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Review

AI and Face-Driven Orthodontics: A Scoping Review of Digital Advances in Diagnosis and Treatment Planning

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Abstract: In the age of artificial intelligence (AI), technological progress is changing established workflows and enabling some basic routines to be updated. In dentistry, the patient's face is a crucial part of treatment planning, although it has always been difficult to grasp in an analytical way. This review highlights the current digital advances that, thanks to AI tools, allow us to implement facial features beyond symmetry and proportionality and incorporate facial analysis into diagnosis and treatment planning in orthodontics. A Scopus literature search was conducted to identify the topics with the greatest research potential within digital orthodontics over the last five years. The most researched and cited topic was artificial intelligence and its applications in orthodontics. Apart from automated 2D or 3D cephalometric analysis, AI finds its application in facial analysis, decision-making algorithms as well as in the evaluation of treatment progress and retention. Together with AI, other digital advances are shaping the face of today's orthodontics. Without any doubts, the era of "old" orthodontics is at its end, and modern, face-driven orthodontics is on the way to becoming a reality in modern orthodontic practices.

Keywords: artificial intelligence; 3D printing; face scan; CBCT; facial analysis; treatment evaluation; treatment planning

Citation: Tomášik, J.; Zsoldos, M.; Oravcová, Ľ.; Lifková, M.; Pavleová, G.; Strunga, M.; Thurzo, A. AI and Face-Driven Orthodontics: A Scoping Review of Digital Advances in Diagnosis and Treatment Planning. *AI* **2024**, *5*, 158–176. https://doi.org/10.3390/ai5010009

Academic Editor: Tim Hulsen

Received: 26 November 2023
Revised: 29 December 2023
Accepted: 3 January 2024
Published: 5 January 2024

1. Introduction

Modern orthodontics (orthodontics of the 21st century) has been shifting from "occlusion-driven" to "face-driven". The term "soft tissues paradigm" emerged at the end of the 20th century and stressed the importance to approach each patient requiring any kind of orthodontic treatment as an individual with a specific appearance, a unique facial composition and, last, but not least, their own expectations, while putting the aesthetics in focus [1]. In contrast, the Angle paradigm considered the ideal dental occlusion as paramount. In so doing, the role of soft tissues was completely disregarded or, at best, understated. With ever-evolving digital technologies and artificial intelligence, as well as established aesthetic rules and guidelines based on the assessment of anatomy, physiognomy and natural aesthetic parameters, the advent of advanced diagnostic methods as well as novel treatment modalities is underway [2].

Traditionally, an orthodontic treatment plan was based purely on hard tissue relationships as diagnosed using dental cast models and 2D cephalometric X-ray analyses [3]. At the end of the 20th century, the cone-beam CT (CBCT), consisting of a cone-shaped beam of X-rays and a reciprocating detector rotating around the patient, was introduced, which enabled obtaining 3D images with lower radiation doses compared to conventional CT scans [4]. With the increasing availability of cameras (especially digital cameras), taking intraoral and extraoral pictures before and after treatment has become a part of orthodontic documentation to help assess the impact of treatment on patients' dental arches and—to some extent—on their facial appearance. However, there are some limitations to the two-dimensional "reality". Three- and four-dimensional imaging methods have been developed to compensate for the missing depth in standard pictures. Active stereophotogrammetry is based on the analysis of a detected image that is projected on the scanned object. Passive stereophotogrammetry merges multiple pictures from different angles and computes one 3D object [5]. Adding the element of time to diagnostics allows for more detailed analyses, e.g., in cases of patients suffering from a cleft lip and/or palate or with facial asymmetries, while age is also an important diagnostic factor [6,7].

Intraoral scanning, laser scanning, cone-beam CT (CBCT), stereophotogrammetry and 3D images form a crucial part of modern orthodontics. Despite the fact that these technologies have their limitations and drawbacks, 3D technologies are taking the lead, especially in more complex cases [8]. They provide detailed and realistic input data to diagnostic and treatment-planning software [9–11]. Data from intraoral and/or facial scanners can combine with CBCT scans in order to allow for a better understanding of underlying clinical conditions [12,13]. Artificial intelligence allows for automatic cephalometric tracing that is both precise and accurate, thus making treatment planning more time-efficient [14,15]. The analysis of 3D images obtained from facial 3D scanners can be automatised using curvature maps and sagittal profile analyses [16]. Furthermore, intraoral scanners feed data into specific software that allows for planning changes in teeth positions, the shape of dental arches and interdental relations. Linking such software to various manufacturers of dental aligners completes the circle of a fully digital workflow in orthodontic treatment planning [17,18]. Modern protocols using pre- and post-treatment intraoral scans and an initial pretreatment CBCT scan can accurately predict the final post-treatment position of roots, thus eliminating the need of repeated X-ray exposure [12]. Even though the radiation dose of modern CBCT scanners is lower nowadays compared to the use of cephalostat in the past, following the ALARA (as low as reasonably achievable) principle, each CBCT scan acquisition should be well justified, even more so in treating growing patients [12,19,20]. As an alternative, MRI scans can be used in some patients (e.g., with craniofacial disorders); however, these remain inferior for orthodontic cephalometric analysis [21]. In a similar manner, digital photography alone can be used, to some extent, for landmark identification and facial analysis to alleviate the need of more invasive investigations [22,23].

Information technology has been applied in orthodontics for many decades. Extracting distances and angles from standardised cephalography and/or taking measurements on dental plaster models leads to the quantification of data. These can be further processed, which allows for the objective diagnosis of malocclusions based on various indices and standards [24]. Artificial intelligence (AI) has received much attention over the last few years. The term refers to such intelligent behaviour of computers that mimics the performance of humans in tasks related to cognition [25]. AI can be divided into two categories when it comes to its application in medicine: virtual AI, which includes electronic health record systems or systems assisting in treatment decisions, including surgical interventions, and predictive models in the disease state; on the other hand, physical AI concerns various "smart" prostheses, smart biomedical implants for health monitoring or robot-assisted surgeries [17,26–29]. Regarding AI-assisted decision making, it is necessary to emphasise that, whereas evidence-based dentistry drives dental professionals' daily decisions, machine-learning models learn from human expertise, and thus AI can serve as a good advisor that absorbs all relevant information available [30]. This might be of added value for less-experienced clinicians; however, some authors stress the need for an individualised approach granted by the human factor [31,32].

It has become clear that AI algorithms and the future of evidence-based orthodontics are inextricably interwoven. With the huge amount of digital data available, AI is expected to be a key player in yielding novel findings, which will ultimately lead to a treatment planning and diagnosis revolution in the future [33]. The aim of this paper is to identify the most-cited articles on digital advances within the field of orthodontics as ranked by the field-weighted citation impact ratio provided by Scopus, and to discuss the most-cited technologies in the context of modern orthodontics and dentistry.

2. Materials and Methods

This scoping review investigates the scope of current research on the use of digital technologies in facially driven orthodontic treatment. A literature search was conducted using the Scopus search engine to identify existing relevant studies: articles, reviews, conference papers and short surveys. The search was limited to papers written in English and published in years 2018–2023. The keywords used for the search were "orthodontics", "digital technologies", "facial analysis", "treatment planning", "stereophotogrammetry", "CBCT", "3D", "4D", "intraoral scan", "facial scan", "soft tissue analysis", "artificial intelligence" and "AI". The search query was as follows:

((orthodontics) AND (digital AND technologies) AND (facial AND analysis) AND ((treatment) AND ((planning) OR (plan)))) AND ((stereophotogrammetry) OR (cbct) OR (3d) OR (4d) OR (intraoral AND scan) OR (facial AND scan) OR (soft AND tissue AND analysis) OR (artificial AND intelligence) OR (ai)) AND PUBYEAR > 2017 AND PUBYEAR < 2024 AND TITLE-ABS-KEY (orthodontics)

Since the objective of this scoping review was to assess the trends of using modern technologies in facially driven orthodontic diagnosis and treatment planning, the goal was to identify the most-cited research in the relevant field and to assess the technologies studied therein. The field-weighted citation impact (FWCI) ratio within the Scopus search engine was used to identify the most-cited articles within the field. Because the aim of this review was to identify novel digital methods, the search was modified to identify articles written from 2018 to 2023. To ensure the searched articles were directly linked to orthodontics, the term "Orthodontics" needed to be included within the title, abstract or keywords.

The titles and abstracts of the searched articles were screened and relevant articles were checked for their FWCI value to identify the top twenty articles. Based on the content of these articles, focus areas to be discussed were identified.

3. Results

The search was carried out on 31 October 2023 at 1:47 pm. The search query yielded 147 results. After selecting only articles, reviews, conference papers and short surveys written in English, the number of papers dropped to 133. Their distributions with regard to the year of publication, subject area and document type are depicted in Figures 1–3, respectively.

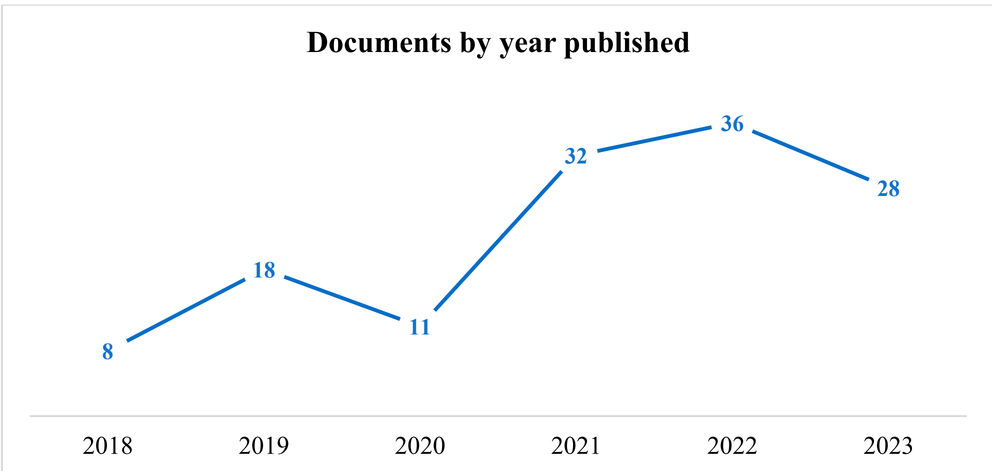

Figure 1. Number of searched documents per year from 2018 to 2023.

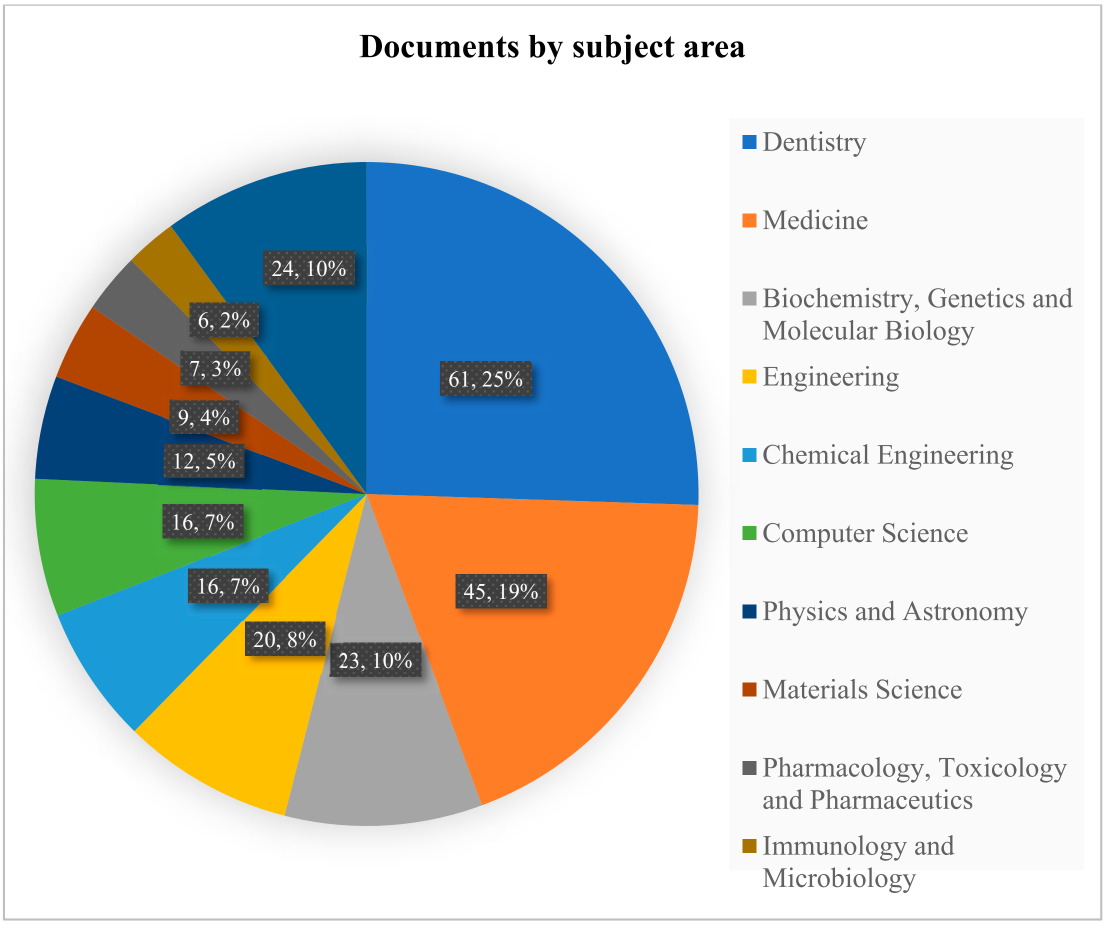

Figure 2. Distribution of searched documents within various subject areas.

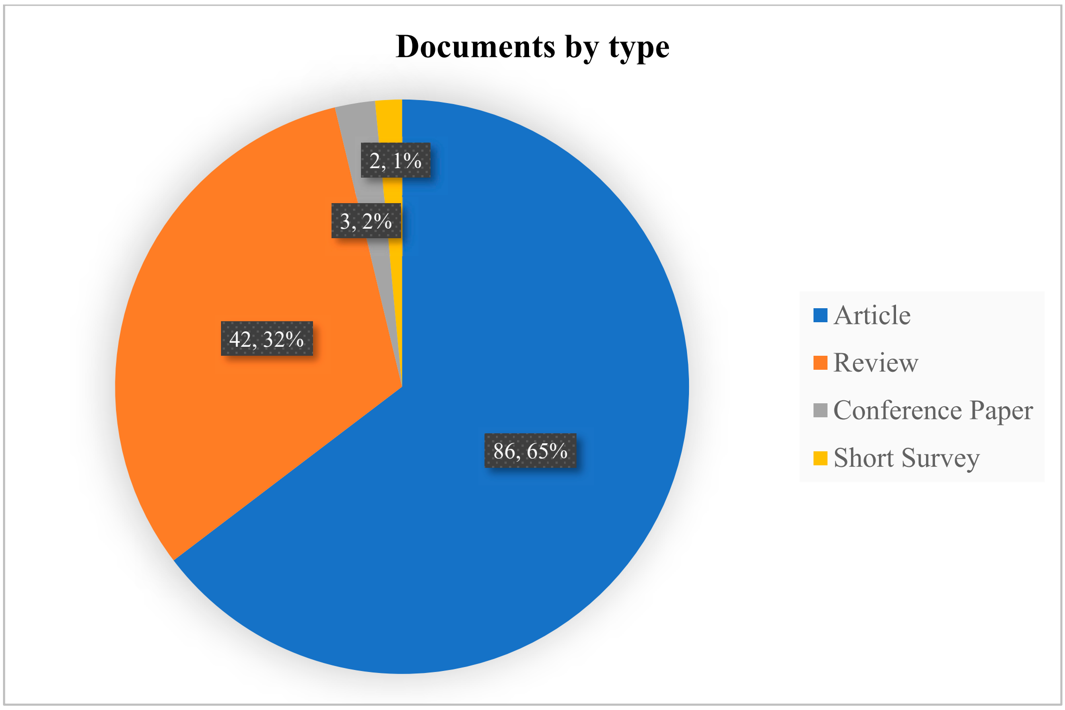

Figure 3. Proportion of various types of searched documents.

The greatest number of searched articles (n = 36) was published in 2022, whereas the smallest number (n = 8) was published in 2018. More than a quarter of all documents (25.5%) were published with a primary focus on dentistry, followed by medicine (18.8%), biochemistry, genetics and molecular biology (9.6%), engineering and chemical engineering (8.4% and 6.7%, respectively) and computer science (6.7%). The subject matter of the remaining fifty-eight documents varied from social sciences to material science. The largest proportion of searched documents (64.7%, n = 86) were articles, followed by reviews (31.6%, n = 42).

Based on the titles and abstracts, papers that were not relevant to the studied topic were excluded, which downsized the number from 133 to 101. Only sixty-nine articles had their FWCI value calculated. Table 1 lists twenty articles with the highest FWCI values.

Table 1. Top twenty most-cited articles relevant to the search query.

#	Title	Authors	Year	Main Focus	FWCI
1	A comparison between stereophotogrammetry and smartphone structured light technology for three-dimensional face scanning [34]	D'Ettorre, Giorgio; Farronato, Marco; Candida, Ettore; Quinzi, Vincenzo; Grippaudo, Cristina	2022	Face scanning	15.68
2	Deep convolutional neural network-based automated segmentation and classification of teeth with orthodontic brackets on cone-beam computed-Tomographic images: A validation study [35]	Ayidh Alqahtani, Khalid; Jacobs, Reinhilde; Smolders, Andreas; Van Gerven, Adriaan; Willems, Holger; Shujaat, Sohaib; Shaheen, Eman	2023	AI	13.2
3	Artificial intelligence in dentistry—A review [30]	Ding, Hao; Wu, Jiamin; Zhao, Wuyuan; Matinlinna, Jukka P.; Burrow, Michael F.; Tsoi, James K. H.	2023	AI	10.92
4	Artificial Intelligence: Applications in orthognathic surgery [36]	Bouletreau P.; Makaremi M.; Ibrahim B.; Louvrier A.; Sigaux N.	2019	AI	10.67
5	Where Is the Artificial Intelligence Applied in Dentistry? Systematic Review and Literature Analysis [37]	Thurzo, Andrej; Urbanová, Wanda; Novák, B.; Czako, Ladislav; Siebert, Tomáš; Stano; Mareková, Simona; Fountoulaki, Georgia; Kosnáčová, Helena; Varga, Ivan	2022	AI	5.83
6	Current concepts in orthognathic surgery [38]	Naran, Sanjay; Steinbacher, Derek M.; Taylor, Jesse A.	2018	Digital planning	5.62
7	Current state of the art in the use of augmented reality in dentistry: A systematic review of the literature [39]	Farronato, Marco; Maspero, Cinzia; Lanteri, Valentina; Fama, Andrea; Ferrati, Francesco; Pettenuzzo, Alessandro; Farronato, Davide	2019	Augmented reality	5.26
8	Machine learning in orthodontics: Automated facial analysis of vertical dimension for increased precision and efficiency [40]	Rousseau, Maxime; Retrouvey, Jean-Marc	2022	AI	5.22
9	Artificial Intelligence Systems Assisting in the Assessment of the Course and Retention of Orthodontic Treatment [41]	Strunga, Martin; Urban, Renáta; Surovková, Jana; Thurzo, Andrej	2023	AI	4.97
10	A Review of 3D Printing in Dentistry: Technologies, Affecting Factors, and Applications [42]	Tian, Yueyi; Chen, ChunXu; Xu, Xiaotong; Wang, Jiayin; Hou, Xingyu; Li, Kelun; Lu, Xinyue; Shi, HaoYu; Lee, Eui-Seok; Jiang, Heng Bo	2021	3D printing	4.51

Table 1. *Cont.*

#	Title	Authors	Year	Main Focus	FWCI
11	Scope and performance of artificial intelligence technology in orthodontic diagnosis, treatment planning, and clinical decision-making—A systematic review [43]	Khanagar, Sanjeev B.; Al-Ehaideb, Ali; Vishwanathaiah, Satish; Maganur, Prabhadevi C.; Patil, Shankargouda; Naik, Sachin; Baeshen, Hosam A.; Sarode, Sachin S.	2021	AI	4.47
12	Machine learning and orthodontics, current trends and the future opportunities: A scoping review [44]	Mohammad-Rahimi, Hossein; Nadimi, Mohadeseh; Rohban, Mohammad Hossein; Shamsoddin, Erfan; Lee, Victor Y.; Motamedian, Saeed Reza	2021	AI	4.02
13	The last decade in orthodontics: A scoping review of the hits, misses and the near misses! [45]	Gandedkar, Narayan H.; Vaid, Nikhilesh R.; Darendeliler, M. Ali; Premjani, Pratik; Ferguson, Donald J.	2019	3D printing	3.82
14	Advancements in Dentistry with Artificial Intelligence: Current Clinical Applications and Future Perspectives [46]	Fatima, Anum; Shafi, Imran; Afzal, Hammad; Díez, Isabel De La Torre; Lourdes, Del Rio-Solá M.; Breñosa, Jose; Espinosa, Julio César Martínez; Ashraf, Imran	2022	AI	3.59
15	Three-dimensional prediction of roots position through cone-beam computed tomography scans-digital model superimposition: A novel method [12]	Staderini, Edoardo,; Guglielmi, Federica; Cornelis, Marie A.; Cattaneo, Paolo M.	2019	CBCT, intraoral scanning	3.46
16	Augmented reality in dentistry: a current perspective [47]	Kwon, Ho-Beom; Park, Young-Seok; Han, Jung-Suk	2018	Augmented reality	2.83
17	Decoding Deep Learning applications for diagnosis and treatment planning [48]	Retrouvey, Jean-Marc; Conley, Richard Scott	2022	AI	2.35
18	Smartphone-Based Facial Scanning as a Viable Tool for Facially Driven Orthodontics? [49]	Thurzo, Andrej; Strunga, Martin; Havlínová, Romana; Reháková, Katarína; Urban, Renata; Surovková, Jana; Kurilová, Veronika	2022	Face scan	2.19
19	Effectiveness of a Novel 3D-Printed Nasoalveolar Molding Appliance (D-NAM) on Improving the Maxillary Arch Dimensions in Unilateral Cleft Lip and Palate Infants: A Randomized Controlled Trial [50]	Abd El-Ghafour, Mohamed; Aboulhassan, Mamdouh A.; Fayed, Mona M. Salah; El-Beialy, Amr Ragab; Eid, Faten Hussein Kamel; Hegab, Seif El-Din; El-Gendi, Mahmoud; Emara, Dawlat	2020	3D printing	2.18
20	Radiomics and Machine Learning in Oral Healthcare [51]	Leite, André Ferreira; Vasconcelos, Karla de Faria; Willems, Holger; Jacobs, Reinhilde	2020	AI	2.05

Figure 4 depicts the proportion of the primary areas of interest of the top twenty articles ranked by FWCI values. More than half (n = 11) of the selected articles focused on artificial intelligence, while three articles studied or reviewed 3D printing and its application in orthodontics, two articles researched facial scanning, two articles were devoted to augmented reality, one article focused on digital planning in orthodontics and one article was about merging CBCT with intraoral scans.

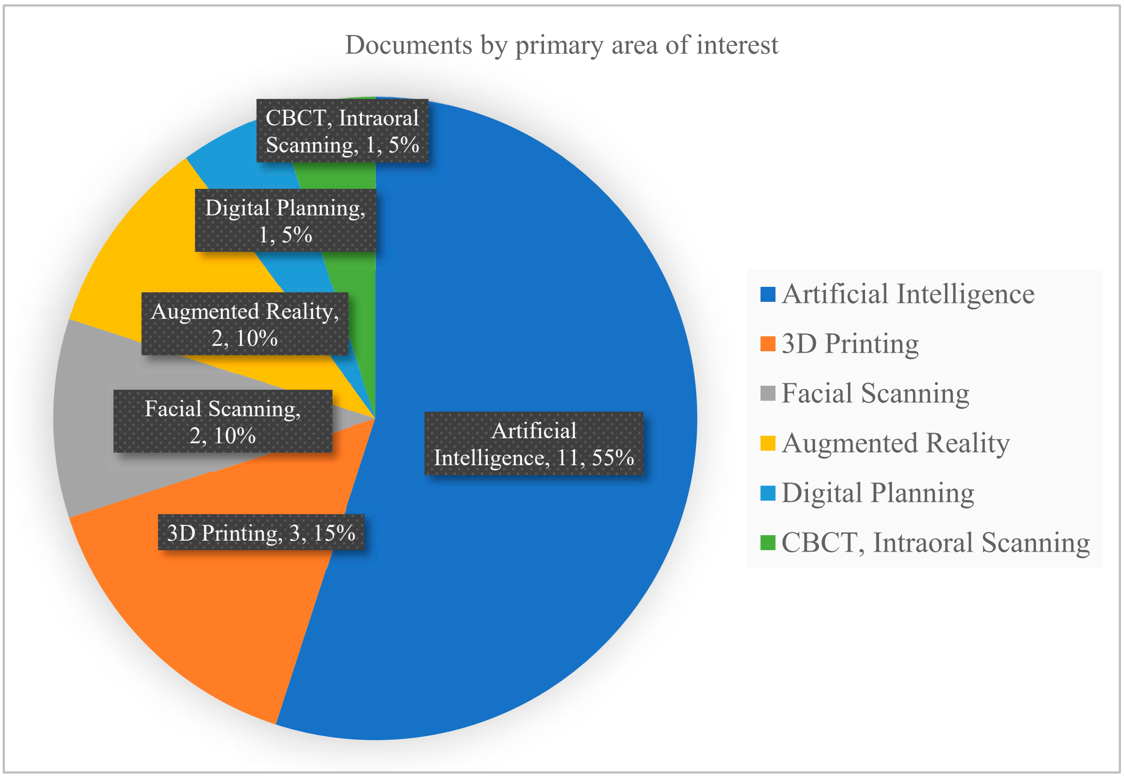

Figure 4. Number of most-cited documents by their primary area of interest.

The results of this scoping review of the recent literature (2018–2023) on the application of digital technologies in orthodontics identified the most relevant articles based on the field-weighted citation impact (FWCI) metric.

The top three digital technologies with the highest research potential were identified as: artificial intelligence (AI), 3D printing and facial scanning. AI has been used in a variety of applications in orthodontics, including cephalometric analysis, facial analysis, treatment planning and patient monitoring. Three-dimensional printing has been used to fabricate orthodontic appliances, surgical guides and aligners. Facial scanning has been used to collect the 3D data of patients' faces, which can be used for diagnosis, treatment planning and aesthetic evaluation.

4. Discussion

Artificial intelligence, 3D printing and facial scanning are the three digital technologies with the greatest research potential, as shown by the FWCI values of the researched articles. In the sections below, their use in orthodontics, as well as the limitations of this scoping review, are discussed.

4.1. Artificial Intelligence Tools and Datasets

Based on the literature search, it seems that radiology is the medical specialty that benefits the most from AI technologies now. A substantial amount of studies focused either on assessing the quality of obtained images or even on identifying CT, MRI scans and X-rays that showed no pathologies [52,53]. On the other hand, AI techniques can also detect pathological processes, e.g., dental caries on radiographs, with an increasing level of accuracy [54].

AI and machine learning—a part of AI that enables machines to expand their capabilities by self-adapting algorithms—find application in various fields within orthodontics [55]. Orthodontists, residents as well as general dentists could use artificial intelligence in diagnosis, decision making, treatment planning as well as patient monitoring. There is an AI functionality that determines the quality of 2D cephalometric X-rays, which could eliminate lower-quality X-rays from being further evaluated due to a possible distortion of the analysis [56]. On top of that, machine learning has found use in both lateral and 3D cephalogram analysis to provide ever-improving quality in landmark localisation [57,58].

Current studies on combining radiomics- and AI-based analysis with a radiologist's input in the field of dentomaxillofacial imaging seem very promising, and it seems that the paradigm shift will have a prominent impact on daily clinical practice as well as curricula in dental schools [51]. What is more, recent research showed that healthcare professionals would prefer if AI algorithms completely replaced manual and semiautomatic approaches in cephalometry—not only because it allows professionals to be more time-efficient, but also because it could increase the accuracy of obtained analysis results [59].

Nowadays, the question is not whether CBCT scans are accurate, but how automated processes can aid professionals in landmark detection, skeletal classification, scan analysis and CBCT data management [57,58,60,61]. Based on current research, it has been concluded that AI can be of great use in assessing mandibular shape asymmetry as well as in the screening of upper airways to measure multiple parameters [62,63].

Artificial intelligence has become an extensively researched field in the past decade [37]. Apart from CBCT analysis and automated teeth segmentation, AI aids professionals in treatment planning, including decisions on teeth extractions [35,43,44]. Even though recent research shows that the AI technology in the abovementioned areas, as well as in determining the degree of cervical vertebra maturation and the prediction of postoperative facial attractiveness, performs exceptionally well, and in its precision and accuracy is comparable to trained professionals, more studies are expected to elucidate and further discuss all the advantages and disadvantages of this novel technology [43,64,65]. It is highly probable that, in a few years, the advantages of AI applications (not only) in orthodontics will be indisputable. The professional opinion shifts depending on the data, experience and evidence. After all, it was only a few years ago that some authors claimed that a lateral cephalogram is more precise and accurate than a 3D CBCT scan [66]. Nobody argues for that now. One of the means of making AI more believable could be demystifying the AI algorithms ("the black box") and making them comprehensible to humans, which may become quite challenging—especially with the ever-increasing complexity of used algorithms [67]. Another way of ensuring trust towards an AI algorithm is its robustness, i.e., good practice in plentiful varied subject populations [68].

AI finds its application at all levels of decision-making processes in orthodontics and medicine (e.g., in such specialties as radiotherapy): data collection, storage, management, processing in-depth analysis, communication and education [69,70]. In-depth analysis also includes automated facial analysis and the use of AI in spotting craniofacial deformities and syndromes on facial scans, and even predicting diseases [27,36,40,48]. There has been some research on scoring facial attractiveness in relation to facial proportions and profiles [71,72]. It is likely that AI will soon enough enable automated aesthetic evaluation, smile design and treatment planning [2]. Based on machine-learning algorithms, given pretreatment variables, AI can successfully predict the duration of an orthodontic treatment [73]. Apart from that, dental monitoring software that uses AI has proven effective during the treatment phase to track progress, as well as during the retention phase to detect relapse and assess the stability of treatment outcomes, with the benefit of assessing the compliance of patients even without regular in-office visits [41]. After all, the goal of modern technologies is to make dental care high-quality, smooth, time-efficient and cost-effective, with improved treatment planning as well as risk management, and AI certainly adds up to that [46,74,75].

AI has found application in human genome sequencing and in analysing large volumes of data that provide priceless information on various biological processes. Information regarding genes that scientists are still gathering and figuring out will play a crucial role in the transition towards a truly personalised medicine. These so-called omics records will likely become an integral part of orthodontic medical records that will be routinely used in diagnosis and treatment planning. It is, therefore, crucial to update orthodontic residency programs, for one needs to adapt and evolve to provide orthodontic care of the highest quality [76].

AI algorithms are currently used for automatic landmark identification, cephalometric analysis, the staging of skeletal maturation, facial recognition and the detection of syndromes, the automatic segmentation of CBCT scans and predicting the need for orthognathic surgery or extractions, and more. The diapason of recent research demonstrates that the accuracy of the discussed technologies is clinically acceptable, rendering them extremely useful in orthodontic practice [77–86]. Recent developments in the area of automated 3D landmarking has led to accuracy improvements [87]. Despite that, some authors emphasise that human intervention is still needed to minimise errors in automatic cephalometric analysis [88]. To eliminate that, more research is needed to increase both the precision and accuracy of AI algorithms. Furthermore, demystifying and explaining how AI works would very much add to its believability.

The rapid advancement of AI has led to the development of numerous AI tools, each with its unique capabilities and applications in orthodontics. These tools can be broadly classified into three categories: supervised learning, unsupervised learning and reinforcement learning.

Supervised learning algorithms are trained on labelled data, where the correct output for each input is known. This type of learning is well-suited for tasks such as cephalometric analysis, where the goal is to identify landmarks and measure facial dimensions. Popular supervised learning algorithms in orthodontics include support vector machines, random forests and neural networks.

Unsupervised learning algorithms are trained on unlabelled data, where the goal is to uncover patterns or structure in the data without the guidance of labelled examples. This type of learning is useful for tasks such as facial recognition and the detection of syndromes, where the focus is on identifying patterns that distinguish between different facial features. Common unsupervised learning algorithms in orthodontics include k-means clustering, principal component analysis and autoencoders.

Reinforcement learning algorithms interact with an environment to maximise a reward signal. This type of learning is well-suited for tasks such as treatment planning, where the goal is to optimise the outcome of orthodontic treatment. Popular reinforcement learning algorithms in orthodontics include deep Q-learning and policy gradient methods.

The choice of AI tool depends on the specific task at hand and the available data. For instance, supervised learning algorithms are typically used for tasks where there is a large amount of labelled data, while unsupervised learning algorithms are more suitable for tasks where there is less labelled data or where the goal is to uncover patterns rather than make predictions. Reinforcement learning algorithms are particularly well-suited for tasks that involve sequential decision making, such as treatment planning.

The quality and quantity of data used to train AI algorithms play a crucial role in the accuracy and performance of those algorithms. In orthodontics, datasets can be obtained from various sources, including cephalometric X-rays, 3D CBCT scans, facial photographs and clinical records.

The evaluation of AI algorithms in orthodontics typically involves measuring their accuracy and precision on a held-out test dataset. Accuracy measures the proportion of predictions that are correct, while precision measures the proportion of positive predictions that are correct. Additional metrics that are often used to evaluate AI algorithms in orthodontics include:

F1-score: A weighted harmonic mean of the accuracy and precision.

ROC–AUC: The area under the receiver operating characteristic curve, which measures the ability of an algorithm to distinguish between positive and negative examples.

Sensitivity: The proportion of true positives that are correctly identified.

Specificity: The proportion of true negatives that are correctly identified.

By carefully selecting AI tools, training them on high-quality datasets and evaluating their performance on rigorous benchmarks, orthodontists can harness the power of AI to revolutionise the field of orthodontics.

A persisting issue when it comes to AI is data protection and safety.

4.2. Three-Dimensional Printing

In contrast to subtractive manufacturing (also called milling processes) that give rise to objects by removing excesses from a chunk of material, additive manufacturing (three-dimensional printing) is a process that creates objects by adding material layer-by-layer. In dentistry, 3D printing finds its application in maxillofacial surgery, implantology, prosthodontics and orthodontics. Metals (e.g., titanium), ceramics (e.g., zirconia), polymers (e.g., polylactic acid—PLA, polyetheretherketone—PEEK) and hydrogels (e.g., gelatine methacryloyl-based hydrogel, hyaluronic acid) are used for 3D-printing purposes. More recently, (bio)printing that uses cells, matrices and growth factors to produce tissues, such as tooth, jawbone and periodontal tissues, has achieved more and more attention. Various methods are used in 3D printing: stereolithography, laser-based techniques, electron beam melting, fused deposition modelling, laminated object manufacturing and inkjet printing [89]. Just like everything else, 3D-printing technologies have both advantages and disadvantages. The disadvantages include a high cost and rather time-demanding postprocessing. Undoubtedly, the advantages include the high yield of materials used, the possibility to fabricate complex structures and the high precision and accuracy of 3D-printed objects [42,90].

Orthodontics and orthognathic surgery have been transformed by 3D-printing methods. Additive manufacturing is used to fabricate study models, clear aligners (direct printing or using 3D-printed models), surgical guides of any kind (including guides for mini-implant insertions), components for fixed or removable appliances and occlusal splints [18]. It seems that having highly individualised lingual appliances have the added value of excellent outcomes [32,91]. In the same manner, there have been attempts to promote in-office custom-made brackets for vestibular appliances [92]. In patients with unilateral complete cleft lip and palate, a 3D-printed nasoalveolar moulding appliance was used prior to surgery to achieve better treatment results [50].

Considering all aspects of additive manufacturing, it seems reasonable to state that it will be used increasingly in individualised orthodontics, regenerative dentistry, implantology and maxillofacial surgery. Therefore, both the knowledge and skills necessary for mastering digital workflow in daily practice need to be cultivated in pre- and postgraduate students, residents as well as specialists. In order to provide patients with quality care, dental curricula and elective courses must respond to technological advances without any delay [93,94].

4.3. Facial Scanning

One of the most popular topics in the current research on digital technologies used in orthodontics is facial scanning. As with other novel diagnostic or therapeutic methods, one needs to first step out of their comfort zone to start considering them, then study the evidence behind them and decide to move on with current trends and technological developments in clinical settings. Proper theoretical background and some practical experience prior to approaching patients are essential to eliminate possible errors due to a total lack of expertise. This is where modernised formal education, lectures, study groups and various practical courses play an indispensable role [93].

The key prerequisite for digital transformation is the purpose of the change. It was noted that progress for the sake of progress is not wise. Reliability, accuracy and time-efficiency are some of the measures that might drive the change. Facial scans obtained using the 3D light scanner Artec Eva were compared to direct craniofacial measurements using a calliper. The study showed the excellent accuracy of the digital workflow. However, the digital method required twice as much time compared to the direct method [95].

Multiple studies have evaluated less-pricey devices in terms of the accuracy and reliability. Stereophotogrammetry seems to have great potential as an alternative to laser scanning in medical practice [96]. Based on a meta-analysis, professional 3D scanning systems are more precise than current facial scanning software in smart portable devices [8]. However, the differences seem to be clinically acceptable [97]. Kinect devices offer a low-cost 3D imaging technique that can be used in orthodontics and/or surgical planning [98]. The Bellus3D and Capture applications seem promising when compared to the method of stereophotogrammetry carried out by a 3dMD system; however, they require much more patience on the patient's side, as both the capturing and processing times are considerably greater [34]. Another study compared Bellus3D captures and facial surfaces segmented from CBCT scans. The authors concluded that there is some clinical applicability of Bellus3D in orthodontics; however, current technologies have their limitations when it comes to accuracy [49]. More studies are needed to showcase to what extent the differences between various face-scanning systems influence clinical outcomes and how they correlate with pre- and post-treatment CBCT scans. One such study did not show that acquisition technologies play a major role in measurement variations [99].

A question remains: Can we reconstruct faces using already-taken pictures? The process of creating 3D faces from 2D pictures is validated, as the acquired measurements are clinically acceptable. Nonetheless, this process is time- and labour-demanding [100].

With no doubts, the advantage of this radiation-free diagnostic tool needs to be emphasised, especially for growing subjects. Research shows that facial scans and subsequent soft tissue analyses can be used for the evaluation of extraction or orthognathic surgery outcomes with both sufficient reproducibility and reliability [101,102].

This paper highlighted the potential of AI to revolutionise the domains to which it is applied. The analysis demonstrates the versatility and adaptability of this technology. For example, in the case of bioelectronics, AI is helping to overcome the challenges associated with material development, fabrication processes and system integration. Similarly, in orthodontics, AI is enabling facial analysis to go beyond mere symmetry and proportionality, providing a more comprehensive understanding of facial structure and its impact on dental alignment. AI empowers the tailoring of treatment strategies to individual patient needs. AI can personalise device design and selection based on patient-specific characteristics in bioelectronics. In orthodontics, AI-driven facial analysis can identify unique facial features and optimise treatment plans accordingly. Data-driven decision making is fundamental for guiding AI-based decision-making processes. In bioelectronics, AI algorithms analyse vast amounts of data to identify patterns and optimise device performance. Similarly, facial analysis tools in orthodontics rely on patient data, such as 2D or 3D scans, to generate insights for treatment planning [103].

4.4. Limitations of the Paper

For this scoping review, only one search engine was used. Scopus was chosen because of the quality metrics it provides. The field-weighted citation impact (FWCI) of a paper is calculated as a ratio between received citations in a 3-year window after its publication and the expected average of paper citations in the subject field. Unfortunately, papers that may receive a high FWCI score in the coming months and/or years did not rank high in our search because their FWCI has not been calculated yet or was lower compared to older papers, only because of the time factor. To eliminate this, only articles older than 3 years could have been considered. However, had the search been carried out that way, the majority of articles would have been eliminated and our results would not have been valid, only because the point of finding the most researchable digital technologies in orthodontics would have been missed. There was a steep incline in the number of published articles corresponding to our search query from the year 2020 onwards, and so this trend should not be disregarded.

Despite the endeavour to propose the most suitable search query based on the current literature, it is possible that some novel digital technologies and applications of AI in orthodontics were not mentioned at all. As a consequence, some high-quality papers may have been potentially missed.

While reading the abstracts and titles of all searched articles, a human error needs to be accounted for. This is why there were two reviewers, each performing the literature search twice—one week apart.

Some searched papers, albeit interesting and seemingly relevant, did not have any relation to orthodontics and thus were excluded from the final list. In a similar manner, it might be possible that some relevant papers were not listed by the search engine in the original search and thus were not found.

Only papers written in English were studied. Papers written in other languages (n = 10) were additionally screened and some of them were considered as relevant and intriguing; however, none would have qualified for the top twenty FWCI articles, even if they had been included in the search.

In conclusion, this scoping review acknowledges the limitations of its scope and selection criteria. While the use of Scopus and the FWCI metric provided a valuable framework, the review's focus on English-language publications and the possibility of overlooking novel technologies and applications underscore the need for continued exploration and refinement. As AI continues to evolve in orthodontics, it is imperative to address the challenges and limitations identified in this study to ensure the responsible and effective integration of AI-powered tools into clinical practice. And while AI holds immense potential to revolutionise orthodontics, it is crucial to acknowledge the limitations, current challenges, and potential risks associated with its integration into clinical practice [37].

The current limitations are:

Data dependency: AI algorithms require vast amounts of high-quality data to train and develop their predictive capabilities. In orthodontics, acquiring comprehensive datasets with standardised measurements and clinical outcomes can be challenging due to ethical considerations and the variability of patient presentations.

Interpretability and explainability: The inner workings of complex AI algorithms can be opaque, making it difficult for clinicians to understand the rationale behind their recommendations. This lack of transparency can hinder the development of trust and acceptance among practitioners.

Bias and discrimination: AI algorithms can inherit biases from the data they are trained on. If the training data inadvertently reflect societal or systemic prejudices, these biases can be perpetuated in AI-generated predictions, leading to unfair treatment or misdiagnosis.

Human oversight and decision making: AI should not replace the expertise and judgment of qualified orthodontists. AI tools should serve as assistants, providing data-driven insights and recommendations that complement, not replace, human clinical decision making.

The current problems are:

Limited clinical validation: Many AI-powered orthodontic tools are still in their early stages of development and lack extensive clinical validation. Their effectiveness in real-world settings and their ability to translate into improved patient outcomes require rigorous testing and evaluation.

Interoperability and integration: Integrating AI tools into existing orthodontic workflows and software systems can be challenging. Compatibility issues and the lack of standardised data formats can hinder the seamless integration of AI into clinical practice.

Standardisation and regulatory oversight: Establishing standardised protocols for the development, validation and deployment of AI tools in orthodontics is essential to ensure their safety, efficacy and ethical use. Regulatory oversight and guidelines are needed to ensure compliance with professional standards and patient protection.

The potential risks are:

Overreliance on AI: Overconfidence in AI-generated predictions can lead to complacency and a decreased emphasis on clinical judgment and experience. Practitioners must maintain a critical approach, carefully evaluating AI suggestions and ensuring they align with patient-specific needs and clinical aspects.

Automation of decision making: While AI can assist in decision making, it should not entirely automate the process. Orthodontic treatment planning requires a comprehensive understanding of patient factors, clinical considerations and the nuances of treatment options. Overreliance on AI could diminish the patient-centred aspect of care and reduce the opportunity for shared decision making.

Privacy and data security: AI-powered orthodontic tools often handle sensitive patient data, including images, dental records and personal information. Ensuring the security and privacy of these data is paramount to protect patient confidentiality and prevent unauthorised access or misuse.

AI offers a transformative approach to orthodontics, providing greater accuracy, personalisation and efficiency. While AI should complement and augment human expertise, its integration holds the promise of revolutionising orthodontics and delivering the highest quality care for patients [41]. A comparison of the possibilities of AI with current orthodontic treatment concepts is shown in Table 2.

Table 2. Comparison of the possibilities of AI with current orthodontic treatment concepts.

Feature	Current Orthodontic Treatment Concepts	AI-Powered Orthodontics
Approach	Subjective interpretation and limited data analysis	Objective and data-driven
Diagnosis	Manual assessment of patient records and imaging	AI algorithms analysing digital scans and images
Treatment Planning	Generalised approaches	Personalised treatment plans tailored to individual patients
Monitoring	Periodic checkups	Real-time insights and the prediction of potential issues
Efficiency	Manual tasks and time-consuming assessments	Automation and streamlining of workflows
Outcomes	Potential for misdiagnoses and treatment errors	Improved patient outcomes, increased treatment efficiency and reduced diagnostic errors
Engagement	Limited patient involvement	Enhanced patient understanding and engagement

4.5. Attention-Based Models

Attention-based models and hybrid solutions are increasingly being employed in orthodontics to enhance diagnostic accuracy, treatment planning and patient management. These models leverage the power of deep learning to extract meaningful insights from complex dental data, including images, measurements and patient records.

Attention-based models, in particular, excel at capturing long-range dependencies and contextual relationships within these datasets. This ability is crucial for orthodontic applications, where the intricate relationships between various dental structures and their overall alignment play a critical role in diagnosis and treatment planning [104–108].

Here are some specific examples of how attention-based models and hybrid solutions are being used in orthodontics:

1. Dental image segmentation: Attention-based models can be used to accurately segment and identify specific dental structures in images, such as teeth, alveolar bones and soft tissues. This information can then be used for various purposes, such as measuring tooth positions, assessing periodontal health and predicting orthodontic treatment outcomes.
2. Predicting orthodontic treatment outcomes: Attention-based models can be trained on large datasets of patient records and treatment outcomes to identify patterns and correlations that predict the success of orthodontic treatment. This information can be used to personalise treatment plans and make informed decisions about the treatment duration and complexity.
3. Automated tooth segmentation: Attention-based models can be used to automate the segmentation of teeth in dental images, removing the need for manual segmentation

by orthodontists. This can save time and improve the efficiency of patient diagnosis and treatment planning.

4. Real-time patient monitoring: Attention-based models can be used to analyse real-time data from intraoral cameras or sensors to monitor patient progress and provide feedback to orthodontists. This can help ensure timely interventions and optimise treatment outcomes.
5. Virtual orthodontic simulations: Attention-based models can generate virtual simulations of orthodontic treatment outcomes, allowing orthodontists and patients to visualise the expected changes in tooth positions and facial aesthetics. This can enhance patient understanding and engagement in the treatment process.

The use of attention-based models and hybrid solutions in orthodontics is still in its early stages, but they hold immense promise for improving the accuracy, efficiency and personalisation of orthodontic care. As these technologies continue to evolve, they are expected to play an increasingly important role in the future of dentistry [104–108].

4.6. Current Trends and Future Directions

The digital transformation of orthodontics is rapidly progressing, with AI, 3D printing and facial scanning leading the way. These technologies are not only improving the accuracy and efficiency of diagnostics, treatment planning and patient monitoring, but they are also paving the way for personalised and patient-centric orthodontic care.

Current Trends

AI-powered cephalometry: AI algorithms are being developed to automate the analysis of cephalometric X-rays, 3D CBCT scans and facial photographs. This reduces the time and effort required for manual analysis, leading to more efficient diagnoses and treatment planning.

Real-time patient monitoring: AI-powered dental monitoring software is being used to track patient progress during treatment and detect the early signs of relapse. This is enabling orthodontists to intervene quickly and prevent the treatment from failing.

Three-dimensionally printed orthodontic appliances: Three-dimensional printing is being used to fabricate custom-made orthodontic appliances, such as aligners, retainers and surgical guides. This improves the fit and comfort of appliances, reducing the treatment time and reducing the need for adjustments.

Facial scanning for aesthetic evaluation: AI-powered facial-scanning software is being used to assess facial symmetry, proportion and attractiveness. This is helping orthodontists to create more aesthetically pleasing treatment plans.

Future Directions

AI-powered treatment optimisation: AI algorithms will be used to optimise the timing, sequencing and intensity of orthodontic treatment. This will result in more efficient and effective treatments.

Personalised orthodontic care: AI will be used to create personalised orthodontic treatment plans based on each patient's individual needs and goals. This will create a more patient-centric approach to orthodontic care.

Virtual reality and augmented reality: Virtual reality and augmented reality will be used to provide patients with a more immersive and interactive orthodontic experience. This will help patients to better understand their treatment and participate more actively in the decision-making process.

Data-driven orthodontic research: AI will be used to analyse large datasets of patient data to identify new insights and develop new treatment protocols. This will lead to a better understanding of the causes of malocclusions and more effective treatment methods.

5. Conclusions

The integration of AI, 3D printing and facial scanning into orthodontics is leading to a paradigm shift in the field. These technologies are transforming the way orthodontics is practiced, making it more accurate, efficient and patient-centred. As these technologies continue to develop, they will have an even greater impact on the future of orthodontics.

The integration of AI into orthodontics has opened a new world of possibilities and promises to revolutionise the field and transform patient care. While AI is still at an early stage of development, its potential to improve diagnosis, treatment planning and patient outcomes is undeniable. As AI continues to advance, it is imperative for orthodontists and dental students to keep up-to-date with the latest advancements and develop a solid foundation in digital technologies. This will ensure that orthodontics embraces the power of AI and paves the way for a new era of personalised data-driven care.

This scoping review shows that face-guided (facially driven) orthodontics is on the rise and is part of a complex AI revolution in the field, leading to an unprecedented paradigm shift. AI will make it possible to handle even difficult tasks, such as analysing complex facial features and simulations. We are currently at the beginning of incorporating AI into daily orthodontic practice.

Author Contributions: Conceptualisation, J.T. and A.T.; methodology, J.T. and A.T.; software, J.T.; validation, A.T., M.Z. and L'.O.; formal analysis, J.T. and M.Z.; investigation, J.T. and L'.O.; resources, J.T. and M.Z.; data curation, J.T. and L'.O.; writing—original draft preparation, J.T.; writing—review and editing, M.Z., L'.O., M.S., M.L., G.P. and A.T.; visualisation, J.T.; supervision, A.T.; project administration, J.T.; funding acquisition, A.T. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Slovak Grant Agency for Science (KEGA)—grant no. 054UK-4/2023, and by Slovak Research and Development Agency—grant no. APVV-21-0173.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

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