopus were searched on 30 October 2020. In addition, the reference lists of included full texts and excluded reviews were screened and cross-referred. The search strategies were defined appropriately for each database together with an information specialist (RS). An overview of the search strategy for all three databases can be found in Tables 1–3.

2.2. *Eligibility criteria*

The definition of a robot differs throughout literature. For the purpose of this review it was decided that, when an author used the term robot for the described technology, it was considered as such and was therefore eligible for inclusion. Since the first robot in medicine was described in 1988, only publications in or after 1985 were included. Articles in all languages were included. (Non-)Systematic reviews, patents, presentation slides, posters and video content were excluded from data synthesis. Robots used for research purposes only, i.e., standardized impression taking to evaluate material properties, were excluded. Literature regarding robot technology in oral and maxillofacial surgery was excluded since most of the medically used robot systems are infeasible for usage in general dentistry.

2.3. *Study selection*

Articles identified using the search strategy were imported into a web application for systematic reviews (Rayyan, Qatar Computing Research Institute, Doha, Qatar) [11]. Duplicates were removed before uploading to Rayyan by an inhouse

Table 1 – PubMed search strategy. Number of articles found = 347.

	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 = 634.

	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 = 272.

	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

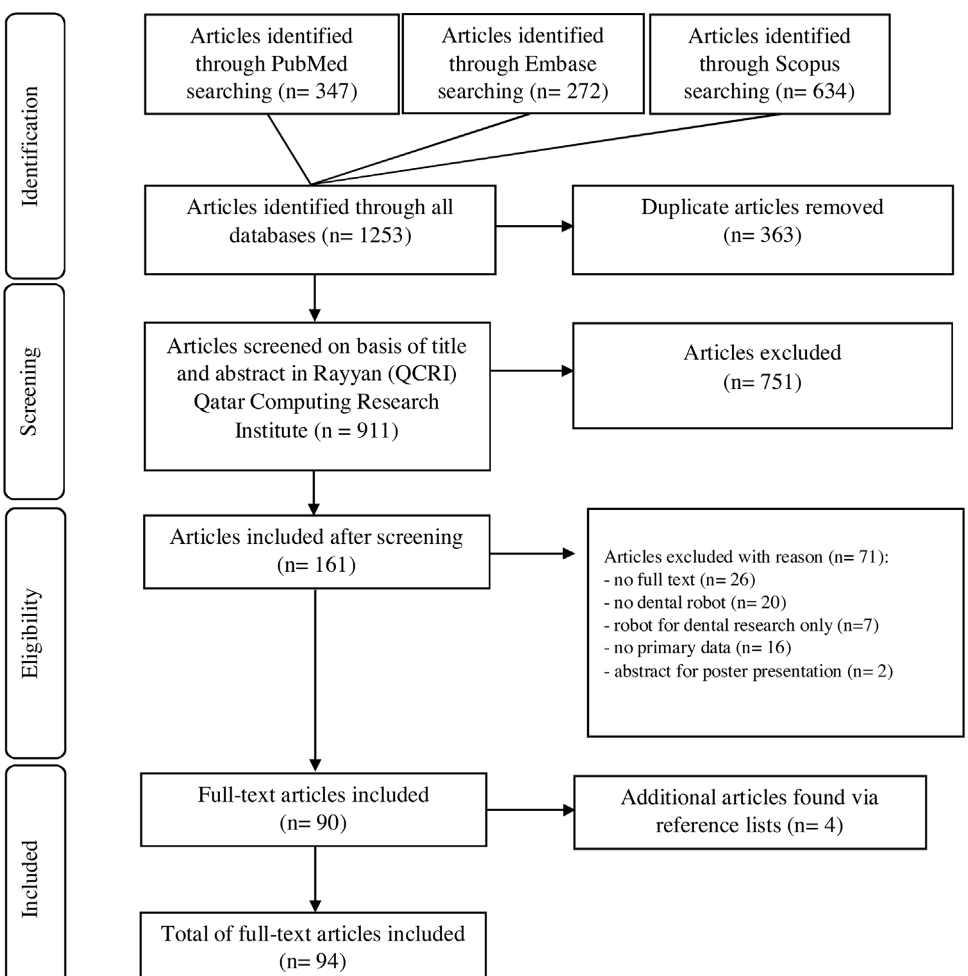

Fig. 1 – Diagram of the search process and results.

Table 4 – A modified version of the classification of types of medical research described in Röhrig et al. [13].

Main classification of study design	Examples
Basic research — theoretical	Method development (no experiments)
Basic research — applied	Experiments on models, animals, cadavers, or humans Material development
Clinical research — observational	Therapy study, case series, case reports, prognostic studies
Clinical research — experimental	Clinical intervention studies
Epidemiological research — observational	Case control studies Observational studies Comparative studies
Epidemiological research — experimental	Field/group studies

Table 5 – Technological Readiness Level (TRL) description.

Group	Technology readiness levels	Description
Discovery	TRL 1	Basic principles of the technology are observed.
	TRL 2	Technological concept is formulated.
	TRL 3	After laboratory tests a proof of concept is made.
Development	TRL 4	Proof of concept is validated in laboratory with prototypes.
	TRL 5	Technology is tested and validated in the relevant environment.
	TRL 6	Technology is demonstrated in relevant environment; the prototype is not yet optimized for operational environment.
Demonstration	TRL 7	Technology is integrated in operational environment.
	TRL 8	The system is completed and qualified; the technology performs properly.
Deployment	TRL 9	Actual system is proven in operational environment; technology is commercially ready.

application, after which two independent reviewers screened all 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. After title and abstract screening, a full text screening was performed. Articles were excluded when full-text was unavailable (see Fig. 1).

2.4. *Data charting process and data items*

Full text of all articles meeting the inclusion criteria for further analysis were acquired. Data extraction was performed in duplicate by two authors (TR, KC) using a customized data extraction form. The following data items were collected: field of dentistry, year of publication, Technological Readiness Levels, country of origin, authors' professional background (either clinical or technical) and the subject of interaction with the robot. The type of study was recorded according to a modified classification of study types in medical research (see Table 4) [12].

The technology readiness level (TRL) of each proposed initiative was estimated on the information provided in the original research paper. The TRL scale, originating from the National Aeronautics and Space Administration (NASA), consist of 9 stages and 4 groups of development levels in which technology can be categorized (see Table 5) [14]. 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, excluding duplicated articles, resulted in 911 articles eligible for title and abstract screening. After title and abstract screening 161 articles were deemed valuable for inclusion of which 71 articles had to be excluded with reasons specified (Fig. 1). The most frequent reason for exclusion (26 times) was the unavailability of a full-text version of the articles. The complete texts of 90 articles were carefully reviewed and screened by hand searching to find four additional articles matching the inclusion criteria [15–18]. In total 94 articles were included in this systematic review for qualitative synthesis (Fig. 1).

3.2. *Study demography and professional background*

Articles included from countries in East Asia (China, Japan, and Korea) formed the largest group with 54 articles in total (57%), followed by the USA with 17 articles (18%) (Fig. 2). All included articles were in English except for four Chinese articles [19–22] and one article in Turkish [23]. These five articles were translated to English before data extraction. After hitting a peak number of articles around the year 2012 (nine articles), the number of published articles stabilized to around six per year, since then (Fig. 3). In 15 calendar years between 1985 and 2008, no articles were included in this study.

In total 373 authors were counted of which most (253, or 60%) had a technical background. The majority of first authors had a technical background (70 articles, 84%) and in 30 articles, no authors with a dental or medical background were involved at all (36%). In 15 articles (18%), no authors with a technical background were involved.

3.3. *Fields of dentistry and study design*

Orthodontics, implantology and surgery, together responsible for 43% of all included articles, formed the largest groups in this study. Dental radiology (2%) formed the smallest group with only two included articles (Fig. 4) [24,25]. With

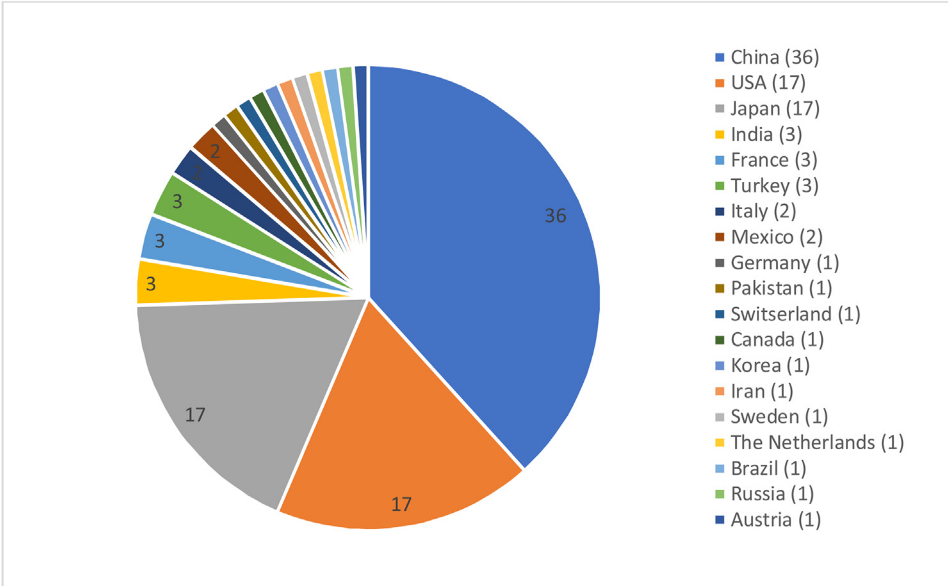

Fig. 2 – Country of origin of the research project.

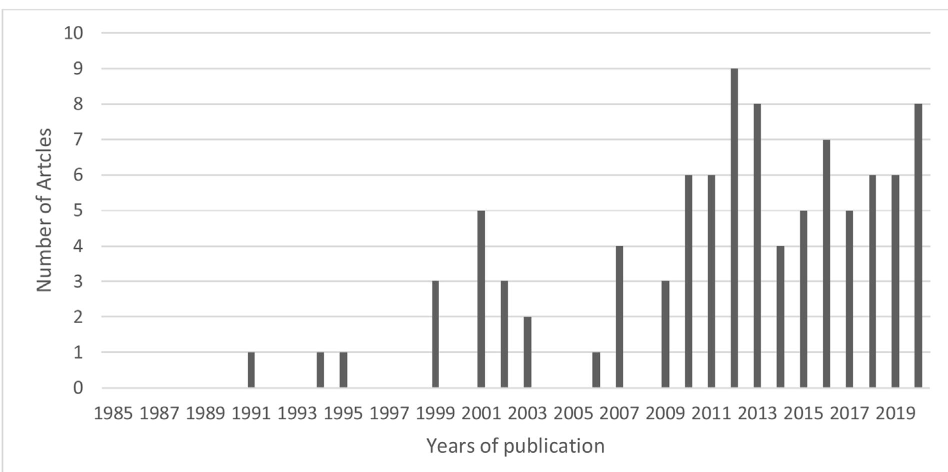

Fig. 3 – Number of included articles per year of publication.

eight articles concerning the 'Suresmile' robot, it was the most frequently mentioned robot in literature [15,26–32]. In total, 75 articles (80%) were categorized as basic research of which 55 consisted of applied research containing some type of experiment. Outside articles describing basic research, six were categorized as observational clinical research, 12 as observational epidemiological research and one as clinical experimental research (Fig. 4). The observational clinical research category consisted of three case- reports [28,33,34], and three case-series [27,29,32]. All but one case report [34] were reported in the field of orthodontics. Observational epidemiological research consisted of five case-control [15,26,31,35,36], three observational [30,37,38], and four comparative studies [23,39–41]. Other than basic research study designs were only to be found in the field of orthodontics, implantology and in the education of both patients and students.

3.4. *Subject of experiments and Technological Readiness Levels (TRL)*

The robots in the included articles interacted mostly with dental materials (33%) such as orthodontic wires or non-dental experimental models (29%, Table 6). Interaction with humans was seen most frequently in the field of education (9 out of 11 articles) avoiding the need of physical contact of robots with their target audience. Only two articles concerning a master-slave system for the evaluation and training of the mouth opening and one case report on implantology robot Yomi had direct robot-to-patient interaction [34,42,43].

The mean level of technological readiness for all 94 studies was 4.3, median 3 (Table 7). Commercially available technology was found in the field or orthodontics (9), implantology (2), gnathology (1) and education of students (1).

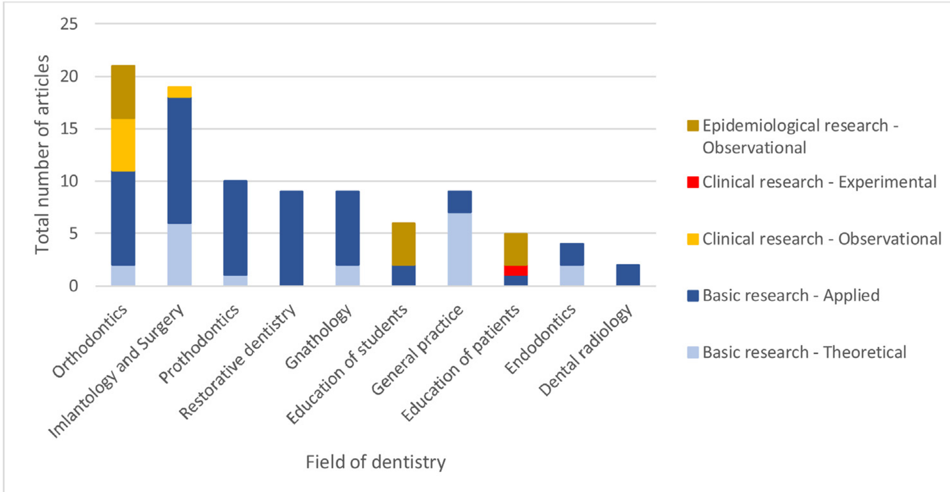

Fig. 4 – Total number of articles and the study design per field of dentistry.

Table 6 – Subject of interactions with the robot.

Object of experiments	Number of articles (%)
Dental material • Orthodontic wires (18) • Resin teeth (6) • Dental impressions (6)	30 (32%)
Experimental model	27 (29%)
Humans	12 (13%)
Cadavers	11 (12%)
Other	14 (15%)

4. Discussion

4.1. *Summary of the evidence*

The aim of this study was to provide dental practitioners and researchers with a comprehensive, transparent and evidence-based overview of the main characteristics of literature regarding physical robot initiatives in dentistry.

Although a rising trend following the years of robotic developments for oral and maxillofacial, craniofacial, and head and neck surgery was found by De Ceulaer et al., this trend was not seen as strongly for robots in dentistry where the number of publications has stabilized to around 6 per year [108].

The present study showed 94 articles concerning a wide array of interesting robot initiatives in all fields of dentistry. The largest group of articles (80%) was classified as basic research, either purely theoretical or applied. This means that the technique has not yet been compared to any existing techniques nor tested in, for example, a series of patients. Studies categorized in the clinical or epidemiological research groups were only found in the field of orthodontics, implantology and education. Reason for this might be the relative easiness of testing on patients in most these groups, in which direct interaction of a robot with patients is unnecessary.

Where some basic research articles might describe well-designed experiments, most articles in the epidemiological and clinical research groups were, overall, very limited in their design. Only a few observational studies described the effectiveness of a workflow containing robot technology compared to the conventional workflows [15,23,26,31,35–37]. One prospective interventional study could be included [103]. No cost-effectiveness studies were found. The overall quality of literature in this review should be considered as low.

In more than half (55%) of all included studies the technology readiness of the initiatives did not exceed level three, a proof of concept. One quarter (24%) of the described technology was validated in either a laboratory setting or relevant environment and 13% of all articles described a workflow containing commercially available robot technology. It is important to realize that, especially concerning technology in the higher TRL levels, often the same robot technology is described in more than one paper of which the Suresmile system is an example as it used in eight articles. These findings are in accordance with the recent article by Grischke et al. [7] which described 49 articles, of which approximately 75% did not reach a level of technology readiness higher than level three [7].

With 76% of all first authors having a technological background and 30% of all papers lacking an author with a dental or medical background the average article has a strong technological character. The authors emphasize that, for successful development of technology in dentistry, clinicians should be more involved in the process.

According to the demographic findings (Fig. 2) well over half of all included articles was either from China or Japan (East-Asia). It must be noted that some included articles seem to have similar research data published either in a different journal or in another language. These studies were included in the overview nevertheless, which might cause an overestimation of results originating in East Asia. Another finding in this study was the limited number of articles (12) describing robots interacting with humans [23,34–36,38–43,101,103]. In the last 20 years all projects avoid direct contact between a robot and human subject, except for a recent case report with implantology robot Yomi.

Table 7 – Total number of articles with their respective Technological Readiness Levels (TRL) within the different fields of dentistry.

	Discovery			Development			Demonstration		Deployment	Number of articles per field (%)
	TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9	
Orthodontics		2 [18,44]	8 [22,37,45–50]	2 [51,52]					9 [15,26–33]	21 (22%)
Implantology and Surgery		5 [53–57]	12 [16,17,21,58–66]						2 [34,67]	19 (20%)
Prosthodontics		1 [68]	9 [19,69–76]							10 (11%)
Restorative dentistry			1 [77]	5 [78–82]	3 [3,20,83]					9 (10%)
Gnathology			6 [84–89]			2 [42,43]			1 [90]	9 (10%)
General practice	1 [91]		1 [92]	7 [93–99]						9 (10%)
Education of students			1 [100]			2 [38,101]	2 [39,40]		1 [41]	6 (6%)
Education of patients				1 [102]		1 [23]	3 [35,36,103]			5 (5%)
Endodontics		4 [104–107]								4 (4%)
Dental radiology			1 [24]	1 [25]						2 (2%)
Number of articles per TRL (%)	1 (1%)	12 (13%)	39 (42%)	16 (17%)	3 (3%)	5 (5%)	5 (5%)		13 (14%)	
Number of articles per TRL group (%)		52 (55%)			24 (26%)		5 (5%)		13 (14%)	

4.2. *Limitations*

This review is not free of limitations. Firstly, a relative high number (26 out of 161) of articles were excluded based on the lack of full-text articles available. This has to be taken into account when interpreting these results. Most articles were unavailable either because they concerned articles originated before 1990 or were published in local/regional or commercial journals to which the authors did not have access to. Based on the available titles and abstracts of the excluded articles, the topics and methods covered in these excluded articles were well in line with the included articles. The authors are convinced that inclusion of these articles would not have led to significant changes in the conclusions of this article.

Secondly, the determination of the level of technological readiness is made on the information supplied in the paper. In some articles information regarding the development level was limited which might lead to minor misjudgments of the TRL level.

Finally, in our search strategy an assumption was made that, if an author used the term robot technology, it was considered as such. This might lead to an underestimation since authors might describe their technology with different keywords. Despite this, the authors do not expect to have missed important articles on robot technology in dentistry by using this strategy.

5. Conclusion

This study provides a comprehensive overview of the characteristics of literature on robot technology in dentistry since its very beginning. While there were many interesting robot initiatives reported, the overall quality of the study design is low which was similar to the general level of technological readiness. Robots interact mostly with dental material (i.e., orthodontic wires) and interact with humans mostly when direct contact can be avoided (i.e. educational purposes). The amount of publications seems to stabilize in recent years to about six articles per year and most first authors have a technical background (84%).

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REFERENCES

[1] Chauhan S, Coelho R, Kalan S, Satava R, Patel V. Evolution of robotic surgery: past, present, and future. Robot Urol Surg 2011:3–10.

[2] Kwoh YS, Hou J, Jonckheere EA, Hayati S. A robot with improved absolute positioning accuracy for CT guided sterotactic brain surgery. IEEE Trans Biomed Eng 1988;35(2):153–60.

[3] Yuan F, Lyu P. A preliminary study on a tooth preparation robot. Adv Appl Ceram 2019:1–6.

[4] Abe S, Noguchi N, Matsuka Y, Shinohara C, Kimura T, Oka K, et al. Educational effects using a robot patient

simulation system for development of clinical attitude. Eur J Dent Educ 2018;22(3):e327–36.
[5] Wisdom tooth extraction done by a robot on a human patient in Tokyo. https://www.juniordentist.com/wisdom-tooth-extraction-done-by-a-robot-on-a-human-patient-in-tokyo.html.
[6] Jiang JG, Zhang YD, Wei CG, He TH, Liu Y. A review on robot in prosthodontics and orthodontics. Adv Mech Eng 2015;7(1).
[7] Grischke J, Johannsmeier L, Eich L, Griga L, Haddadin S. Dentronics: towards robotics and artificialintelligence in dentistry. Dent Mater 2020:14.
[8] Wu Y, Wang F, Fan S, Chow JK. Robotics in dental implantology. Oral Maxillofac Surg Clin North Am 2019;31(3):513–8.
[9] Aromataris E, Munn Z. Chapter 11: scoping reviews (2020 version). In: Aromataris E, Munn Z, editors. JBI manual for evidence synthesis. JBI; 2020.
[10] Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. Ann Intern Med 2018;169(7):467–73.
[11] Ouzzani M, Hammady H, Fedorowicz Z, Elmagarmid A. Rayyan—a web and mobile app for systematic reviews. Syst Rev 2016;5(1):210.
[12] Rohrig B, du Prel JB, Wachtlin D, Blettner M. Types of study in medical research: part 3 of a series on evaluation of scientific publications. Dtsch Arztebl Int 2009;106(15):262–8.
[13] Röhrig B, Prel J-Bd, Wachtlin D, Blettner M. Types of study in medical research. Part 3 of a series on evaluation of scientific publications. Dtsch Arztebl Int 2009;106(5):262–8.
[14] Héder M. From NASA to EU: the evolution of the TRL scale in public sector innovation. Innov J 2017;22(2):3.
[15] Sachdeva RC, Aranha SL, Egan ME, Gross HT, Sachdeva NS, Currier GF, et al. Treatment time: SureSmile vs conventional. Orthodontics (Chic) 2012;13(1):72–85.
[16] Syed AA, Soomro AM, Khizar AN, Duan X-G, Qiang H, Manzoor F. Tele-robotic assisted dental implant surgery with virtual force feedback. Telkomnika Indones J Electr Eng 2014;12.
[17] Yu K, Ohnishi K, Kawana H, Usuda S. Modulated potential field using 5 DoF implant assist robot for position and angle adjustment. IECON 2015 — 41st Annual Conference of the IEEE Industrial Electronics Society, Yokohama 2015:002166–71.
[18] Zhang W. Research of 3D virtual design and automated bending of oral orthodontic archwire. Int J Adv Comput Technol (IJACT) 2013;5(8):741–9.
[19] Lu P, Wang Y, Li G. Development of a system for robot aided teeth alignment of complete denture. Zhonghua Kou Qiang Yi Xue Za Zhi 2001;36(2):139–42.
[20] Yuan FS, Wang Y, Zhang YP, Sun YC, Wang DX, Lyu PJ. Study on the appropriate parameters of automatic full crown tooth preparation for dental tooth preparation robot. Zhonghua Kou Qiang Yi Xue Za Zhi 2017;52(5):270–3.
[21] Yuan FS, Zheng JQ, Zhang YP, Wang Y, Sun YC, Lyu PJ. Preliminary study on the automatic preparation of dental implant socket controlled by micro-robot. Chin J Dent Res 2018;53(8):524–8.
[22] Jiang J, Chen H, Ma X, Zhang Y, Liu Y. Forming planning method and experimentation of personalized orthodontic archwires. Zhongguo Jixie Gongcheng/China Mech Eng 2020;(11), 1323–1330 and 1336.
[23] Yasemin M, Kasimoğlu Y, Kocaaydin S, Karsli E, Ince EBT, Ince G. Management of dental anxiety in children using robots. Institute of Electrical and Electronics Engineers Inc.; 2016.
[24] Burdea GC, Dunn Stanley M, Immendorf CH, Mallik M. Real-time sensing of tooth position for dental digital subtraction radiography. IEEE Trans Biomed Eng 1991;38(4):366–78.
[25] Burdea GC, Dunn SM, Levy G. Evaluation of robot-based registration for subtraction radiography. Med Image Anal 1999;3(3):265–74.
[26] Amm EW. Clinical outcomes for patients finished with the SureSmileTM method compared with conventional fixed orthodontic therapy. Angle Orthod 2011;81(5):926.
[27] Larson BE, Vaubel CJ, Grünheid T. Effectiveness of computer-assisted orthodontic treatment technology to achieve predicted outcomes. Angle Orthod 2013;83(4):557–62.
[28] Moles R. The SureSmile system in orthodontic practice. J Clin Orthod 2009;43(3):161–74, quiz 184.
[29] Muller-Hartwich R, Jost-Brinkmann PG, Schubert K. Precision of implementing virtual setups for orthodontic treatment using CAD/CAM-fabricated custom archwires. J Orofac Orthop 2016;77(1):1–8.
[30] Sachdeva RC. SureSmile technology in a patient—centered orthodontic practice. J Clin Orthod 2001;35(4):245–53.
[31] Saxe AK, Louie LJ, Mah J. Efficiency and effectiveness of SureSmile. World J Orthod 2010;11(1):16–22.
[32] Smith TL, Kusnoto B, Galang-Boquiren MT, BeGole E, Obrez A. Mesiodistal tip and faciolingual torque outcomes in computer-driven orthodontic appliances. J World Fed Orthod 2015;4(2):63–70.
[33] Kheirollahi H, Rahmati S, Abesi F. A novel methodology in design and fabrication of lingual orthodontic appliance based on rapid prototyping technologies. In: Innovative Developments in Design and Manufacturing — Advanced Research in Virtual and Rapid Prototyping. Taylor & Francis Group; 2010. p. 711–8.
[34] Mozer PS. Accuracy and deviation analysis of static and robotic guided implant surgery: a case study. Int J Oral Maxillofac Implants 2020;35(5):e86–90.
[35] Rodrigues JA, dos Santos PA, Garcia PP, Corona SA, Loffredo LC. Evaluation of motivation methods used to obtain appropriate oral hygiene levels in schoolchildren. Int J Dent Hyg 2003;1(4):227–32.
[36] Rodrigues JA, dos Santos PA, Baseggio W, Corona SA, Palma-Dibb RG, Garcia PP. Oral hygiene indirect instruction and periodic reinforcements: effects on index plaque in schoolchildren. J Clin Pediatr Dent 2009;34(1):31–4.
[37] Gilbert A. An in-office wire-bending robot for lingual orthodontics. J Clin Orthod 2011;45(4):230–4, quiz 236.
[38] Takanobu H, Omata A, Takahashi F, Yokota K, Suzuki K, Miura H, et al. Dental patient robot as a mechanical human simulator. Proceedings of International Conference on Mechatronics 2007:1–6.
[39] Tanzawa T, Futaki K, Tani C, Hasegawa T, Yamamoto M, Miyazaki T, et al. Introduction of a robot patient into dental education. Eur J Dent Educ 2012;16(1):e195–9.
[40] Tanzawa T, Futaki K, Kurabayashi H, Goto K, Yoshihama Y, Hasegawa T, et al. Medical emergency education using a robot patient in a dental setting. Eur J Dent Educ 2013;17(1):e114–9.
[41] Abe S, Noguchi N, Matsuka Y, Shinohara C, Kimura T, Oka K, et al. Educational effects using a robot patient simulation system for development of clinical attitude. Eur J Dent Educ 2018;22(3):e327–36.
[42] Takanobu H, Yajima T, Takanishi A, Ohtsuki K, Ohnishi M. Three degrees of freedom mouth opening and closing training robot. IEEE SMC'99 Conference Proceedings. 1999 IEEE International Conference on Systems, Man, and Cybernetics (Cat. No. 99CH37028) 2 1999;2:448–53.

[43] Takanobu H, Nakazawa M, Takanishi A, Ohtsuki K, Ohnishi M. Clinical training with mouth opening and closing training robot WY-3. Proceedings 1999 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human and Environment Friendly Robots With High Intelligence and Emotional Quotients (Cat. No. 99CH36289) 1999;3:1604–9.
[44] Zhang Y, Jia X, Jiang J, Liu Y, Wang Y. Simulation and analysis of orthodontic archwire bending robot. Int J Smart Home 2016;10(8):263–70.
[45] Sassani F, Elmajian A, Roberts S. Computer-assisted fabrication of orthodontic appliances: considering the possibilities. J Am Dent Assoc 1995;126(9):1296–300.
[46] Zhang Y, Jiang J. Analysis and experimentation of the robotic system for archwire bending. Appl Mech Mater 2012;121–126:3805–9.
[47] Jiang JG, Zhang YD, Jin ML, Wei CG. Bending process analysis and structure design of orthodontic archwire bending robot. Int J Smart Home 2013;7(5):345–52.
[48] Jiang JG, Bo P, Yong De Z, Xiao Yang Y, Yi L, Bei Xin S. Control system of orthodontic archwire bending robot based on LabVIEW and ATmega2560. Int J Control Autom 2016;9(9):189–98.
[49] Jiang JG, Han YS, Zhang YD, Liu YJ, Wang Z, Liu Y. Springback mechanism analysis and experiments on robotic bending of rectangular orthodontic archwire. Chin J Mech Eng 2017;30(6):1406–15 (English Edition).
[50] Jiang J, Ma X, Zhang Y, Huo B, Liu Y. Study on three-dimensional digital expression and robot bending method of orthodontic archwire. Appl Bionics Biomech 2018;2018:2176478.
[51] Deng H, Xia Z, Weng S, Gan Y, Xiong J, Ou Y, et al. Motion planning and control of a robotic system for orthodontic archwire bending. 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2015;2015.
[52] Xia Z, Deng H, Weng S, Gan Y, Xiong J, Wang H. Development of a robotic system for orthodontic archwire bending. 2016 IEEE International Conference on Robotics and Automation (ICRA) 2016;2016:730–5.
[53] Chaumont R, Vasselin E, Lefebvre D. Forward kinematics and geometric control of a medical robot;Application to dental implantation. Proceedings of the Fourth International Conference on Informatics in Control, Automation and Robotics 2007;2:110–5.
[54] Kim G, Seo H, Im S, Kang D, Jeong S. A study on simulator of human-robot cooperative manipulator for dental implant surgery. IEEE International Symposium on Industrial Electronics (ISlE 2009) 2009:2159–64.
[55] Yilmaz S, Konukseven EI, Gurocak H. Optimum design of 6R passive haptic robotic arm for implant surgery. In: Lecture Notes in Computer Science LNCS 6191; 2010. p. 105–10.
[56] Rao YVD, Parimi AM, Rahul DSP, Patel D, Nitin Mythreya YV. Robotics in dental implantation. Mater Today Proc 2017;4:9327–32.
[57] Meleshnikov AM, Vorotnikov AA, Klimov DD, Poduraev YV. Prototype probe determining waveguide–Gum contact for a robot surgical system. Russ Eng Res 2020;40(1):86–8.
[58] Dutreuil J, Goulette F, Laurgeau C, Zoreda JC, Lundgren S. Computer assisted dental implantology: a new method and a clinical validation; 2001. p. 384–91.
[59] Fortin T, Champleboux G, Bianchi S, Buatois H, Coudert J-L. Precision of transfer of preoperative planning for oral implants based on cone-beam CT-scan images through a robotic drilling machine: an in vitro study. Clin Oral Implants Res 2001;13(6):651–6.
[60] Sun X, McKenzie FD, Bawab S, Li J, Yoon Y, Huang JK. Automated dental implantation using image-guided robotics: registration results. Int J Comput Assist Radiol Surg 2011;6(5):627–34.
[61] Chiarelli T, Franchini F, Lamma A, Lamma E, Sansoni T. From implant planning to surgical execution: an integrated approach for surgery in oral implantology. Int J Med Robot Comput Assist Surg 2012;8:57–66, http://dx.doi.org/10.1002/rcs.422.
[62] Kasahara Y, Kawana H, Usuda S, Ohnishi K. Telerobotic-assisted bone-drilling system using bilateral control with feed operation scaling and cutting force scaling. Int J Med Robot Comput Assist Surg 2012;8(2):221–9.
[63] Sun X, Yoon Y, Li J, McKenzie FD. Automated image-guided surgery for common and complex dental implants. J Med Eng Technol 2014;38(5):251–9.
[64] Yu K, Uozumi S, Ohnishi K, Usuda S, Kawana H, Nakagawa T. Stereo vision based robot navigation system using modulated potential field for implant surgery. 2015 IEEE International Conference on Industrial Technology (ICIT) 2015;2015:493–8.
[65] Yeotikar S, Parimi AM, Daseswar Rao YV. Automation of end effector guidance of robotic arm for dental implantation using computer vision. 2016 IEEE Distributed Computing, VLSI, Electrical Circuits and Robotics (DISCOVER) 2016:84–9.
[66] van Riet TCT, de Graaf WM, van Antwerpen R, van Frankenhuyzen J, de Lange J, Kober J. Robot technology in analyzing tooth removal — a proof of concept. Conf Proc IEEE Eng Med Biol Soc 2020:4721–7.
[67] Eliasson A, Ortorp A. The accuracy of an implant impression technique using digitally coded healing abutments. Clin Implant Dent Relat Res 2012;14:e30–8.
[68] Zhang Y, Zhao Z, Lu J, Tso Shiu K. Robotic manufacturing of complete dentures. Proceedings 2001 ICRA. IEEE International Conference on Robotics and Automation (Cat. No. 01CH37164) 2001;3:2261–6.
[69] Zhang Y, Zhao Z, Song R, Lu J, Lu P, Wang Y. Tooth arrangement for the manufacture of a complete denture using a robot. Ind Robot Int J 2001;28(5):420–5.
[70] Zhang Y, Zhao Z, Lu P, Wang Y, Song R, Lu J. Robotic system approach for complete denture manufacturing. IEEE/ASME Trans Mechatron 2002;7(3):392–6.
[71] Zhang Y, Jiang J, Lv P, Wang Y. Coordinated control and experimentation of the dental arch generator of the tooth-arrangement robot. Int J Med Robot Comput Assist Surg 2010;6(4):473–82.
[72] Zhang Y, Jiang J, Liang T, Hu W. Kinematics modeling and experimentation of the multi-manipulator tooth-arrangement robot for full denture manufacturing. J Med Syst 2011;35(6):1421–9.
[73] Zhang Y, Jiang J, Lv P, Wang Y. Study on the multi-manipulator tooth-arrangement robot for complete denture manufacturing. Ind Rob 2011;38(1):20–6.
[74] Jiang J, Zhang Y, Zhang W. Collaborative simulation and experimentation on the dental arch generator of a multi-manipulator tooth-arrangement robot. Int J Adv Robot Syst 2012;9.
[75] Jiang J, Zhang Y. Motion planning and synchronized control of the dental arch generator of the tooth-arrangement robot. Int J Med Robot Comput Assist Surg 2013;9(1):94–102.
[76] Ren L, Yang J, Tan Y, Hu J, Liu D, Zhu J. An intelligent dental robot. Adv Robot 2018;32(12):659–69.
[77] Wang L, Wang D, Ma L, Zhang Y, Yuan F, Sun Y, et al. Preliminary experiments of a miniature robotic system for tooth ablation using ultra-short pulsed lasers. 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2013:2566–71.
[78] Ma L, Zhang Y, Wang D, Lv P, Sun Y, Wang H. Trajectory tracking control of a miniature laser manipulation robotic

end-effector for dental preparation. 2013 IEEE International Conference on Robotics and Biomimetics (ROBIO) 2013:468–73.
[79] Wang L, Wang D, Zhang Y, Ma L, Sun Y, Lv P. An automatic robotic system for three-dimensional tooth crown preparation using a picosecond laser. Lasers Surg Med 2014;46(7):573–81.
[80] Wang D, Wang L, Zhang Y, Lv P, Sun Y, Xiao J. Preliminary study on a miniature laser manipulation robotic device for tooth crown preparation. Int J Med Robot Comput Assist Surg 2014;10(4):482–94.
[81] Otani T, Raigrodski AJ, Mancl L, Kanuma I, Rosen J. In vitro evaluation of accuracy and precision of automated robotic tooth preparation system for porcelain laminate veneers. J Prosthet Dent 2015;114(2):229–35.
[82] Yuan F, Zheng J, Sun Y, Wang Y, Lyu P. Regulation and measurement of the heat generated by automatic tooth preparation in a confined space. Photomed Laser Surg 2017;35(6):332–7.
[83] Yuan F, Wang Y, Zhang Y, Sun Y, Wang D, Lyu P. An automatic tooth preparation technique: a preliminary study. Sci Rep 2016;6:25281.
[84] Takanobu H, Takanishi A, Ozawa D, Ohtsuki K, Ohnishi M, Okino A. Integrated dental robot system for mouth opening and closing training. Proceedings 2002 IEEE International Conference on Robotics and Automation (Cat. No. 02CH37292) 2002;2:1428–33.
[85] Takanobu HU, Takanishi A. Dental robotics and human model. First International IEEE EMBS Conference on Neural Engineering, 2003. Conference Proceedings 2003:671–4.
[86] Nishigawa K, Satsuma T, Shigemoto S, Bando E, Nakano M, Ishida O. Development of a novel articulator that reproduced jaw movement with six-degree-of-freedom. Med Eng Phys 2007;29(5):615–9.
[87] Araie T, Ikeda T, Nishizawa U, Kakimoto A, Toyama S, Ragulskis M. Study of the chewing assistance mechanism in powered robotic dentures. Vib Procedia 2018;19: 163–8.
[88] Kizghin DA, Nelson CA. Optimal design of a parallel robot for dental articulation. 2019 Design of Medical Devices Conference 2019.
[89] Takanobu HT, Takashi, Takanishi Atsuo, Kato Ichiro. Adaptive masticatory jaw motion using jaw position and biting force information. Proceedings of the 1994 IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems 1994:360–5.
[90] Carossa M, Cavagnetto D, Ceruti P, Mussano F, Carossa S. Individual mandibular movement registration and reproduction using an optoeletronic jaw movement analyzer and a dedicated robot: a dental technique. BMC Oral Health 2020;20(1):271.
[91] Chen L. The application of robots and eye tracking devices in a general dentist's clinic. 2013 IEEE Third International Conference on Consumer Electronics - Berlin (ICCE-Berlin) 2013:5–7.
[92] Bula I, Hajrizi E. Cost oriented autonomous mobile service robot. IFAC PapersOnLine 2019:91–4.
[93] Ortiz Simon JL, Martinez AM, Espinoza DL, Romero Velazquez JG. Mechatronic assistant system for dental drill handling. Int J Med Robot Comput Assist Surg 2011;7(1):22–6.
[94] Li J, Shen Z, Xu WYT, Lam WYH, Hsung RTC, Pow EHN, et al. A compact dental robotic system using Soft Bracing technique. IEEE Robot Autom Lett 2019;4(2):1271–8.
[95] Li J, Lam WYH, Chiu Hsung RT, Pow EHN, Wang Z. A customizable, compact robotic manipulator for assisting multiple dental procedures. 2018 3rd International Conference on Advanced Robotics and Mechatronics (ICARM) 2018:720–5.
[96] Li J, Lam WYH, Hsung RTC, Pow EHN, Wu C, Wang Z. Control and motion scaling of a compact cable-driven dental robotic manipulator. 2019 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM) 2019:1002–7.
[97] Iijima T, Matsunaga T, Shimono T, Ohnishi K, Usuda S, Kawana H. Development of a multi DOF haptic robot for dentistry and Oral surgery. Proceedings of the 2020 IEEE/SICE 2020:52–7.
[98] Li J, Lam J, Liu M, Wang Z. Compliant control and compensation for a compact cable-driven robotic manipulator. IEEE Robot Autom Lett 2020;5(4):5417–24.
[99] Tao Y, Zhang T, Xu W, Tsang HY, Li J, Wang Z. A compact asymmetrical manipulator for robotic dentistry. Proceedings of the 9th IEEE International Conference on CYBER Technology in Automation, Control and Intelligent Systems 2019:164–8.
[100] Yu K, Matsunaga T, Kawana H, Usuda S, Ohnishi K. Frequency-based analysis of the relationship between cutting force and CT number for an implant-surgery-teaching robot. IEEJ J Ind Appl 2017;6(1):66–72.
[101] Takanobu H, Takanishi A, Okino A, Madokoro M, Miyazaki Y, Maki K. Dental patient robot. Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems 2006:1273–8.
[102] Ahire M, Dani N, Muttha R. Dental health education through the brushing ROBOTUTOR: a new learning experience. J Indian Soc Periodontol 2012;16(3):417–20.
[103] Kasimoglu Y, Kocaaydin S, Karsli E, Esen M, Bektas I, Ince G, et al. Robotic approach to the reduction of dental anxiety in children. Acta Odontol Scand 2020;78(6):474–80.
[104] Dong J, Everett H. The development of endodontic micro robot. 2007 ASME International Mechanical Engineering Congress and Exposition 2007;2:201–4.
[105] Dong J, Hong SY. Design of Z axis actuator & quick tool change assembly for an endodontic micro robot. ASME 2010 International Mechanical Engineering Congress and Exposition 2010;10:507–11.
[106] Gulrez T, Shahid AK, Sana U, Chaudhary NG. Visual guided robotic endodontic therapeutic system. International Conference on Information and Emerging Technologies, IEEE 2010:1–6.
[107] Nelson CA, Hossain SG, Al-Okaily A, Ong J. A novel vending machine for supplying root canal tools during surgery. J Med Eng Technol 2012;36(2):102–16.
[108] De Ceulaer J, De Clercq C, Swennen GR. Robotic surgery in oral and maxillofacial, craniofacial and head and neck surgery: a systematic review of the literature. Int J Oral Maxillofac Surg 2012;41(11):1311–24.