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Review

Technology Readiness Level of Robotic Technology and Artificial Intelligence in Dentistry: A Comprehensive Review

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Abstract: This comprehensive review assessed the integration of robotics and artificial intelligence (AI) in dentistry, offering a transparent overview of developments across dental fields. Covering articles in prosthodontics, orthodontics, implantology, surgery, and radiology, the review included 39 articles on robotics and 16 on AI. Screening adhered to PRISMA guidelines, with searches conducted on Medline, Google Scholar, and IEEE. Incorporating the search strategy, the review used keywords related to dentistry, robotics, and AI. For robotics, 296 articles were screened, resulting in 39 qualifying for qualitative synthesis. A separate AI search on PubMed identified 142 studies within the last decade, with 16 studies selected for a detailed full-text analysis, offering a consolidated overview of the current state-of-the-art knowledge in the AI domain. Geographic distribution highlighted East Asia as a major research contributor. The findings indicate an increasing trend in dentistry robotics since 2000 and, particularly since 2016, in AI dentistry. The majority of the literature fell under the category of basic research. The technology readiness level did not cross "three" (proof of concept) in 41% of all articles. Therefore, the overall literature quality remains low, particularly regarding clinical validation.

Keywords: dentistry; review; robotics; artificial intelligence (AI); technology readiness level (TRL); machine learning (ML); surgery; radiology

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1. Introduction

In the ever-evolving field of dentistry, the integration of robotic systems and artificial intelligence (AI) technologies has significantly transformed conventional approaches to oral diagnosis and treatment. The term "robot" originated from Karel Čapek's 1920 science fiction script, deriving from the Czech word "Robota," signifying "labour" or "drudgery" [1]. The American National Standards Institute (ANSI) characterizes a "robot" as a mechanical assembly capable of programming and executing specific operations and mobile tasks through automatic control [2]. Initially prevalent in sectors like machinery, electronics, and aerospace, robotics has now penetrated medicine significantly.

The inception of digitally operated and programmable robots dates back to the industrial robot 'Unimate' (Unimation, Inc., Trenton, NJ, USA) in 1961, marking a pivotal moment in automation. Subsequent advancements led to medical robots [3]. Robotics in dentistry has witnessed experimentation in implantology, restorative dentistry, and education [4,5]. Commercially available solutions, such as the implantology robot "Yomi" (Neocis, Miami, FL, USA), have been introduced to dental practice [6].

Artificial intelligence (AI) refers to computer programs capable of reasoning and learning from experience beyond their original programming. Its integration into dentistry has revolutionized patient assessment, enhancing diagnostic precision and treatment efficacy. Machine learning (ML), a key paradigm within AI, focuses on algorithmic learning from data. Deep learning (DL), a subset of ML, employs multi-layered neural networks resembling the complexity of the human brain [7]. Despite the benefits, concerns include the lack of human-like understanding, potential biases, security vulnerabilities, ethical dilemmas, job displacement, and high implementation costs. Overreliance on AI may lead to dependency issues, emphasizing the need to maintain a balance between leveraging AI capabilities and ensuring human oversight [8].

In the realm of dental robotics, several previous studies have demonstrated the potential and realized applications. For example, the introduction of the "Yomi" robotic system provides a notable development towards enhanced precision in dental implant surgery, which allows for real-time surgical guidance and has been shown to improve outcomes [4]. Moreover, the integration of AI in dentistry is not only limited to surgical procedures but also extends to diagnostics and treatment planning. AI technologies such as the Thermalytix technology developed by Niramai Health Analytics (Koramangala, Bengaluru, Karnataka, India) have been outlined as groundbreaking, capable of detecting breast cancer years earlier than traditional methods, indicating the disruptive potential of AI in healthcare beyond just oral health [4–6]. The educational impact of using a humanoid robot patient simulation system in comparison to traditional mannequin-based training has been discussed by Susumu Abe et al. Their study concluded that students' attitudes significantly improved when using the robot patient, thereby suggesting a positive educational effect in dental training when incorporating robotics [5].

As dental practices increasingly incorporate robotic systems and AI, it is critical to examine their development, applications, and implications within the field. Robot technology in dentistry is not a new concept—Otani and colleagues evaluated an automated robotic tooth preparation system's accuracy and precision for porcelain laminate veneers [6]. Developments in the area of robotic assistance for various dental procedures also include jaw movement and chewing assistance mechanisms, as noted in a previous study. These systems aim to replicate human oral movements with a high degree of freedom and precision [6].

Amidst this technological surge in dentistry, there is a need to systematically understand and evaluate the scientific development of diverse initiatives. Existing reviews often lack a structured approach and the available evidence in dental robotics calls for a comprehensive and transparent overview [6,7,9]. Thus, this comprehensive review examined the literature seeking characteristics and developmental stages of robotics and AI initiatives in dentistry. By offering a synthesized and evidence-based perspective, this review seeks to guide the trajectory of future research and applications at the dynamic intersection of robot technology and AI within the dental domain. The null hypothesis was that no evidence was found to support robotic technology and AI in dentistry.

2. Materials and Methods

2.1. Search Strategy

This study searched bibliographic databases, including MedLine (via PubMed), Google Scholar, and IEEE, and was conducted on 7 February 2024. The keywords were robotics, dentistry, artificial intelligence, machine learning, deep learning, and application, which were combined with Boolean terms (AND, OR). Supplementary Table S1 delineates the search strategy employed. A comprehensive screening and cross-reference process involved hand-searching the included full texts and excluded reviews to identify the literature not found through the search strategy.

2.2. Inclusion and Exclusion Criteria

The inclusion criteria were full-text articles without language restrictions, specifically focusing on the application of robotics and AI to aid treatments in various dental disciplines, such as prosthodontics, orthodontics, implants, endodontics, and oral surgery, among others.

Exclusion criteria included studies on using robots and AI as simulated patients or in conversational applications, designs of robots lacking autonomous action capabilities, publications that did not support open access with free availability, and publications featuring essays, conference abstracts, letters, and commentaries. Additionally, works published prior to 2015 were excluded from consideration. Literature on robot technology in oral and maxillofacial surgery was also excluded, given that most robot systems utilized in medical contexts are not practical for application in general dentistry.

2.3. Selection of Articles and Information Extraction

Two researchers (K.J. and G.V.O.F.) independently screened the articles by initially reading the title and abstract; in case of divergences, a third author was consulted (L.M.N.). Then, the studies that met the inclusion criteria or those with insufficient data in the abstract to make a clear decision were selected to evaluate the entire manuscript. Duplicate articles were removed. The same researchers and process were applied to the full-text reading. The following information was extracted from the articles: author and year of publication, details about robotics and AI, and general results.

3. Results

3.1. Study Selection

A comprehensive search across all three databases yielded 296 articles; two [4,5] were included after a manual search. After removing 83 duplicates, 215 were eligible for initial screening based on titles and abstracts. Following this screening, 190 articles were identified as valuable, of which 135 were subsequently excluded. The primary reasons for exclusion were the unavailability of full-text versions and literature published before 2015. The complete texts of 55 articles were included in this comprehensive review for qualitative synthesis (39 articles for robotics in dentistry and 16 articles for AI, including its subset, machine learning (ML), in dentistry (Figure 1).

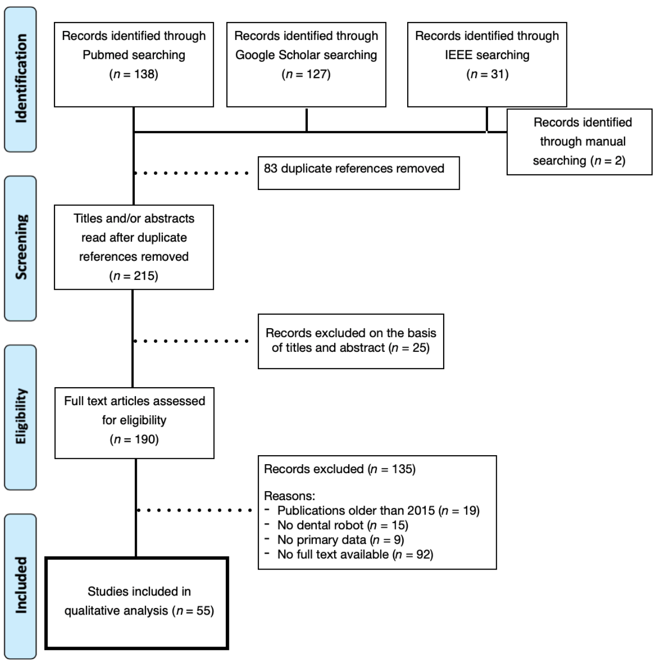

Figure 1. PRISMA flow diagram for study selection.

3.2. Study Demography

In terms of the geographical distribution of robotics publications, Chinese authors emerged as the leading contributors, trailed by Japan and the United States. When examining the timeline of publications, it is evident that since 2000, there has been a consistent upward trajectory in the number of articles dedicated to dentistry robots, with the peak occurring between 2011 and 2015. On the other hand, a significant rise in publications related to ML dentistry was observed, indicating an increase from 2 publications in 2016 to 14 in 2018 (Figure 2).

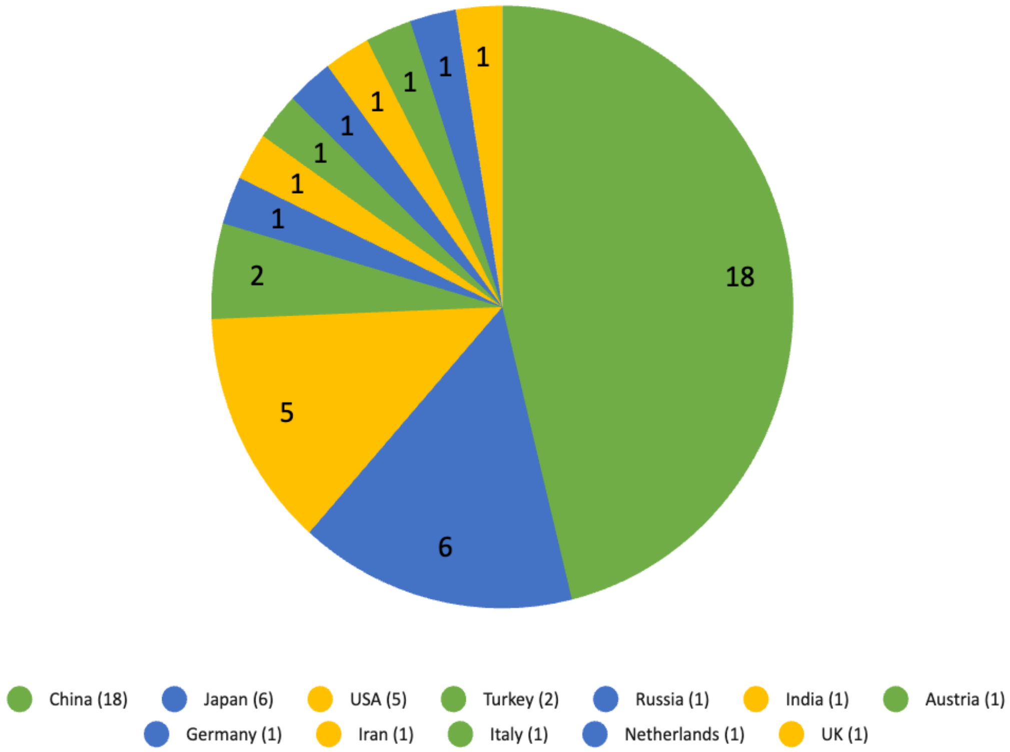

Figure 2. Country of origin of the robotics research project.

3.3. Robotics Results per Field of Dentistry

Orthodontics, implantology, and surgery comprised 17 articles in this study, establishing them as the predominant categories. Among the various robots discussed in the literature, the "Suresmile" robot stood out, mentioned in eight articles [1–4,10–13].

3.3.1. Orthodontics

SureSmile, developed by Werner Butscher, is a prominent robot in orthodontics for the automated bending of orthodontic wires, utilizing 3D imaging, computer techniques, and CAD/CAM for patient orthodontic care. Clinical evidence extensively explores its advantages, comparing outcomes with manual bending and assessing accuracy in tooth positioning, reporting a 34% increase in result outcomes [10–12,14,15]. Other archwire bending initiatives, particularly from Eastern Asia, focus on design improvement [13,14,16,17]. Lingual Archwire Manufacturing and Design Aid (LAMDA), developed by Alfredo Gilbert, involves limited experiments, with its application restricted by a robot bending the archwire in two planes [18]. Additionally, the Cartesian-type archwire bending robot system and Motoman UP6 have been introduced in the market. The Cartesian-type archwire bending robot system has limitations that restrict its application in orthodontics. Challenges include concerns about the accuracy and flexibility of these robots, necessitating constant human supervision to ensure precise work, particularly within the complexities of an oral cavity [18–20]. The clinical evidence for all other robotic systems, besides SureSmile, is scarce and needs further research.

3.3.2. Implantology and Surgery

The reviewed literature included eight articles on implantology and dental surgery, collectively representing the second-largest category within the field of robot technology in dentistry. Except for two articles discussing a commercially available robot, the majority fell under the basic research group [21]. Techniques included indirect assistance in creating drill guides, direct drill guidance through coordinate measuring machines or computer vision, and telerobotic systems with haptic feedback during implant drilling [21–24]. Yuan et al. [25] highlighted the development of an ultra-short pulse laser robot-controlled system for implant site preparation. Most articles focused on hard tissue surgery, while a Russian [26] research group developed a soft tissue contact probe for (diode) laser surgery, and another study utilized a robot in a measurement setup for analyzing tooth removal procedures for scientific and educational purposes [27].

The THETA robotic dental implant system, developed by Hangzhou Jianjia Robot Company (Hangzhou, China), is an integrated implant surgical robot with a mechanical arm, a binocular camera, and an operation tool capable of performing dental implant surgery. The Yizhimei computer-assisted dynamic navigation system by Digital-health Care Co., Ltd. in Suzhou, China, is another system designed for dental implant surgery, featuring a cart, infrared tracking, and an implant handpiece with a locator [28]. Sun et al. proposed automated dental implantation using image-guided robotics [29]. Li et al. developed a compact robotic system for dental implant surgery with tendon-sheath transmission [30]. “Yomi,” the first FDA-approved robotic surgery system for dental implant surgery in the United States, was introduced in 2017 [31]. An optical-based dental implant robot system (DIRS) employs the “Eye to Hand” type and focuses on achieving high accuracy through system calibration, spatial registration, and needle tip positioning [32].

3.4. AI Results per Fields of Dentistry

3.4.1. AI in Orthodontics

In orthodontics, ML optimizes aligner planning by learning from historical treatment data, promising more personalized and effective interventions. Thanthornwong [33] utilized orthodontic impressions and facial photographs to assess orthodontic treatment needs. They divided the data into 80% training data and 20% test data, creating five models and selecting the one with the highest specificity (100%), sensitivity (95%), and accuracy (96%). Two experienced orthodontists predicted treatment needs, and the model was validated with data from 200 patients. The model demonstrated high agreement with orthodontists (kappa value = 1.00 with orthodontist A, kappa value = 0.894 with orthodontist B), establishing its effectiveness for evaluating treatment needs. Data ownership involves legal and ethical rights over generated or collected data. Kim et al. [34,35] applied CNN to lateral cephalograms and CBCT for posterior–anterior cephalometric landmark tracing, achieving high accuracy (88.43%, 80.4%). Although a 2 mm error was reported for landmark identification in postero–anterior (PA) cephalograms, the overall results were deemed satisfactory. In machine learning, including dental applications, the entity owning the training data holds central rights. Data mining extracts insights from large datasets, supporting decision-making. Currently, there is no specification on data ownership for machine learning models, emphasizing the need for clear policies, especially in healthcare, where historical treatment data may belong to institutions, healthcare providers, or patients. Table 1 summarizes a few of the many studies supporting AI use in orthodontics.

Table 1. AI in orthodontics.

Author and Year	Purpose	AI Techniques	Accuracy
Thanthornwong et al., 2018 [33]	Orthodontic treatment assessment	Bayesian-based decision support system	96%
Kim et al., 2021 [35]	Posteroanterior (PA) cephalometric landmark analysis	Multi-stage CNN	88.43% (lateral cephalograms), 80.4% (CBCT)
Jung et al., 2016 [36]	Diagnosis of extractions	Neural network machine learning	93% (identification of patients needing extractions), 84% (extraction plan)
Tanikawa et al., 2021 [37]	Prediction of facial morphology after orthognathic surgery and orthodontic treatment	Landmark-based geometric morphometric methods (GMMs), deep learning	81% at a system error of <1 mm, 100% at a system error of <2%

3.4.2. AI in Dental Radiology

Artificial neural network (ANN) methodologies have been implemented in dentistry for diagnosing visually confirmed conditions such as dental caries and impacted teeth, as well as for diagnostic purposes in dental radiography [38]. Diagnocat [39], an AI-based radiology software, employs advanced algorithms to analyze dental imaging precisely, detecting conditions such as caries, restorations, root canals, missing teeth, implants, and apical pathology through tooth density changes, pattern recognition, and shape and density analysis. To identify the distal root shape of the mandibular first molar on panoramic dental radiographs, Hiraiwa et al. [40] employed deep learning systems, specifically AlexNet and GoogleNet. The outcomes revealed that both deep learning algorithms exhibited slightly enhanced diagnostic performance compared to radiologists with substantial training. This revolutionary technology significantly extends its impact to head and neck pathology detection, enhancing dental diagnostics. Despite its capabilities, AI software does not provide a formal diagnosis. Instead, it serves as an additional instrument for healthcare professionals. Healthcare providers remain responsible for a comprehensive evaluation, incorporating clinical information and patient history, to ensure accurate and reliable diagnoses. Table 2 shows a comprehensive overview of the literature discussing the use of AI in dental radiology.

Table 2. AI in dental radiology.

Author and Year	Purpose	Diagnostic Techniques	AI Methods	Accuracy
Setzer et al., 2020 [41]	Periapical lesion diagnosis	CBCT	Deep learning algorithm	93%
Johari et al., 2017 [42]	Vertical root fracture diagnosis	Periapical radiographs	PNN	96.6%
Jeon et al., 2021 [43]	Root canal morphology	Panoramic radiography	CNN-based DL	95.1%
Qiao et al., 2020 [44]	Root canal length measurement	Circuit system	Neural network model	95%

3.4.3. AI in Dental Implantology

The integration of AI in implantology, particularly with cone beam computed tomography (CBCT), proves impactful in radiographic anatomic pattern recognition. AI processes extensive datasets, allowing it to discern subtle patterns in a patient's anatomy, which is crucial for recognizing structures like nerves. This capability enhances surgical planning by precisely locating structures using CBCT data, contributing to more informed and safer implant procedures. Lee and Jeong [45] utilized a dataset of 10,770 radiographic images representing three implant types to train a deep CNN model. The study compared the implant recognition accuracy of board-certified periodontists and the AI model, considering periapical, panoramic, or combined images. The results showed varying accuracy for different implant types, with both the AI model and periodontists exhibiting higher specificity and sensitivity when both periapical and panoramic images were used. Beyond anatomical recognition, AI in implantology reviews historical implant data and factors like bone density, patient anatomy, and treatment outcomes, providing suggestions for implant models, sizes, and makes. Two studies included in this review utilized AI models to optimize implant design through finite element analysis (FEA) methods [46,47]. Li et al. [48] replaced the FEA model with an AI algorithm to optimize implant design variables, resulting in a 36.6% reduction in stress at the implant–bone interface compared to the FEA model. Roy et al. [47] aimed to optimize implant design parameters using an artificial neural network (ANN) and genetic algorithms, showing the feasibility of AI in substituting FEA calculations. Multiple other studies also discuss the role of AI in dental implantology (Table 3). While these studies agreed on the potential of AI models to optimize implant designs, further investigations are warranted to enhance AI calculations and evaluate outcomes in vitro, animal, and clinical studies.

Table 3. AI in dental implantology.

Author and Year	Purpose	Conventional Technique	AI Methods
Elgarba et al., 2023 [46]	Segmentation of dental implants	Automated segmentation (AS)	CNN
Roy et al., 2018 [47]	Design of dental implants	Finite element analysis	Genetic algorithm, ANN
Li et al., 2019 [48]	Reduction in stress at the implant–bone interface	Finite element method	Support vector regression, k-sigma method, interval method
Liu et al., 2018 [49]	Prediction of dental implant failure	Statistical correlation significance analysis	Decision tree (DT), support vector machines, logistic regressions, bagging, and AdaBoost

3.4.4. Technology Readiness Level

Technology readiness levels (TRLs) are a measurement system assessing the maturity of a technology project. With nine levels (Table 4), from TRL 1 (lowest) to TRL 9 (highest), it evaluates progress based on specific parameters, providing a standardized measure of a technology's developmental stage. The average technological readiness level across all 39 robotics studies was 4.3, with a median of 4 (Table 5). Commercially available technology was identified in orthodontics (2), implantology (1), gnathology (1), endodontics (1), and student education (1).

Table 4. Technology readiness levels.

Technology Readiness Level	Description
1	Basic Principles Observed
2	Technology Concept Formulated
3	Experimental Proof of Concept
4	Technology Validated in Laboratory Environment
5	Technology Validated in Relevant Environment
6	System Demonstrated in Relevant Environment
7	System Prototype Demonstrated in Operational Environment
8	Actual System Completed and Qualified
9	Full-Scale Deployment

Table 5. Technology readiness level of all articles in different dental fields.

Fields	Discovery			Development			Demonstration		Deployment	Number of Articles per Field
	TRL									
	1	2	3	4	5	6	7	8	9	
Orthodontics			[50–54]	[13,17]					[14,15]	9
Implantology and surgery		[26,32]	[22–25,27]						[21]	8
Prosthodontics			[55]							1
Restorative dentistry				[4,56]	[52,57,58]					5
Gnathology			[59,60]						[61]	3
General practice			[62]	[29,63–67]						7
Education of students				[68]					[9]	2
Education of patients						[69]	[70]			2
Endodontics		[71]							[72]	2

4. Discussion

4.1. Summary of Results

The objective of this systematic research was to evaluate the existing dental literature to provide dental clinicians with a comprehensive and transparent overview of robotics and AI initiatives in dentistry. While De Ceulaer et al. identified a rising trend in robotic developments for oral and maxillofacial, craniofacial, and head and neck surgery, a similar robust trend was not observed in dentistry, with publications stabilizing at around six per year [73]. Similarly, a review by Grischke et al. revealed a notable surge in ML dentistry from 2016 to 2018 [7]. However, few studies on machine learning have been published in dental journals. Still, it is clear that there is a lot of potential in this specific area of research. Future studies could reveal new opportunities, like making data openly available and creating easy-to-use machine learning tools. These developments could be used to improve and personalize things like diagnosis, prognosis, decision-making, and treatment planning in dentistry.

Our review identified 39 articles on robotics and 16 AI articles covering diverse initiatives across all dental fields. The majority fell under the category of basic research, encompassing theoretical and applied aspects where the technology had yet to be compared to existing techniques or tested in patient series. Clinical or epidemiological research articles were predominantly found in orthodontics, implantology, and education, possibly due to the ease of testing on patients in these areas without requiring direct interaction between the robot and patients. No cost-effectiveness studies were identified, and the overall quality of the literature in this review can be considered low.

Approximately half (41%) of the included studies had a technology readiness level (TRL) not exceeding level three, indicating a proof of concept. About 34% of the described technology was validated in a laboratory or relevant environment, while 15% described a workflow involving commercially available robot technology. Notably, the same robot technology was often described in multiple papers, exemplified by the Suresmile system, which appeared in eight articles. These findings align with a recent study by Grischke et al. [7], which reported that approximately 75% of the articles were within a TRL of three.

Demographically, over half (61%) of all included articles originated from China, South Korea, or Japan (East Asia). However, it is crucial to note that some articles may have similar research data published in different journals or languages, potentially leading to overestimating East Asian results. In the past two decades, projects have largely avoided direct contact between robots and human subjects, except for a recent case report featuring the implantology robot Yomi. In the research community, various approaches are being explored to understand the potential and challenges of incorporating robotics, AI, and ML into dentistry. As a result, an increase in the speed of innovation in this field over the next few years is anticipated.

Moreover, the application of AI in dentistry is expansive, leaving virtually no aspect unaffected. As many AI dental studies are available to potentially continue the discussion, we will focus on recent AI topics that may interest readers, encompassing pediatric dentistry, collaboration, dental education, limitations, and risks.

4.2. Pediatric Dentistry

A 2023 systematic review of AI in pediatric dentistry revealed that most studies used AI to evaluate radiographs or photographs, with a handful analyzing questionnaires and samples. Generally, the use of AI in pediatric dentistry appears to be limited, requiring further studies [74]. Another 2023 review found that AI was frequently used to diagnose, support clinical decisions, develop preventive strategies, and plan treatment [75]. With the availability of smart toothbrushes from manufacturers such as Kolibree, Colgate, Philips Sonicare, and Oral-B (among others), children can access AI dental technology. Notably, a Kolibree app gamifies brushing using augmented reality, and its AI-embedded smart-connected toothbrushes can create personalized recommendations based on users' brushing patterns [76]. These features could potentially improve compliance and oral hygiene in children.

4.3. Collaborations

AI can be used to improve collaborations on many levels. The application of AI in dentistry is an interdisciplinary collaboration. This relationship is dependent on other specialties such as computer science, data science, statistics, and engineering. Therefore, dental professionals should ideally have some knowledge of these specialties. Barring this, a close collaborative relationship between these specialties will be necessary for continued innovation in this new space. In dentistry, collaborations will undoubtedly form, given AI's ability to learn from large and complex multimodal datasets. An AI model could conceivably draw upon other datasets such as patient demographics, caries risks, intraoral photographs, radiographs, clinical findings, and prior treatment to not only assist in diagnosis but also recommend treatment, assist during treatment, and predict outcomes. This could result in a more comprehensive patient treatment model that starts from the first point of contact and ends when a patient leaves a dental practice. The interaction between the dentist and the AI software takes AI collaboration one step further. The concept of clinical decision support could allow AI algorithms to provide real-time guidance, helping the dentist make informed decisions and thereby reducing the risk of errors [77]. With collaboration occurring at many levels, AI use in dentistry will undoubtedly allow dental professionals to provide more specialized and comprehensive care, elevating the profession and improving patient outcomes.

4.4. Dental Education

The role of AI in educating dental students and residents is less explored relative to other aspects of dentistry. Although most dental educators have limited ability to assess AI applications, as they are not trained to do so, Thurzo et al. pointed out that updating dental curricula is inevitable as AI is incorporated into dentistry, reshaping diagnostics, treatment planning, patient management, and telemedicine [78]. Cognizant of this gap, Schwendicke et al. have recommended developing and including a core curriculum on oral and dental AI to help increase dental providers' AI literacy. This would allow providers to critically appraise AI applications on an informed basis [79].

Notwithstanding the foregoing, AI has the potential to revolutionize many aspects of dental health education. Recently, the Harvard School of Dental Medicine has begun to explore the use of generative AI to create synthetic patient cases for teaching. This would allow students and residents to interact with an unlimited number of simulated patients to improve their clinical decision-making skills without risk to human patients [80]. An extension of this generative AI is its potential to generate and grade dental examination questions, customizing the evaluation of students individually. AI also can provide an immersive and interactive learning environment. However, a 2021 scoping review of AI and immersive digital tools found only a limited number of studies investigating immersive dental tools and even fewer using AI. The review found that the usefulness of virtual tools in dental education was inconclusive, requiring further studies to study their integration into dental education [81]. AI can personalize learning with information on demand. A 2024 study found that dental students who used ChatGPT, an AI chatbot able to answer questions and assist with tasks in a human-like manner, performed significantly better on their learning assignments than students who used traditional literature research methodology [82]. Unsurprisingly, and perhaps slightly discomforting, ChatGPT created a 2023 publication titled "Artificial Intelligence in Healthcare and Education" [76]. Although repetitive, lacking in creativity, and missing citations, the content was nonetheless factual and informative. It highlighted the challenges of obtaining high-quality data and concluded that with any new technology, further research and regulation are required to maximize benefits, overcome limitations, and minimize potential risks [76].

4.5. Limitations

This review encountered a few limitations: (1) In total, 92 out of 188 articles were excluded due to the unavailability of a full text, potentially influencing the interpretation of results. Upon aligning with included articles based on titles and abstracts, it was found that their inclusion would not significantly alter the conclusions. (2) The assessment of technological readiness levels relied on information in the papers, and limited details in some articles may have led to minor misjudgments. (3) The assumption that any use of the term "robot technology" constitutes its presence might lead to underestimation, as authors might describe their technology differently. Despite these limitations, no vital articles on robot technology in dentistry were missed using this strategy.

There are also practical limitations of AI. AI models are often complex and difficult to comprehend. When the model makes a prediction, the explainability of the decision can be opaque, resulting in a "black box" model. The black box problem refers to the opaqueness and lack of interpretability of AI algorithms, making it difficult to understand how and why the model arrives at its conclusion. Although frameworks are available to improve explainability, such as IBM's explainable artificial intelligence (XAI) [83], they are not widely used, so this area requires further development. Another limitation is the overreliance on commercial companies. Their software is usually proprietary, and the product development and data policies can be opaque. Also, if AI software is implemented as a service, recurring costs can be a significant barrier, potentially exacerbating inequities.

4.6. Risks

There are many risks to AI utilization in dentistry. They include, but are not limited to, reduced critical thinking and problem-solving skills (due to overreliance), bias, and AI generalization. AI models are only as good as the data they are trained on. If data quality and quantity are low, predictions can be unreliable, leading to incorrect diagnoses and treatment. Additionally, if AI is superior to humans, such as in the case of some AI detections of radiographs, it could lead to increased treatment that may not necessarily be warranted. Thus, it may be necessary to educate users on different treatment modalities to offset this effect. Perhaps increased awareness and improved education or possibly the recommendation of nonsurgical intervention or "continued observation" can offset overtreatment. Another consideration is that AI bias can be a risk. Typically, better-performing AI models require large datasets. If the dataset is too small or not representative of a population, bias can be introduced into the model. However, the utilization of vast patient datasets for training AI systems raises significant concerns regarding data privacy and security, necessitating robust safeguards to protect patient confidentiality. Moreover, the inherent biases present in these datasets may propagate into AI algorithms, potentially leading to disparities in diagnosis and treatment recommendations, thereby exacerbating existing healthcare inequalities. Furthermore, regulatory complexities surrounding AI in healthcare pose challenges in ensuring compliance with evolving standards and guidelines, necessitating ongoing efforts to navigate legal and ethical landscapes. Ethical limitations of AI in dentistry include concerns over patient autonomy, transparency, and accountability. Patients must remain informed and involved in their care, with dentists transparent about AI's role. Addressing biases in AI algorithms is crucial to prevent disparities. Additionally, preserving the human aspect of care amid AI integration is essential, ensuring that empathy and compassion remain central. Striking a balance between technological advancement and ethical practice is imperative to uphold patient trust and professional integrity in dental care. Technical limitations and errors inherent in AI systems, coupled with concerns about professional displacement and ethical considerations, underscore the importance of a multidisciplinary approach involving dental professionals, researchers, policymakers, and technology developers.

AI is yet another, albeit powerful, tool for learning and assisting dental professionals in treating patients. Like other dental tools, such as a handpiece, users should be taught safe handling by knowing its capabilities, limitations, and risks. If misused, AI has the potential to harm patients (such as overtreatment or the perpetuation of bias). If used correctly, AI can enhance dental care, elevate the profession, and improve patient outcomes.

5. Conclusions

This paper provides an update on the dental field's technology readiness levels for both AI and robotics by capturing the latest developments of these rapidly evolving technologies. The current paper also provides an analysis of the geographical distribution of AI and robotics research in dentistry.

Within the limitations and risks raised and observed, it was possible to reject the null hypothesis. Dentistry is progressing into a new era characterized by data-driven and robot-assisted medicine. Despite this, the recent advancements in modern robot technology, machine learning (ML), and artificial intelligence (AI) have yet to be fully integrated into dental research, and they have not achieved the technological readiness and cost-efficiency required for entry into the dental market. While educational systems have already embraced these changes, applications such as robot dental assistants in oral surgery, tooth arrangement, orthodontics, and material testing show promise. However, Dentronics faces significant challenges, including high costs, operational difficulties, basic sensory and manipulation capabilities of robotic systems, and a lack of learning abilities.

To truly introduce Dentronics, challenges must be overcome, such as enhancing the intuitiveness of systems, implementing widespread education, and introducing more affordable systems. ML is set to advance diagnostic measures, simplify treatment planning, reduce errors, and ultimately enhance the effectiveness of the overall health system. However, the current use of ML is confined to pilot cases and narrowly defined research questions. The key is developing more adaptable systems with broader applications to achieve valuable, human-level performance. Future dentists must be acquainted with Dentronics, acquiring both digital and real-world human–robot interaction skills.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/surgeries5020025/s1, Table S1. Search Strategy per Database.

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