Advanced Digital Technologies in Orthodontics

Márton Zsoldos, D.M.D.

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Advanced Digital Technologies in Orthodontics

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Dr. Márton Zsoldos

Designated supervisor
Dr. Krisztina Karpati D.M.D., Ph.D.

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List of abbreviations

3D - 3 dimensional	FDM - fused deposition modelling
AI - Artificial Intelligence	FFF - fused filament fabrication
AM - additive manufacturing	LLM – Large language model
ANN - Artificial Neural Network	ML - Machine learning
CBCT – cone-beam computer tomography	NN - Neural network
CNC - Computer numerical control	SLA - stereolithography
DL - Deep learning	SLS - selective laser sintering
DPA - Direct Printed Aligners	

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I. Tomášik, J**., Zsoldos, M**., Majdáková, K., Fleischmann, A., Oravcová, Ľ., Sónak Ballová, D., & Thurzo, A. (2024). The Potential of AI-Powered Face Enhancement Technologies in Face-Driven Orthodontic Treatment Planning. *Applied Sciences (Switzerland)*, *14*(17). https://doi.org/10.3390/app14177837
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Summary

This Ph.D. thesis primarily concerns highlighted areas of novel methods in orthodontics, artificial intelligence and 3D printing, investigating their presence and effects, connection to various fields of orthodontics and dentistry, and practical applications.

1. Introduction

1.1. General introduction and background

Artificial Intelligence (AI) refers to the simulation of human intelligence in machines or machines that behave intelligently. [1,2] Artificial intelligence is now increasingly ubiquitous in everyday life; we meet it when we interact with our bank, when we write on Gmail (Alphabet Inc. Mountain View, CA, USA) search on Google (Alphabet Inc. Mountain View, CA, USA), or increasingly when we message a business on Facebook (Meta Inc. Menlo Park, CA, USA). It is also increasingly present in healthcare settings, and considering the trends, it seems most likely that AI will become more widespread in our dental profession.[3]. Even if we are not aware of it, it is used to decide what interest rate we are paying with our loans or whether we are even getting the mortgage we apply for.[4,5] AI is changing the way we work and the way we think; some suggest that it might even make us lazier. It may even affect our security as well as privacy negatively. [6]

The word Artificial Intelligence is surprisingly around 60 years of age. It originated in 1955, from John McCarthy, and describes machines that behave or work in an intelligent way. [1] . Back then, the capabilities of such systems were nowhere close to what we see today. A key milestone where it overcame humans was in 2015, when AI could beat the human world champion in the relatively complicated and intellectually challenging game called “go”. [7] The technology has evolved significantly, and after many iterations, this field now encompasses several subfields such as Neural networks (NN), Deep learning (DL), Machine learning (ML), Convoluted Neural Networks (CNN), and Large language models (LLM) etc. What is common is that they are all fuelled by mountains of data, referred to as Big Data, which is used to train and refine these systems.[8] Nowadays AI research and utilisation is gaining momentum; [9] for example, the field of medical imaging had 85% of the FDA-approved AI programs in 2023.[10] Not just the number of studies is rapidly increasing lately, but its implementation is becoming increasingly widespread.[11] AI is unquestionably changing and will continue to change not just healthcare but also society.

In our research I explored digital technologies in orthodontics, which laid out the theoretical foundation. While I was doing this my interest grew in AI and face-driven orthodontics, and in 3D printing, finding that modern research is also focusing on these areas. This has driven me to explore the interwoven topics of AI with various fields of dentistry, chief among them concerning the topic of facial aesthetics and 3D printing.

1.2. Introduction AI and Face-Driven Orthodontics, Digital Advances in Diagnosis and Treatment Planning

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 of approaching 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 focusing on aesthetics [12]. In contrast, the Angle paradigm considers ideal dental occlusion as paramount. In doing so, the role of soft tissues was, 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 [13].

Traditionally, an orthodontic treatment plan was based purely on hard tissue relationships, as diagnosed using dental cast models and 2D cephalometric X-ray analyses [14]. At the end of the 20th century, cone-beam computer tomography (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 [15]. *These 3D images are indicated for impacted canines, orthognathic surgery, syndromes, cleft-plate,some select cases of exceptional complicatedness, special cases of mini implant utilisation.* 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 projected onto the scanned object. Passive stereophotogrammetry merges multiple pictures from different angles and computes one 3D object [16]. Adding the element of time to diagnostics allows for more detailed analyses, for example, in cases of patients suffering from a cleft lip and/or palate or with facial asymmetries, while age is also an important diagnostic factor [17,18].

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 limitations and drawbacks, 3D technologies are taking the lead, especially in more complex cases [19]. They provide detailed and realistic input data to diagnostic and treatment-planning software [20–22]. Data from intraoral and/or facial scanners can be combined with CBCT scans to allow for a better understanding of underlying clinical conditions [23,24]. Artificial intelligence allows for automatic cephalometric tracing that is both precise and accurate, thus making treatment planning more time-efficient [25,26]. The analysis of 3D images obtained from facial 3D scanners can be automated using curvature maps and sagittal profile analyses [27]. 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 fully digital workflow in orthodontic treatment planning [28,29]. Modern protocols using pre- and post-treatment intraoral scans and possibly an initial pretreatment CBCT scan may accurately predict the final post-treatment position of roots, thus reducing the need for repeated X-ray exposure [23]. Even though the radiation dose of modern CBCT scanners is lower nowadays compared to the use of analoge lateral cephalograms 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 [23,30,31]. As an alternative, MRI scans can be used in some patients (e.g. with craniofacial disorders); however, these remain inferior for orthodontic cephalometric analysis [32]. Similarly, digital photography alone can be used, to some extent, for landmark identification and facial analysis to alleviate the need for more invasive investigations [33,34].

Information technology has been used in orthodontics for several 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 a more objective diagnosis of malocclusions based on various indices and standards [35]. Artificial intelligence (AI) has received considerable attention over the last few years. 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 [28,36–39]. 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 may possibly serve as an assistance that absorbs all relevant information available [40]. This might be of added value for less-experienced clinicians; however, experts stress the need for an individualised approach granted by the human factor [41,42].

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 more refined AI-assisted treatment planning and diagnosis revolution in the future [43]. Our aim was 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.

1.3. Foundational concepts of AI-powered face enhancement technologies and face-drive orthodontic treatment planning

Beauty has been very important for humans for tens of thousands of years, as evidenced by the first figurative artwork from 45,500 years ago [44]. What exactly beauty is has been a very elusive, subjective, and ever-changing concept [45]. Different national and ethnic groups perceive facial beauty differently [34,46,47]. Interestingly, while the exact concept of beauty is changing with time, culture, and individually, there is something deeper allowing us to appreciate a beautiful painting or statue from hundreds of years back or thousands of kilometres away. Intriguingly, beauty as a concept seems to have deep biological roots [48]. However, we must be aware of current trends despite their ephemeral nature, while beauty itself often seems timeless. In clinical practice, if one wants to meet patient expectations, they must provide them with up-to-date services when it comes to for example dental and facial aesthetics and oral function [49–51].

Facial beauty is one of the most significant elements in dentistry (and perhaps of overall beauty); after all, *beauty is power, and a smile is its sword* [52–54]. Nowadays, the focus of patients regarding their smiles has shifted from function to aesthetics [46,55]. Orthodontics plays a special role in smile aesthetics because it can help change the smile in a way that prosthetic dentistry alone cannot, often without compromising the result. Face aesthetics improvement is the most frequent reason to undergo an orthodontic therapy [34,46,56]. Notwithstanding, an orthodontist needs to remember that even though aesthetic perception varies throughout history and among cultures, races, and individuals, a properly functioning occlusion, as characterised by strict morphological features, is a rather stable concept [47,57–62]. To enhance the overall facial aesthetics of a patient while respecting nature's limitations, orthodontists traditionally need to master, as much as possible, the fundamentals of an aesthetic face and smile.

Despite the subjective essence of beauty, some facial features that are generally considered aesthetic, these are often related to symmetry and proportionality. Throughout human history, scientists and philosophers have studied beauty and elucidated aesthetic principles that seem universally accepted. Among others, the Golden ratio (with an approximate value of 1.618) and the Vitruvian man are two well-known examples [34,59]. In aesthetic analysis, the craniofacial height to overall height ratio is important, with the ratios of 1:7.5 and 1:8 being considered most attractive [63]. The face height-to-width ratio is also a value closely linked to aesthetics. Values of 88.5% (± 5.1) and 86.2% (± 46) for young males and females, respectively, are considered the most attractive [34]. Ricketts' aesthetic line—a tangent to nose and chin—has a specific relation to lips. Ideally, the upper and lower lips should be dorsal to this line by 4.3 ± 2 mm and 2 ± 2 mm, respectively, [64]. Leonardo da Vinci identified several human aesthetic concepts, including the following [63,65]:

- The human ear and nose should be equally long.
- The mouth width should be equal to the chin-to-lip distance.
- The distance between the chin and hairline should be 1/10 of the body height, and the head should be 1/8 of the body height.
- Chin, nostrils, eyebrows, and hairline should enclose three equal facial thirds.

The proportions and alignment of individual teeth are also important aspects of facial aesthetics, and the Golden ratio can be observed repeatedly. In en face view, the central incisors' height and width form a Golden rectangle. The width ratios of the central and lateral incisors, lateral incisor and canine, and canine and first premolar are all Golden according to some authors [57]. In addition, new aesthetic ratios have been studied: the eye-to-eye distance should be 46% of the face width and the eyes-to-mouth vertical distance should be 36% of the face height; therefore, the overall concept of facial beauty is becoming increasingly complex [66]. All in all, keeping these figures and relationships in check is a strenuous mental exercise and requires extensive measurements and calculations.

Orthodontists conduct clinical examinations of each patient who is willing to receive treatment, either to correct their malocclusion and/or to enhance their appearance. Diagnosis is arguably the most important part of the entire treatment. Unless it is set right, the whole treatment may not address all the patient's needs. It is not surprising that facial attractiveness assessments carried out by orthodontists and laypersons vary significantly [67]. Still, patients readily assess their smile and teeth with reasonable accuracy when it comes to symmetry (interestingly, men are more accurate than women), so they should also be consulted and become a partner, rather than a mere subordinate, in the whole diagnosis and treatment process [68,69]. Proffit's soft tissue paradigm has made the diagnosis even more complex, since the occlusion, although still important, is no longer the singular driving factor in current treatment concepts [12,34]. The respect for soft tissues and overall appearance has received attention, which corresponds to people's requirements regarding their appearance.

Grasping the difficult, subjective, and elusive concept of human beauty poses a major challenge, not only for artists but also for orthodontists. However, it appears that an increase in complex information may facilitate some level of decoding of beauty. Despite all of that beauty by definition remains a very human concept, since it primarily focuses on being beautiful to other humans.

Our recent research concluded that artificial intelligence (AI) has been the most studied digital technology in orthodontics in the past five years [70]. AI can help orthodontists in a plethora of ways: automated landmark identification and cephalometric analysis, orthognathic surgery planning, soft-tissue changes prediction and assessment, digital picture classification, treatment duration prediction, medico-dental diagnostics, facial biotype classification, supernumerary teeth diagnosis and management, decision making on tooth extractions, diagnosis of temporomandibular joint disorders, facial growth prediction, and airway obstruction diagnosis [71–93]. However, using AI to propose the aesthetic result of orthodontic treatment still remains to be implemented.

The foundations of all these new possibilities within dentistry and orthodontics are the spectacular innovations in the field of computer science, data handling, and AI. The computer science behind these advances in AI is rooted in big data analysis, and there have been significant developments in this field in modern times [94]. These technological advances have led to many new, exciting applications in the fields of medicine and, more broadly, biology and technology, such as image classification based on scene-level semantic content [95–100]. In addition, AI can be used to communicate with patients and provide them with necessary information, which saves human resources [101].

Studies have shown that there are parameters which are generally considered attractive, both in women and men. The most salient features of facial attractiveness are symmetry, eyebrow thickness, jawbone prominence, and face height [102–104]. Contrary to the very frequent general opinion, a study conducted by Przylipiak et al. [105] demonstrated with statistical significance that a smaller mouth was considered more attractive than full, thick lips. Most studies pertaining to face attractiveness use surveys, whereas others use functional magnetic resonance imaging of specific regions of the brain, such as the caudate nucleus, orbitofrontal cortex, or amygdala. Based on these studies, it appears that facial proportions affect attractiveness assessment in a gender-specific manner [106].

With the advancement of AI in the realm of picture editing, new possibilities are present in treatment planning. There have been many applications in the market. For many years, users have been able to utilize various filters, frames, drawings, texts, or props to make their pictures more appealing. Even more so, picture enhancement technologies, such as histogram equalisation, algebraic reconstruction mode, neural networks, adaptive interpolation methods, contrast stretching, range compression, multi-frame super resolution, and adaptive iterative filtering, have been closely studied for over a decade [107]. Currently, AI-powered applications go even further. They combine image processing and machine learning to generally improve the appearance of facial features. The entire process comprises the following steps [108]:

1. Face detection—faces are detected and located using specific face-detecting algorithms that seek and identify facial landmarks and boundaries.
2. Facial feature analysis—facial features (eyes, mouth, skin, nose, ears, etc.) are analyzed, for which the facial geometry needs to be understood.
3. Image processing—certain aspects of the face are enhanced, using various techniques (brightness, contrast, color hue changes, etc.).
4. Deep learning models—models trained on huge datasets of facial images are employed (namely, convolutional neural networks) to grasp representations and patterns of facial features.
5. Feature enhancement—based on learned patterns, specific facial features are enhanced (e.g., nose size, wrinkle reduction, and lip enlargement).
6. Generative adversarial networks—in some cases, a generator and a discriminator interact in such a way that a generated image is evaluated regarding its authenticity, which yields even more realistic results.
7. Customization and user preferences—based on the application, the type as well as the extent of desired enhancement is adjusted.
8. Real-time processing—in case of video processing, multiple processes are employed at the same time.

9. Quality assessment—in the end, the application itself evaluates the outcomes so that the modifications lead to a visually pleasing and natural-looking outcome.

Based on an Internet search (carried out on 6 March 2024), some of the most popular AI-powered face-enhancing applications are: Remini (AI Creativity S.r.l., Milan, Italy), Clipdrop (INIT ML, Montreuil, France), Lensa (Prisma Labs, Inc., Sunnyvale, CA, USA), PhotoApp (ScaleUp, Urla, Turkey), VanceAI (VanceAI Technology, Limited, Hong Kong, China), FaceApp (FaceApp Technology Limited, Limassol, Cyprus), Let's Enhance (Let's Enhance, Inc., San Francisco, CA, USA), Voila AI Artist (Wemagine.AI LLP, Richmond, BC, Canada), Reflect (BrainFeverMedia LLC, West Chester, OH, United States), Fotor (Chengdu Hengtu Technology Co., Ltd, Chengdu, China), Topaz Photo AI (Topaz Labs LLC, Dallas, TX, USA), Adobe Photoshop (Adobe Inc., San Jose, CA, USA), PhotoWorks (AMS Software, Wake Forest, NC, USA), BeFunky (Befunky Inc., Portland, OR, USA), PicMonkey Retouching Tools (Shutterstock Inc., New York, NY, USA), Peachy—Face & Body Editor (Shantanu Pte. Ltd., Singapore) [109,110]. Based on our own research on the listed applications, FaceApp was chosen as the most user-friendly, popular, easy-to-use, and potent application that yields enhanced yet realistic pictures. The application, released in 2017, uses deep learning, specifically convolutional neural networks, to process images [111]. FaceApp uses various algorithms that use complex data to extract statistical distribution of patterns, with the aim to predict an outcome for an input without being explicitly programmed to do so [112,113]. Thus, FaceApp is much more than a compilation of various filters. Each picture is translated into a multidimensional vector, which may be further adapted and redistributed throughout the neural network [114].

Even though the basic concept of machine learning is understandable, the hidden layers of deep learning algorithms make neural networks more complex and difficult to understand [3]. However, it seems that FaceApp succeeds in making most images more pleasant to the eye and attractive. It is not fully necessary to understand all the underlying processes for applying AI in daily practice (including clinical practice), as long as the work is completed and ethical concerns are addressed. Because of the scarcity of studies evaluating AI-enhanced pictures of faces on an attractiveness scale, this paper seeks to investigate whether face pictures are manipulated by the FaceApp algorithms in such a way that human assessors find them more attractive than their original counterparts. After all, it has been clear for some time that machine learning algorithms are neither objective nor neutral technologies, and thus, they can lead to biases and errors with multiple implications [113].

1.4. Foundational concepts in 3D-printed accessories and auxiliaries in orthodontic treatment in the age of AI

Digital technologies, AI assistance, and their advancements have completely changed dentistry, including orthodontics. Among these technologies, three-dimensional (3D) printing has emerged as a particularly transformative tool that, when combined with AI, offers elevated precision and more accessible customization in orthodontic appliances. In fact, 3D printing was the second most researched topic within digital technologies in orthodontics in the years 2018–2023 [70]. Three-dimensional printing creates objects by overlaying materials layer-by-layer [115,116]. This powerful technology began its ascension when Charles Hull discovered stereolithography (SLA) and developed the first three-dimensional printing system in 1986. In the same year, he introduced the first 3D printer. Four years later, in 1990, Scott Crump introduced fused deposition modelling (FDM) [117,118]. The most commonly used types of 3D printers in orthodontics are SLA, FDM, digital light procession, Polyjet photopolymer, fused filament fabrication (FFF), and selective laser sintering (SLS) [118]. Owing to its precision, SLA printing technology has gained widespread popularity [119]. However, several types of 3D printing can produce acceptable results for orthodontic treatment [118]. Currently, the laborious process of designing and individualizing these appliances has been streamlined by applying AI-powered software to assist experts.

SLA is based on a photosensitive liquid, a resin that is polymerized and cured layer-by-layer by localized light. It can be used to print large precise objects; however, it can only use one material in a model and often needs to incorporate sacrificial support structures. In contrast, FDM is a method in which molten plastic is extruded. This process is simple, fast, and can combine various materials [115].

Thanks to the recent progress in biomaterials and CAD-CAM technology, new polymers and metals have emerged as viable alternatives to traditional materials in orthodontics[120,121]. Advances in printable dental materials are accelerating, with ongoing research to optimize additive manufacturing (AM) printing parameters to enhance the mechanical characteristics [122]. Printable materials can be categorized into synthetic polymers, metals, and ceramics [123]. A key aspect to keep in mind is biocompatibility: ensuring the biocompatibility of 3D printing materials is crucial for their application in dentistry [122,124,125]. The materials used in 3D printing for dental applications must meet strict biocompatibility standards owing to their continuous interaction with oral tissues and fluids. They also need to demonstrate high mechanical resilience, such as hardness, to endure chewing forces and wear resistance [126].

One of the first and increasingly popular uses of 3D printing in orthodontics was the manufacture of anatomical study models. In some orthodontic practices, 3D-printed models have replaced conventional stone casts. Numerous studies have evaluated the precision, accuracy, and reproducibility of orthodontic models created using 3D printing. Almost all the studies considered them to be highly accurate and suitable for use in clinical practice [127]. However, according to recent studies [128,129], it is recommended to utilize these models immediately to avoid inaccuracies in retainers and appliances owing to the shrinkage of the 3D-printed models. This occurs regardless of material type or storage conditions [129]. Three-dimensional printing technologies can also be used to customize the size, shape, and prescription of brackets. The mechanical characteristics of 3D-printed brackets were evaluated by indentation testing and were found to be superior to those of available plastic brackets [130]. The frictional resistance of the 3D-printed self-ligating brackets was compared with that of two ceramic, two metal, and one plastic (commercially available) brackets. Across all combinations of brackets and archwires, 3D-printed polymer brackets demonstrated a sliding resistance comparable to that of existing polymer brackets, and lower than that of ceramic and metal brackets [130].

The most studied use of 3D printing in orthodontics is the production of aligners [130]. Directly printed aligners (DPA), introduced in 2021 [128], offer multiple benefits over traditional thermoformed aligners. They offer a better fit to the teeth than traditional methods, thereby possibly reducing the need for attachments [128]. The use of 3D printing technology enables the personalization of aligner features, such as material thickness, surface textures, and overall design, providing greater precision in controlling tooth movement [131]. The ability to adjust the thickness of aligners is a promising approach for enhancing the effectiveness of intended orthodontic movements while reducing unintended tooth movements, thus improving the predictability and accuracy of tooth movements [132]. Furthermore, if printed models and thermoforming are bypassed, the accumulation of errors during the production process can be reduced. While the design of the aligners and treatment is time-consuming, the manufacturing is faster owing to the reduced supply chain: the DPAs can be printed immediately and in practice [133]. Importantly, directly printed aligners present an eco-friendly option by reducing or even eliminating the need for resin models and plastic sheets, which are traditionally used for thermoforming [131]. Obviating the need for 3D printed resin models also decreases costs [128]. It has been shown that the traditional aligner fabrication method has a considerable environmental toll [133]. However, some authors are skeptical of DPAs. Sayahpour et al. in their study showed that thermoformed aligners might still have better mechanical properties than some directly printed aligners [134]. Further research is required to determine the clinical effectiveness of DPAs. DPAs can be effective for mild to moderate malocclusions, and the Aliphatic Vinyl Ester Urethane (Tera Harz TC-85, Graphy; Graphy Inc., Seoul, Republic of Korea) [135] also has some beneficial properties when it comes to elasticity and more physiological flexural strength. However, another point worth mentioning is that the manufacturing process of the Tera Harz TC-85-based DPAs is still very technique sensitive and requires specialized equipment for post-processing. However, the final product is more susceptible to moisture, impairing the ability to deliver forces in the oral cavity [128].

These technological advancements have enabled healthcare professionals to offer more personalized medical devices to each patient. Three-dimensional printed appliances are crafted specifically for an individual’s anatomy, utilizing imaging data and 3D models to design and manufacture medical appliances [123]. The manufacturing workflow for the customized 3D-printed orthodontic accessories is shown in Figure 1.

Our review explored the evolving field of 3D-printed accessories in orthodontics, focusing on the materials, methods, biocompatibility, and clinical applications that characterize this cutting-edge technology. By “orthodontic accessory”, we refer to various supplementary devices or tools used independently or in conjunction with main orthodontic appliances (like braces or aligners) to aid in correcting dental and jaw alignment issues and/or used also in interdisciplinary approach of orthodontic treatment, including guides for brackets or mini-screws placement. These accessories play a crucial role in the management and modification of tooth movements. Moreover, orthodontic accessories encompass a wide range of devices used not only during the main phase of orthodontic treatment to correct dental and jaw alignments but also include preventative devices. These assist in guiding the teeth to their proper positions or stabilizing them, maintaining space in the mouth, or correcting habits that may impact orthodontic health. By exploring both the successes and challenges associated with the 3D printing of these devices, this study aimed to provide a comprehensive overview of their impact on orthodontic practices and their potential to revolutionize future treatments. In this review, the terms “accessories”, “appliances”, and “devices” are used interchangeably, as they are often treated as synonyms in the literature to describe various tools and components used in orthodontic treatments.

2. Materials and methods

2.1. Materials and methods used in our scoping review of AI and face-driven orthodontics, digital advances in diagnosis and treatment planning

Our review investigated 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 relevant studies, including articles, reviews, conference papers, and short surveys. The search was limited to papers written in English and published in the 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)

As the objective of our scoping review was to assess the trends in 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 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 in the field. As 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 that 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. Focus areas for discussion were identified based on the content of these articles.

2.2. Materials and methods used in our research about AI-powered face enhancement technologies in face-driven treatment planning

For this preliminary study, 25 male and 25 female faces generated by the AI were downloaded from the website Generated Photos (Newark, Delaware, USA, https://generated.photos, accessed on 5 Dec 2023 for male pictures and on 14 Dec 2023 for female pictures) based on the following criteria [136]:

- Age: young adult;
- Pose: front facing;
- Ethnicity: Caucasian;
- Pose: natural.

The AI-generated faces were used to eliminate general data protection regulation (GDPR)-related issues and ensure the same projection of all faces (ideal light conditions, constant face angulation, and distance from the camera). The facial pictures were downloaded and further enhanced using AI. AI-powered face enhancement technologies, such as FaceApp, utilize deep learning to improve facial aesthetics by adjusting features such as symmetry and skin texture [111–114]. For this study, FaceApp (ver. 11.10, FaceApp Technology Limited, Limassol, Cyprus) with a premium account was used [137]. The "natural" filter for females (level 1) and "star" filter for males (level 1) were used because the team of three authors concluded these filters yielded the most realistic outcomes. The selection of female and male faces took place on 5 Dec 2023 and 14 Dec 2023, respectively, and based on chosen statistical methods, the number of generated faces was set to 100 pictures.

The goal of the study was to monitor the frequency of individual answers when choosing which picture is more attractive to the respondent as well as to monitor the frequency of point differences in the evaluation of two versions for a given face. For this purpose, the Chi-square goodness of fit test was used. The calculation of Chi-square goodness of fit test was performed by the function *chisq.test* from the *stats* package [138]. This test verifies whether the empirical probability distribution matches the given theoretical probability distribution. In other words, it measures how well a statistical model fits a set of observations.

In this study, when answering the question of which of the two versions of the pictures is more attractive to the respondent, the agreement with the theoretical distribution, where both options are represented equally often, is observed. The idea is similar for the point differences between an AI-edited pictures and the original picture. The differences were examined in this order, because in almost every case, a picture edited by artificial intelligence was evaluated as more attractive. Therefore, a higher score for these pictures options was expected. It means that the difference should be positive or equal to 0. In this case, however, the differences do not have only two options, as was the case when choosing a more attractive picture, but several options. Theoretically, these could be discrete values from -10 (the case where the edited picture has a score of 0 and the original has a score of 10) to 10 (where the edited photo would have 10 points and the original 0). In both cases, the correspondence of the distribution with a discrete uniform distribution is tested. The *ggplot* function from the package *ggplot2* was used to display the plots [139].

Based on a discussion with a psychologist, who considered assessing 100 faces in one go as overly tiring and a potential threat to valid results, it was decided to create two separate online forms to be sent to 1800 respondents in total. The first form contained 50 pictures of male faces and the second online form distributed a week later contained 50 pictures of female faces. The forms were created so that each page showed one altered and one unaltered face picture. The respondents were asked to state their age by selecting one of four age groups. Then, they were supposed to evaluate which face looked more attractive and then to score each picture on a scale 1–10 (1—least attractive, 10—most attractive). To eliminate the tiredness of the assessors, the second form was sent to the respondents after one week. The scores were recorded, and numerical data were analyzed using the software R Studio (ver. 4.1.1, R Core Team, Vienna, Austria) and the level of statistical significance was set to $\alpha = 0.05$ [140]. To assess the interrater reliability, Fleiss' Kappa for *m* Raters was used [141]. For the Fleiss' Kappa for *m* Raters, the *kappam.fleiss* from the *irr* package was used [142].

For the sample size calculation, trial questionnaire research on the research team and their co-workers was performed (a total number of 20 probands) in order to determine the presumed population proportion that would consider the AI-enhanced pictures more attractive. Afterwards, Equation (1) was used [143]: where z is the z-score for the given confidence level (1.96 for 0.95 confidence level), P is the population proportion (0.9), E is the margin of error (0.05), and N is the population size (1800). After substituting into Equation (1), a sample size of 129 respondents was obtained, as demonstrated by Equation (2).

Five pairs of pictures of both male and female faces with highest attractiveness score differences before and after the AI modification were imported into the graphical software Gimp (ver. 2.10.36, Free Software Foundation, Inc., Boston, MA, USA) [144]. In total, 20% of the faces with the highest attractiveness differences were deliberately chosen to try to spot the differences, and correlated given measurements and facial attractiveness. Two layers (before and after AI enhancement) were superimposed, and by manipulating translucency, the distances of the selected facial anthropometric points (Table 1) were measured in both pictures and then compared. The anthropometric points to be studied were selected by an anthropologist. Percentual change for the selected parameters and mean values were calculated and analyzed.

In addition, to demonstrate the power of AI against the power of AI, ChatGPT 4 (OpenAI, San Francisco, CA, USA) was asked to compare each pair of the pictures [145]. The results were then analyzed in several ways:

- Which of the two faces (AI-enhanced or original) was considered more appealing?
- What was the difference of the numeric attractiveness score they achieved?
- What facial modifications were responsible for the biggest score differences?
- Were the observed changes located in the lower facial third?
- Could an orthodontic treatment influence the studied changes?

2.3. Materials and methods in reviewing the literature of 3D-printed accessories and Auxiliaries in orthodontic treatment

In conducting the review, a literature search was conducted using two academic databases: PubMed and Google Scholar. On PubMed, we employed a comprehensive search strategy with the search query: (“orthodontic” OR “orthodontics”) AND (“three-dimensional printing” OR “3D printing” OR “additive manufacturing”) AND (“accessory” OR “accessories” OR “appliance” OR “appliances” OR “auxiliary” OR “auxiliaries” OR “device” OR “devices”). The search on Google Scholar was conducted using the terms (“orthodontic” OR “orthodontics”) AND (“three-dimensional printing” OR “3D printing” OR “additive manufacturing”) AND (“accessory” OR “accessories” OR “auxiliary” OR “auxiliaries”), with both searches last conducted on 13 October 2024.

The studies included in the review were limited to those published in English between 2020 and 2024, focusing exclusively on intraoral 3D-printed orthodontic accessories. Case reports were included in this review to explore unique or pioneering applications of individualized 3D-printed orthodontic devices, providing specific examples of innovative uses and outcomes. In addition, this review included systematic and narrative reviews to provide context and summarize existing knowledge on the application of 3D printing in orthodontics.

All of the identified articles were screened against the inclusion criteria, resolving discrepancies through discussion between authors. No automation tools were employed in this process. In this review, articles were included based on their direct relevance to orthodontics, focusing specifically on the design and use of 3D-printed accessories for orthodontic purposes.

Studies that primarily addressed applications of 3D printing outside of orthodontics were excluded to maintain a targeted scope. Additionally, articles primarily focusing on anatomic models, directly printed brackets, directly printed or thermoformed aligners, and retainers were not included. This decision was made to narrow the focus to 3D-printed auxiliary devices and accessories, allowing for a more in-depth exploration of lesser-studied applications beyond aligners and brackets, which have been widely researched elsewhere.

Each article was thoroughly reviewed to ensure it met the inclusion criteria, focusing on the methodological rigor, the scope of the study, and the relevance of findings to the topic of orthodontic 3D-printed accessories. The review focused exclusively on the analysis of evidence regarding 3D-printed orthodontic accessories designed for intraoral application.

3. Results

3.1. Our results concerning AI and Face-Driven Orthodontics, Digital Advances in Diagnosis and Treatment Planning

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 2–4, respectively.

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 2 lists twenty articles with the highest FWCI values.

Figure 5 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.

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.

3.2. Our findings regarding AI based face enhancement technologies in orthodontic treatment planning

Altogether we received 441 responses. The first round of questionnaire (male faces) was submitted by 159 respondents. The gender and age composition of respondents is depicted in Figures 6 and 7, respectively. The second round of questionnaire (female faces) was submitted by 282 respondents. The gender and age composition of the second-round respondents is depicted in Figures 8 and 9, respectively.

Table 3 shows the percentage of respondents who judged the original or the AI-enhanced picture as the more attractive one—for 25 pairs of male and female faces each. Regarding the male faces assessment, all observations showed that the FaceApp-enhanced pictures were more attractive, and the observations were statistically significant ($p < 0.05$). For male faces, the interrater reliability rate was 0.01, which stands for a slight agreement between raters. In all female faces, except for one, the results were similar: the respondents judged the FaceApp-enhanced pictures as more attractive, and the statistical analysis showed statistical significance ($p < 0.05$). For female faces, the interrater reliability rate was 0.02. This number also indicated a slight agreement between raters. Neither age nor gender of the respondents was shown to have a significant impact on the attractiveness score.

The pair of male pictures (original and after the AI enhancement) and the attractiveness score difference for the pair is depicted in Figure 10 and 11, respectively. The pair of female pictures (original and after the AI enhancement) and the attractiveness score difference for the pair is depicted in Figures 12 and 13, respectively.

The five pairs of male and female faces with the highest difference between the attractiveness score of the original and AI-enhanced pictures were further analyzed to find out which anthropometric distances (Table 1) changed the most. The results for male faces and female faces are shown in Figures 14 and 15, respectively.

The results show that in 49 out of 50 cases, the AI-enhanced picture was rated as more attractive compared to the original one. The results are statistically significant, with age and gender being of no statistical importance. On average, the AI-enhanced pictures of male and female faces were rated 1 point higher on the attractiveness scale from 1 to 10 (10 being the most attractive) than the original faces.

The facial changes that were correlated with the biggest changes in attractiveness score were most related to lips, eyes, nose, and chin (Figure 16). The most prominent changes were related to lip fullness (Li-Cph distance), followed by the eye size (Ps-Pi as well as Ect-Ect) and lower face height (Sl-Me as well as Prn-Me). Other important changes were related to nose width (Al-Al), lower jaw width (Go-Go), and mouth width (Ch-Ch). Less prominent changes were observed in the dimensions Ft-Ft, Zy-Zy, Sn-Me, Fz-Fz, N-Me, and Tr-Me. The order of most prominent changes was different for male and female faces. In male faces, the lip fullness, vertical eye dimension, distance between the nose tip and chin, and nose and mouth width changed the most. On the other hand, in female faces, the most prominent changes were observed in the lip fullness, vertical eye dimension, chin height, and facial horizontal dimensions at the eyes and eyebrows levels (Ect-Ect and Ft-Ft).

As noted by the research team, the pictures differed in skin texture, the enhanced versions being somewhat brighter and less wrinkled. The enhanced female eyes were bigger with darker contours. On the contrary, the enhanced male eyes decreased in the height, yet became more prominent.

Upon being asked about differences between an enhanced (first) and an original (second) face picture, ChatGPT 4 identified the following differences:

- Hair: the first picture depicts more abundant and slightly wavy hair that is surrounding the face, as opposed to more smooth hair reaching behind the ears in the second picture.

- Chin: the chin in the first picture is wider and more rounded, as opposed to a more prominent and narrower chin in the second picture.
- Smile: the person in the first picture has a wider smile, showing more teeth.
- Nose: the nose has a wider ala nasi area in the first picture.
- Eyes: in the first picture, the eyes are more open and seem to be bigger than in the second picture.
- Face: the face in the first picture has more rounded and smoother shape, whereas the face in the second picture has more rough and sharper edges.
- Cheeks: the first face has fuller cheeks compared to the second face.

3.3. Our results concerning the 3D printed orthodontic accessories and auxiliaries

A systematic search of PubMed and Google Scholar was conducted using specific keywords and a date range from 2020 to 2024, as described in the materials and methods section. This initial search yielded a total of 582 publications, with 143 articles from PubMed and 439 articles from Google Scholar. Only articles published in English that focused on orthodontics and 3D printing were retained, based on a preliminary examination of article titles. This filtering step reduced the pool to 239 articles. After duplicates were excluded, 153 unique articles remained for further screening.

A detailed assessment of abstracts and, where necessary, full texts was then performed to exclude studies focused on aspects outside the intended scope. This refined the selection to a final count of 75 articles based on their relevance to the focus of this review, which includes advancements in 3D printing technologies in orthodontics and their application in the design and manufacturing of orthodontic accessories and appliances for intraoral use. Out of the 75 articles included in the review, 25 original articles were retrieved from PubMed and 17 were identified through Google Scholar. The remaining articles were found to overlap across both databases, demonstrating the complementary nature of these search tools in capturing the relevant literature. Figure 17 provides a detailed overview of the study selection process conducted for this review.

The articles included in our study cover a range of orthodontic devices and their applications, with each study focusing on specific categories of devices and orthodontic techniques. The breakdown of device types and the number of articles studying each is as follows in Figure 18.

We grouped reviewed articles into the following categories: Original Research and Experimental Studies, Clinical Studies and Related Designs, Case Reports and Case Studies, Reviews, and Technical and Methodological Notes. This categorization, by clustering articles with similar goals, reflects their distinct purposes, methodologies, and contributions to the scientific field. The number of articles in each category is described in Figure 19.

It was possible to determine the type of 3D printing technology used for the fabrication of orthodontic accessories in 31 studies. Among these, the most utilized technologies were SLA, appearing in 11 publications, and Digital Light Processing (DLP), used in 9 papers. Regarding materials, where specified, the majority of orthodontic accessory devices were fabricated using resin-based materials, accounting for 27 occurrences, followed by metal-based materials, used in 12 cases. This highlights the prevalence of resin and metal as primary materials for 3D-printed orthodontic applications.

Throughout the 75 articles, the most commonly described advantages of using a digital workflow in manufacturing orthodontic accessories were precision and accuracy, highlighted in 45 articles (60%). These workflows also contributed to improvements in patient safety and predictability and better clinical outcomes, as noted in 37 articles (49%). Additional advantages included improved patient comfort and reduced chair time, mentioned in 17 articles (23%), along with increased efficiency and reduced manual labor in 16 articles (21%). Regarding disadvantages where explicitly stated, the most frequently described were financial issues, including high initial costs of the digital workflow equipment and/or high material costs, reported in 46 articles (61%). The steep learning curve for dental staff and specialized training requirements was another significant issue, mentioned 34 times (45%), followed by the complexity of the digital workflow and increased manufacturing time, as described in 25 articles (33%). Material limitations were noted in 15 articles (20%), and limited data on the long-term success of these devices were highlighted in 12 articles (16%).

4. Discussions

4.1. Discussion of AI and Face-Driven Orthodontics, Digital Advances in Diagnosis and Treatment Planning

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.

3.1.1. 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 at the time of research. 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 [146,147]. On the other hand, AI techniques can also detect pathological processes, e.g., dental caries on radiographs, with an increasing level of accuracy [148].

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 [149]. Orthodontists, residents 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 [150]. On top of that, machine learning has found use in both lateral and 3D cephalogram analysis to provide ever-improving quality in landmark localisation [151,152].

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 [153]. According to some research many professionals are more than open to use AI assisted cephalometrics, due to its efficiency and the possibility of high accuracy. [154].

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 [151,152,155,156]. 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 [157,158].

Artificial intelligence has become an extensively researched field over the past decade [74]. Apart from CBCT analysis and automated teeth segmentation, AI aids professionals in treatment planning, including decisions on teeth extractions [159–161]. 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 [160,162,163]. It is possible that in a few years, the advantages of AI applications (not only) in orthodontics will be even more pronounced. The lack of opacity in AI decision making is an issue that needs to be solved. Often, it is very hard to know, even for people programming the software, why exactly a certain output of AI is what it is. This makes it harder to meaningfully check the output of AI software and build arguments for or against a certain statement. This is likely to worsen unless specific steps are taken to resolve the issue. This so called "black box" effect is even more significant in healthcare settings. However, solving this problem would greatly enhance reliability and build trust in AI assistance. [164]. We should also consider ensuring quality information and data given to AI as foundational to build trust [165].

AI finds application at all levels of decision-making processes in orthodontics and medicine (e.g. in specialties such as radiotherapy) and various fields of dentistry: data collection, storage, management, processing in-depth analysis, communication and education, oral surgery [166,167]. 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 [37,75,168,169]. There has been some research on scoring facial attractiveness in relation to facial proportions and profiles [170,171]. AI may soon enable automated aesthetic evaluation, smile design, and treatment planning to assist specialists [13]. This aspect was investigated in another research project [172]. Based on machine-learning algorithms, given pretreatment variables, AI may successfully predict the duration of an orthodontic treatment [82]. 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 [173]. 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 [174–176].

In the field of oral surgery AI has also been extensively utilised [3], there are now tools available to predict postoperative swelling and the pain related to it [177] and even detecting classifying various cysts such as keratocysts, odontogenic cysts, radicular cysts and dentigerous cysts. [178]. Tools such as these are invaluable for the precise diagnosis and correct planning of surgical interventions. These not only reduce the pain associated with the treatment but also decrease postoperative inflammation and pain. The aforementioned occurrences must be managed properly, and the correct choice of methods and proper planning combined with adequate medications should reduce patient suffering. [179]

AI has been applied in human genome sequencing and the analysis of 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 truly personalised medicine. These so-called omics (genomics) records are likely to become an integral part of orthodontic medical records that will be routinely used in diagnosis and treatment planning. Therefore, it is crucial to update orthodontic residency programs as one needs to adapt and evolve to provide orthodontic care of the highest quality [180].

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 [181–190]. Recent developments in the area of automated 3D landmarking has led to accuracy improvements [73]. Despite this, many authors emphasise that human intervention is still needed to minimise errors in automatic cephalometric analysis [191]. To eliminate that, more research is needed to increase both the precision and accuracy of AI algorithms and we must emphasise the importance of specialist orthodontist control and supervision. 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 random forests and neural networks.

Unsupervised learning algorithms are trained on unlabeled data, the goal of which is to uncover patterns or structures in the data without the guidance of labelled examples. This type of learning is useful for tasks such as facial recognition and syndrome detection, 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 the environment to maximise reward signals. 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, whereas unsupervised learning algorithms are more suitable for tasks where there is less labelled data or where the goal is to uncover patterns rather than to 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 using a held-out test dataset. Accuracy measures the proportion of predictions that are correct, whereas precision measures how close the predictions are to each other. Additional metrics that are often used to evaluate AI algorithms in orthodontics include the following:

F1-score: Weighted harmonic mean of accuracy and precision.

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

Sensitivity: Proportion of true positives correctly identified.

Specificity: Proportion of true negatives 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 persistent and important issue in AI is data protection and safety.

3.1.2. Three-Dimensional Printing

In contrast to subtractive manufacturing (also called milling processes), which gives 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 is used 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.[192] Various methods are used in 3D printing: stereolithography, laser-based techniques, electron beam melting, fused deposition modelling, laminated object manufacturing and inkjet printing [193]. Just like everything else, 3D-printing technologies have both advantages and disadvantages. The disadvantages include a high cost and rather time-demanding post-processing. 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 [194,195].

Orthodontics and orthognathic surgery have been transformed by 3D-printing methods and 3D printing is itself being transformed by AI. 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 [29]. It seems that highly individualised lingual appliances have the added value of excellent outcomes [42,196]. Similarly, attempts have been made to promote in-office custom-made brackets for vestibular appliances [197]. 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 [198].

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 among pre- and postgraduate students, residents, and specialists. To provide patients with quality care, dental curricula and elective courses must respond to technological advances without any delay [199,200]. We discuss 3D printing in more detail later.

3.1.3. Facial Scanning

Facial scanning is one of the most popular topics in current research on digital technologies used in orthodontics. 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 lack of expertise. This is where modernized formal education, lectures, study groups, and various practical courses play an indispensable role [199].

The key prerequisite for digital transformation is the purpose of the change. Progress for the sake of progress is neither wise nor useful. Reliability, accuracy, and time efficiency are some of the measures that might drive this change. Facial scans obtained using the 3D light scanner Artec Eva were compared with direct craniofacial measurements using a caliper. The study showed the excellent accuracy of the digital workflow. However, the digital method required twice as much time compared to the direct method [201] on top of that we must consider the costs and learning curve.

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 [202]. Based on a meta-analysis, professional 3D scanning systems can be more precise than the current facial scanning software for smart portable devices [19]. However, these differences seem to be clinically acceptable [203]. Kinect devices offer a low-cost 3D imaging technique that can be used in orthodontics and/or surgical planning [204]. The Bellus3D and Capture applications seem promising when compared to the stereophotogrammetry method 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 [205]. 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 limitations in terms of accuracy [206]. Scanners can be used to monitor soft tissue changes that occur with maxillofacial surgery.[207] More studies are needed to showcase the extent to which the differences between various face-scanning systems influence clinical outcomes and how they correlate with pre- and post-treatment CBCT scans. One study did not show that acquisition technologies play a major role in measurement variations [208].

An interesting question is whether we can reconstruct faces using already-captured pictures. The process of creating 3D faces from 2D pictures was validated as the acquired measurements were clinically acceptable. Nonetheless, this process is time- and labour-demanding [209].

The advantage of this radiation-free diagnostic tool needs to be emphasized, particularly 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 [210,211].

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 [212].

3.1.4. Limitations of the Paper

For the 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. As with any literature search there are temporal limitations: 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 our best 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 multiple 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, the 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.

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[74].

Key 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.

Hallucination: Due to possible errors in the data, data labelling or in the internal structure of the AI software it can happen that AI produces responses which are significantly wrong. What is more, these are stated by AI with same confidence as the correct answer, easily misleading those whoa are not necessarily familiar with the subject. These errors extremely hard to reassuringly eliminate, since source and reason of these errors are often not clearly identifiable due to the opaque nature of most AI software. This consideration again highlights the continued supervision by trained human experts, such as orthodontic specialist when it comes to applications of this field. This leads us to the next consideration:

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 long-term 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 among many:

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 evaluate AI suggestions, and ensure alignment 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 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 could complement and augment human expertise, its integration holds the promise of revolutionising orthodontics and delivering the highest quality care for patients [173]. A comparison of the possibilities of AI with current orthodontic treatment concepts is shown in Table 4

3.1.5. Attention-Based Models

Attention-based models and hybrid solutions are increasingly 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. These methods are based on the principle of weighing inputs (focusing “attention” on parts of it), then compressing a number of inputs that belong together into a complex vector, which is then propagated to the following layers of the NN:

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 [213–217].

The following 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 be used for various purposes, such as measuring tooth positions, assessing periodontal health, and predicting orthodontic treatment outcomes, and may serve as a basis for automating further diagnostics and evaluations.
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 may predict the success of orthodontic treatment. This information can be used to

personalise treatment plans and make an approximation for informed decisions regarding treatment duration and complexity.

3. Automated tooth segmentation: Attention-based models can be used to automate the segmentation of teeth in dental images, eliminating the need for manual segmentation by orthodontists. This can save time and improve the efficiency of the 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 [213–217]

3.1.6. Current Trends and Future Directions

Digital transformation of orthodontics is rapidly progressing, with AI, 3D printing, and facial scanning leading the way. These technologies not only improve the accuracy and efficiency of diagnostics, treatment planning, and patient monitoring but also pave the way for personalized 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 used to track patient progress during treatment and detect early signs of relapse. This enables orthodontists to intervene quickly and prevent treatment failure.

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.

3.2. Discussing our findings regarding the potential of AI-powered face enhancement technologies in face-driven orthodontic treatment planning

In today's world, our virtual representation is increasingly important; not just in professional but also in private life, how we present ourselves is increasingly important [218]. Increasingly, the first impression of us comes from an online photo. This has led to the widespread availability of photo-enhancing [219].

The practical handling of complex cultural-psychological and philosophical questions of human beauty has been successfully performed by AI [220]. Our research underlines these findings because the ability to enhance photos is anchored in the capacity to estimate features that are considered beautiful. AI has been proven to be able to handle the question of beauty, extract measurements, and evaluate its expected effect on facial beauty [221]. These are necessary steps to choose the features to be enhanced and to support our findings of AI's ability to handle the question of beauty with reasonable success. In addition, previous research found that an increase in attractiveness in digitally changed photos is to no a certain proportion a result of improved skin texture [222].

Our study found that AI-enhanced images were consistently rated as more attractive than the original pictures, suggesting that these align well with the general aesthetic preferences of humans. We can thus argue, that AI does indeed seem to be able to grasp the elusive concept of beauty. AI often increased the lower face height and lip fullness, and these values can be influenced with orthodontic tooth movements [223,224]. Previous research has shown that lower face height, when outside of a specific range for males and females, is a good predictor of an orthodontic treatment need [223].

The AI-generated male and female faces may differ from what is considered the average male and female face, respectively (based on the datasets used to train the AI). A different enhancement filter was used for each of these two groups—because there were different enhancement filters available for each of the gender (as guessed by the application). While researching various face enhancement applications prior to this pilot study, we discovered that FaceApp offered the option to change the detected gender that for some female and male faces. In future research, it would be very interesting to choose an enhancement application that offers the same enhancement filter for all patients so that changes in both male and female faces can be compared without a different enhancement filter possibly affecting the results.

It appears that human judgement of beauty is a very complex mechanism, and thus, precisely analyzing it still poses a challenge or humans as well [225]. The integration of AI-powered face enhancement technologies in orthodontic treatment planning represents a significant advancement in the field, enchanting repeatability and (depending on the datasets and programming used) possibly objectivity. The number of studies on various orthodontic applications of AI and machine learning has increased exponentially [226]. These technologies, leveraging sophisticated algorithms and deep learning models, provide orthodontists with powerful tools to enhance diagnostic precision and treatment outcomes [70].

Importantly, as mentioned above, many enhancements by AI are particularly in the lower facial third, which is the area that can be most changed by orthodontics [223,224,227]. This synergy suggests that AI can help orthodontists visualize potential treatment outcomes, assisting decision making, improving communication and guiding patient’s acceptance. It may also support not just the orthodontist’s but also the patient’s decision making when it comes to virtual treatment plan objectives. However, our paper suggests that mere visualization of treatment outcomes is not the most crucial benefit of deep learning algorithms in orthodontics. Orthodontists could possibly even go so far as to set their treatment goals based on the AI-enhanced pictures of patients. A patient comes for a consultation, their pictures are taken and processed using AI, and in a few moments, the clinician can have a roadmap or even ready-made solutions to the patient's aesthetics-related challenges. Reservations shall be emphasized here: some changes and their stability are limited by the anatomy and physiology of the patient, while others may only be possible with relatively invasive orthognathic surgery. However, as utopian this may sound, with huge amounts of data being fed into the system for some time, including the pictures and rigorous assessments of all inputs (including intraoral scans, X-rays or CBCT scans, dental and medical history, and even body height), with treatment plans for those patients designed by state-of-the-art orthodontists, deep learning can make sense of these data and in the future possibly provide assistance to the specialist orthodontist by recommending for expert consideration possible treatment plans all by itself. Many more studies need to be well-designed and executed, and their results analyzed with emphasis on comparison with the current treatment standards and best practices, in order to move forward on the AI highway.

However, there are many underlying ethical, legal, and social implications to the use of AI in healthcare, and these need to be discussed further [228–232]. In fact, more than forty different ethical issues regarding the use of AI in dentistry were identified [11]. For example, reinforcing societal beauty biases and ensuring transparency in AI algorithms must be addressed. Privacy, anonymity, security, and informed consent are but a few of the most common challenges regarding novel digital technologies in dentistry [233]. Privacy and secrecy have special importance, since they are two cornerstones of healthcare ethics. The safety of data and ensuring privacy is of utmost importance in the field of healthcare. Most of today's AI system use the uploaded data and interactions to learn and better themselves, thus possibly incorporating parts of the data and interaction in their database and later replies. This must be considered when uploading healthcare information to the AI. The most unacceptable situation, where AI learns about healthcare issues of a person and then later uses that data for queries of third parties, must be avoided stringently. Thus, any software company using AI to handle patient data needs to have implemented the strictest comprehensive privacy and data control protocols and consistently prioritize privacy in building and maintaining their AI. The company running the AI is responsible for the actions of that AI and the fate of any sensitive data uploaded to the system [3]. Another significant concern is the variability in AI algorithm performance across different populations and clinical settings, necessitating adaptation for diverse patient groups [234].

What we should also think about is AI's effect on changing the job of orthodontists. While due to AI's inbuilt limitations (limited dataset, possible bias, opaque decision-making etc.) it is impossible to imagine AI taking over the role of orthotists, and due to these and legal, responsibility considerations it may never do so.

Another important aspect is that AI is, as of now, unable to consider how realistic the facial changes shown by the software are. The limitations of orthodontic treatment should be observed and respected, and the patient needs to be informed about possible treatment options and limitations from the very beginning, to prevent their disappointment and unrealistic expectations based on AI-powered face enhancement. This is especially true in case of non-surgical orthodontics' effects on the face, but also when it comes to any orthodontic therapy [34]. AI enhanced pictures, like all predictions and plans, are inherently fickle and capricious. Implementing them is subject to many factors outside of the clinician's control when it comes to removeable appliances, fixed appliances, and aligners. It is something patients should be aware of [3]. This is another aspect why AI software can only be used as assistance not instead of orthodontist: what may be deemed possible by one doctor could well be impossible for another.

It may be a challenge to compare the new AI-assisted diagnosis and treatment planning with their traditional counterparts. Standard measurements of facial beauty and proportions up to this point were often based on older anthropometric data, which were limited by the number of inputs that could be handled by human researchers—the number of photos, the number of patients, etc. [34]. AI can handle and acquire much larger and complex modern datasets. Furthermore, it can continuously improve and adapt the modern trends and concepts of beauty since it is possible to add more and more data constantly [226]. However, the constant nature of traditional standard measurements may continue to offer a fix reference point, and thus, continue to provide a valuable source for consideration. The traditional datasets may also be more transparent than the decision making of AI [164]. Using AI-driven diagnosis and aesthetic planning helps to add a possibly more distanced and maybe more objective input; however, the final decisions should be made by the treating doctor, whose oversight is remains to be invaluable and who should be cautious regarding the treatment plan limitations.

Our study has some limitations that need to be addressed as well. The participants were only asked to identify themselves with an age group. This was suggested by a psychologist because asking about one's age might make feel some respondents uncomfortable, and have an effect on their scoring. However, having no exact data about age or profession of the respondents makes more complex analyses impossible. It is well known that one's profession and experience influence one's judgement. For example, orthodontists and laypersons give different importance to various facial features when it comes to a facial attractiveness assessment [67].

Another limitation was the total number of respondents. Out of 1800, only 159 and 282 respondents in the first and second round, respectively, submitted the completed forms. Given the number of respondents, it would have been very difficult to make more complex analyses that are proper and relevant, as the more categories of assessors there are, the higher the overall number of respondents is desired. Despite splitting the original form into two forms, it is possible that many respondents considered the form dull and repetitive, and gave up on it halfway through. A possible solution would be to fully explain the aim of the study to the participants to make them feel more involved and responsible for this research; however, we considered the possibility that this could also impact their judgement due to biases of various types [235,236].

Our research studied changes of AI-generated faces, not actual human faces. Naturally, the changes of human faces could be quite different from the changes of AI-generated faces, based on the mere fact that they just do not look the same. However realistic the generated faces are, they are different from real-world patients. As described in the section Materials and Methods, we did not ask for any faces with orthodontic anomalies to be generated. In our experience, however, patients with perfect teeth rarely come for diagnosis and treatment. Using AI-generated faces, thus, poses a possible limitation to our study, as the faces did not show any obvious orthodontic anomalies. On the contrary, all the original pictures were quite average faces [237]. Our choice was based on our aims of having a preferably neutral starting point, and on increased protection of personal data. When we upload photos to most current AI systems, we are also letting the AI learn from the uploaded data and our interactions with the AI [3]. Before our research, we did not know the clear benefits of AI facial enhancement of photos. Using actual photos and asking for the patients' consent in this regard was not yet underpinned scientifically to a high enough level to support such actions. Therefore, we took an inspiration from the pharmaceutical industry, in which a computer-aided drug design is streamlined and successfully integrated, using computers and programs first and only later proceeding to other stages of drug discovery [238–240]. We modified AI-generated faces with AI algorithms to obtain results that could be potentially used as a base for our future study with actual patients. This research was a pilot study, so a rather simple study design was chosen. In more complex future research on this topic, all mentioned limitations should be prevented. Judging by the increase in the number of orthodontics and AI-themed articles, the role of AI is sure to increase with time [70]. Our research suggests using artificial intelligence as a tool for analyzing facial aesthetics, highlighting areas which could be improved, and discusses possible improvements are directions which merit further scientific research.

AI's reliability and transparency, and resiliency to undue influence, possibly hacking is something that would benefit from further research and further focus should also be on concerning the protection of private data, which is of key importance in a healthcare settings. A possible area for further research is AI systems that use a local database without uploading, "learning from" and memorizing data of healthcare importance—so-called federated learning. In such a system, the model (the AI software) could be trained with data, without actually uploading them from a local computer.

As mentioned above there are many ways in which AI software can be influenced either on purpose or accidentally, maliciously or with the best intent. It can happen at the level of data given. What the AI learns from, or the data it uses for decision making may very well have flaws and due to the almost infinite number of possible variations it is necessarily limited. Most AI software weights and value the inputs, how this is done greatly influences the outcome. The opacity of decision-making and the database used to teach AI-s pose a limitation, which does not seem to be reasonably solved so far. This also poses a challenge and possible limitation to its role as assisting the experts: when receiving suspicious output from the AI it might be extremely hard if not impossible to surely determine whether that output is actually correct or not. Thus, the judgement of a trained specialist doctor should not just control, but when necessary, override the judgement made by AI. Another key factor to consider is that when giving input to the AI what it regards as important and what it "sees" is limited by its programming and what it's given. There might well be a multitude of factors the AI is not considering but an experienced doctor would (for example, personality of patient, attitude of parents, some special individual factors not foreseen at the programming of the software. This again reinforces the necessity of human specialist to interact with the patient, exercise oversight and judgement.

AI has great potential to help humanity with boring, repetitive or risky tasks, but also has potentially harmful effects [3,241]. AI can significantly affect an individual's life when used to discover illness or evaluate risks. Further research should focus on the AI's effect on both individuals and society. Since AI may have negative effects that are difficult to predict and control, researchers should focus on accountability, transparency, good software, and quality sources of information for AI to help AI reach its maximal potential, safety, and benefits [3,242]. Additionally, it would be interesting to match artificial intelligence both with smartphone applications or daily used computer software in order to test the reliability of AI-based programs in daily clinical practice more easily [243,244].

Future research could also focus on potential biases in the AI-driven improvements and the psychological effects of AI-enhanced images. Bilateral symmetry, averageness, facial normality, youthfulness, clean skin, sexual dimorphism, and the Golden ratio—these features and parameters greatly influence attractiveness [34,63,245–247]. Other research teams add facial profile and proportions to the attractiveness matrix [170,171]. Our results show that AI changes facial proportions and features in a favorable way, and thus, we suppose orthodontists could, after much technological developments, modify treatment plans according to the AI's suggestions. In the future our research findings may enable advanced AI software's to assist the orthodontists by proposing aesthetic goals. After all, one could consider AI and its algorithms as crowdsourcing, taking models from various databases into account. In the past, crowdsourcing has been proven efficient, leading to novel knowledge [248]. Data collection remains to play a pivotal role in further research, and it may be wise to streamline modern methods of information retrieval.

However, AI has been proven to be biased before. AI uses huge datasets to train itself, and these datasets typically come from the Internet. As a result, they encode inequalities, stereotypes, and power asymmetries throughout society, as they are commonly trained on white faces [249]. Moreover, a phenomenon termed AI hyperrealism has emerged, which refers to the fact that interestingly AI-generated faces are perceived to be more "human" than actual human faces, and this points towards the unnaturally high credibility of AI, which is its disadvantage [237]. If the programming or other aspects of deep learning go awry or the AI is exposed to some challenges for the first time, automated treatment planning might produce undesired results. Following such incorrect directions by untrained providers could potentially harm patients and hinder in achieving desired treatment outcomes, not to mention patients' unrealistic expectations from the very beginning, which could also have a detrimental effect on their compliance and willingness to continue the treatment. Being not trained enough is one of the reasons why experts stress the importance of reviewing and if necessary overruling the results given by AI to prevent mistakes and damages [191]. For that, however, one needs to be educated and skilled both as clinician and analyst. That is why it seems that, for time being, specialist orthodontists are indispensable and cannot be fully replaced by machines.

Without any doubt, AI has a long way to go to fully develop its potential for the good of all. Guidelines on AI development and use that fit human-rights-based frameworks need to be further studied and developed [250,251]. With careful integration, continued human oversight and input, and ethical management, AI technologies can revolutionize and greatly support orthodontic treatment planning, leading to more personalized and effective patient care.

3.3. Discussing our findings regarding 3D-Printed Accessories and Auxiliaries in Orthodontic Treatment

Our literature research showed a wide variety of already established and possible uses. Here, we discuss the application of 3D-printed accessories in orthodontics, underscoring how this innovative technology is revolutionizing the field. With AI and machine learning precision orthodontics such as 3D printing is making a significant leap forward. This is projected to continue into the near future. [252] As 3D printing continues to advance, its integration into orthodontic practice offers unprecedented customization and efficiency, from the production of small auxiliaries to complex devices. In the coming section we will delve into various 3D printing methods, examining their implications for clinical outcomes and workflow optimization. This discussion not only highlights current uses but also future trends and developments in 3D-printed solutions in orthodontics.

Contemporary Use of 3D-Printed Accessories in Orthodontics

This section explores the application of 3D-printed accessories in orthodontics, underscoring how this innovative technology is revolutionizing the field. As 3D printing continues to advance, its integration into orthodontic practice offers unprecedented ease of customization and efficiency, from the production of aligners and retainers to complex individualized devices detailed further. Currently we see a widespread potentiating effect of AI, in many steps of 3D manufacturing, right from the start of segmenting We will delve into various 3D printing methods, examining their implications for clinical outcomes, patient satisfaction, and workflow optimization. This discussion highlights current uses and also anticipates future trends and developments in 3D-printed solutions within the orthodontic field.

Various Auxiliary Devices

A variety of personalized orthodontic accessories, such as distalizers [253,254], power arms [255], powerchains[256], or support devices for impacted teeth [257–260] can be fabricated using 3D printing technology.

One such example is a biocompatible individualized distalizer made from photo-polymeric resin as an aesthetic alternative to conventional methods. This was produced through 3D printing and can be applied in a tooth-borne hybrid method for treating Class II unilateral malocclusions[254]. It is also possible to create a library with various sizes of 3D-printed distalizers, which enables the possibility of personalizing distalizers at any time when needed [253].

Another study examined the clinical results from using various 3D designed and printed orthodontic power-arms. This promises more consistent treatment outcomes and thus more effective orthodontic care. When comparing the 3D printed power-arms with manually crafted or pre-fabricated ones, it is evident that biocompatible AM overcomes many of the common obstacles faced by non-AM power-arms, such as patient discomfort, loss of attachment, or aesthetic handicap [255].

Ratzmann et al. presented the possibility of producing individualized 3D-printed elastic chains with the predefinition of exact forces needed. This could be a possible next step for force-driven planning of orthodontic treatment [256]. The other two case reports described the disimpaction of canines by bone-anchored customized 3D-printed metal devices. In both cases, the device was used for the traction of impacted canines with satisfying results [257,261].

Space Maintainers

The premature loss of primary molars often results in the loss of space in both primary and mixed dentition stages. This can cause misalignment or even impaction of the permanent teeth. Space maintainers are a key tool in preventive orthodontics and help to avoid this loss of space. The band and loop space maintainers are specifically recommended following the early loss of a primary molar. While traditionally fabricated band and loop space maintainers are commonly used, they have certain drawbacks such as cement loss or breakage as the most common reasons for the failure of conventional space maintainers [261]. Digitally designed space maintainers can also be beneficial for non-compliant pediatric patients to avoid gag reflex via the elimination of conventional impressions [262]. Recent studies explored the application of 3D printing technologies in the production of space maintainers, focusing on their clinical feasibility, fit, stability, and manufacturing time [261,263,264,264,265]. Tokuc and Yilmaz compared the fit of metallic space maintainers' bands made conventionally and through CAD/CAM. They found no significant differences in fit between the two methods, suggesting that both meet clinical requirements. However, further research was recommended to explore other aspects such as fracture strength and patient comfort [263]. The case of Khanna et al. highlighted the precise detailing and excellent fit of a 3D-printed space maintainer, although it was not deemed the cost-effective option [261]. Zarean et al. pointed out, in their systematic review, that while 3D-printed space maintainers are increasingly popular in pediatric dentistry and show promise in overcoming the limitations of traditional methods, comprehensive evaluations of their accuracy, efficacy, and overall clinical success are still needed [265]. Another advantage is that with 3D design, we can print more periodontally friendly versions of bands[264]. A 3D-printed lingual arch space maintainer is another possibility for maintaining lower arch length, preventing not only mesial movement of the first permanent molar but also lingual tilting of incisors. However, the authors also stated that this might be not the cost-effective method, even though the predictability and minimal invasiveness could validate the expenses [266].

Bone-Anchored Maxillary Protraction (BAMP) Devices

Bone-anchored maxillary protraction (BAMP) is an orthodontic technique used for the treatment of skeletal Class III malocclusion with maxillary deficiency. The method is based on the modification of the growth of the maxilla while minimizing dental side effects [267]. This can be performed with simultaneous rapid palatal expansion (RPE) [267–269]. While it could be challenging to place conventional protraction plates into the preferred exact location, the using of preoperative simulation and individualized 3D-printed titanium BAMP plates can be more precise [270]. It was demonstrated that satisfying results of maxillary protraction with digital protocol improved the speed and safety of the treatment, while also improving patients' comfort [267–270].

Palatal Expanders

Rapid palatal expansion (RPE) is used in orthodontics for the treatment of maxilla transverse deficiency. It includes widening of the maxilla by rupture of the palatal suture, preferably without dental movement [271]. Bone-borne maxillary expansion [271,272] appliances enable skeletal expansion while minimizing the side effects associated with tooth-anchored palatal expanders [258,273,274], especially undesired teeth movement [272]. RPE devices are traditionally produced using investment casting, also known as lost-wax casting. While this method is highly accurate, it is labor-intensive and costly. Krey and Ratzmann aimed to lower the expenses by integrating fused filament fabrication (FFF) 3D printing using wax-based filaments with investment casting to manufacture orthodontic appliances [275]. However, another study claims high acquisition costs and the necessity of training needed for the digital workflow, incorporation of digital planning, and additive manufacturing promise of higher time-efficient treatment with better patient comfort [272]. The findings of Wang et al. showed that mini implant-assisted palatal expansion could be achieved without traditional impressions or lab processes and successfully expanded the palate in an adult patient [271]. Another study also described the use of a digital laser-sintered palatal expander, with satisfying results [258].

Removable Orthodontic Appliances

Removable orthodontic appliances can be used for the treatment of Class II malocclusions, typically in the early stages of the treatment. However, the shortage of skilled technicians and financial limitations prevent the accessibility of widely recognized removable functional appliances [276]. Several studies described the manufacturing of variable removable orthodontic appliances by 3D printing [276–281]

A paper by Al Mortadi et al. outlined a novel digital technique for creating a removable orthodontic appliance directly from intraoral scans, eliminating the need for traditional impressions. The quality of the intraoral fit was evaluated, confirming a comfortable fit. The study demonstrated the feasibility of digitally manufacturing removable dental appliances and highlighted a shift towards more integrated CAD/CAM processes in dental manufacturing [278]. Kujirai et al., in their study, demonstrated successful manufacturing of myofunctional appliance by implementing the 3D-printed protocol [281].

Mandibular advancement devices (MADs) are widely used for mild to moderate obstructive sleep apnea (OSA). OSA is a prevalent and potentially life-threatening condition, primarily treated medically with continuous positive airway pressure [280]. The clinical report of Piskin et al. highlighted a fully digital workflow for creating a custom nonadjustable MAD, utilizing computer-aided design/manufacturing (CAD/CAM) and additive manufacturing. This innovative approach allows for the rapid production of MADs without the need for traditional intermediate materials or lab processes. Nonetheless, further research is needed to validate these findings comprehensively and the authors highlight the fact that OSA needs medical treatment and not, primarily, orthodontic treatment [282].

Devices for Craniofacial Disorders

Craniofacial disorders (CDFs) represent one-third of congenital defects and affect the shape and function of the head, face, airways, occlusion, and aesthetics. In the treatment of CDF, multidisciplinary cooperation is required, including orthodontists [283]. Treatment strategies involve a comprehensive approach, incorporating both non-surgical and surgical interventions to promote the most natural development possible for infant patients with CDF [284]. Some studies suggest that thanks to the advance of digital technologies and the availability of additive manufacturing methods, it is only a matter of time before pre-surgical treatment with 3D-printed appliances becomes a standard [285]. Digital scans provide a safer alternative to conventional impressions for infant patients with craniofacial disorders and the production of clinically relevant devices is possible [286].

The utilization of computer-aided design in the pre-surgical treatment of infants with cleft lip and cleft palate relies on digitally altering scanned models of the upper jaw to create a sequence of adjusted models. These models are the base for constructing plates that incorporate the designed alveolar movements. Utilizing these plates sequentially has been shown to achieve pre-surgical alignment of the alveolar ridge while minimizing the time spent in the dental chair and the number of appointments. CAD/CAM treatment was claimed to be a more effective method that lessens the overall demand for patient care [198,287–290]. Other papers studied customized appliances in the treatment of airway constriction due to micrognathia associated with the Pierre Robin sequence while demonstrating an additive manufacturing process, using a 3D integration of intraoral scans combined with segmented CT or CBCT images [283,284,286,291,292].

Temporary Anchorage Device (TAD) Insertion Guides

Temporary anchorage devices (TADs), also referred to as mini-screws or mini-implants, are small devices used in orthodontics to offer additional anchorage and support during tooth movement. They are temporarily inserted into the bone and removed once they are no longer needed [293]. Their usage enhances the biomechanics and procedures in orthodontics [260].

Three-dimensional printers have been utilized to create customized surgical guides that ensure the precise placement of TADs. This helps to avoid critical anatomical structures like dental roots, nerve-vascular bundles, and thin bone areas. The guides can provide clear images of hard tissue (bone–teeth) for selecting mini-implant locations, while the contours of teeth–brackets–mucosa ensure the guide's proper fit in the mouth [127]. Several studies provided evidence of the successful implementation of 3D-printed TAD insertion guides in their practices [260,294–296]. The key benefits of using a digital workflow in guide production include reducing the risk of complications, minimizing chair time, and enhancing patient comfort [297].

Brackets Placement Guides

The effectiveness of orthodontic treatment with fixed appliances depends on precise bracket positioning [298]. Advanced direct and indirect bonding techniques are continuously investigated, highlighting the effectiveness of different technologies and techniques in achieving precise bracket placement [298–306]. Indirect bonding is an alternative to manually placing brackets. This approach involves planning and positioning the brackets on a model before transferring them to the oral cavity. Advances in scanning and manufacturing have significantly enhanced the accuracy of bracket placement [300]. Technological progress has opened new research opportunities in the development of indirect techniques. The use of individual 3D transfers is particularly advantageous in difficult clinical cases, enhancing the efficiency of the procedure, reducing the number of technical steps, and reducing the overall time spent in the orthodontic practice [300].

Zhang et al. assessed the accuracy of indirect bonding using 3D printing guides versus double-layer guide plates. The study concluded that the 0.6 mm double-layer guide plate group was more accurate than the 0.8 mm group, and while the accuracy of 3D printed guides was comparable, there was no significant difference between the types of guides used [301] . Nucera et al. introduced a digital workflow creating a detailed 3D model of dental arches, enhancing the precision of indirect bonding and reducing errors in bracket positioning, aiming for easier and reproducible bracket placement for clinicians in the future [302] . A randomized clinical trial (RCT) of Schwärzler et al. found that CAD/CAM technology is reliable for indirect bracket bonding, with low rates of bracket loss compared to the previous literature [299]. A study by Soares Ueno et al. showed significantly shorter chair times, demonstrating that while its accuracy was comparable to conventional methods, it provided the added advantage of reducing chair time, thereby improving the experience for both patients and professionals [303].

Artificial Intelligence and 3D Printing, Future Possibilities

Artificial intelligence (AI) is already used to support the 3D design of appliances. Right from the start, at the imaging phase, AI can help with the segmentation and optimization of 3D data. AI already helps in clinical practice by identifying anatomical structures [115]. In the design phase, it can automatically recognize teeth from raw scan data, segment them, and make measurements of them with minimal help from the doctor. It can already be used to adapt existing appliance designs to a new situation without the need for a completely new design. AI can assist 3D design by adapting a structure automatically to the tooth surface, finding and matching the same or similar objects in different 3D structures [29].

Artificial intelligence is already used to overcome the previous limitation of printing only on flat surfaces; it offers flexibility by performing on irregular surfaces as well. On top of this, AI can help optimize the trajectory of printing nozzles to ensure high quality and accuracy. Predictive modeling can help compensate for expected material shrinkage and distortions [115]. Given that AI is already used in other areas of orthodontics or 3D printing as a powerful problem-solving tool [101,115]. AI can be effectively applied to detect and predict errors in 3D printing processes, enhancing the quality and reliability of 3D-printed devices. This approach allows for greater precision and optimization, addressing common issues such as surface quality and structural integrity [307]. We can expect further uses empowering the specialist orthodontists [70]. However, there are concerns over over-reliance on AI tools for 3D appliance design and evaluation, emphasizing that AI remains an assistive technology and cannot replace clinical expertise or manual validation for now.

Future research could focus on the artificial intelligence (AI)-supported design of appliances to reduce the workload and skills required in the dental practice. In the future, the research could explore the AI-supported adaptation of one design to another similar clinical situation without the need for a completely new design process. AI could also support the work, by the automatic fabrication of study models from raw scan data [29]. In orthodontics, 3D applications are expected to overtake 2D applications in the future [308], and this technological advancement must be supported by adequate evidence provided by up-to-date research. Future development should aim to harness AI to help the specialist during everyday orthodontic practice and assist in the specialist’s job.

Another area for future research is the question of long-term biocompatibility. Patient safety and occupational safety are critical with all medical devices. Monomers, incomplete polymerization, and microplastics all pose possible health challenges that need to be investigated [308–310]. Even after rigorous polymerization and cleaning, leads to some unpolymerized monomers are left over and these molecules can escape from the plastic [310].

Three-dimensional printing raises the important aspect of occupational safety. During the manufacturing of 3D-printed plastics, nanoparticles and volatile organic compounds (VOC) can be released, which have direct and indirect toxic effects on humans. Exposure to some of these materials can lead to asthma, allergies, neurological damage, and even DNA damage [311]. Microplastics have been shown to accumulate in the human body. As of now, there is more evidence accumulating about the potential toxic and adverse effects [312], not just through their physical presence but also through the chemical effects of substances leaching out, through altering the microbiome, and even through the possibility of microplastics bringing other toxic substances with them on their surface. Ingesting microplastics were shown to cause harm to marine organisms and similar results came from other animal studies [313]. As of now, there is limited evidence that suggests that a smaller part of the microplastics cross the epithelial barriers in the intestines and airways, but it might be important considering the length and amount of exposure and the fact that the effects may be cumulative. There is increasing concern about micro and nano plastics and their effects on human health and this is an important area to explore with future research [314].

4.1. Benefits of 3D-Printed Accessories in Orthodontics

When it comes to 3D-printed accessories and appliances in orthodontics, there are many benefits to consider. Making use of the digital workflow processes that enable dentists to maintain full control of the designed appliance and to completely bypass dental technicians in many cases, the in-house production of orthodontic appliances transforms and optimizes patient care as well as reducing the costs [315–317]. Patients can be provided with fully customized 3D-printed orthodontic brackets or other dental or maxillofacial devices that may better reflect the patient needs; this concept is also known as biological customization [197,318]. Being able to produce removable appliances without any dental technician, without compromising the final result, brings new possibilities to orthodontists working in areas with scarce dental technicians, whose services may take too much time [319]. In fact, that is a reason why working in private practices and being exposed to an increasing patient load are both associated with the likelihood of possessing a 3D printer in an orthodontic office [320].

In fact, 3D printing of various appliances is often only one component of digital workflows in orthodontic practices that need to be appreciated as a whole. Making use of 3D printing is but a terminal step; at first, digital data acquisition takes place, then data processing (often using Artificial Intelligence algorithms) is performed, and only then are countless appliances to be 3D-printed designed [70].

4.2. Challenges, Limitations, and Future Possibilities

As with other technologies, 3D printing has multiple limitations that need to be considered. To start with, to make proper use of the whole 3D printing apparatus, the clinician is also required to have other hardware and software in the office and to know how to operate other programs and machines, not only the 3D printer [321]. Of course, there are also instances of making use of freeware; however, it is often more complicated and presumes the good digital skills of the team [254,322]. In any case, the skills of the operator are essential, and life-long education and training are needed. These limitations emphasize the importance of comprehensive training and significant investments in infrastructure for successful implementation. However, they also highlight that the long-term success of 3D printing in orthodontics depends on achieving a balance between embracing advanced technology and ensuring cost-efficiency and accessibility. Overcoming these challenges will be essential to make 3D printing a practical and scalable solution for smaller practices and varied healthcare environments.

Overengineering the whole treatment process only for the sake of using the newest technologies, with no or little benefit, can be avoided. Thus, using the digital approach to fabricate a custom-made appliance using 3D printing should be justified by a clear benefit to the patient rather than by the desired image of the practice [323]. By improving precision, reducing chair time, and enhancing clinical outcomes, this technology paves the way for more efficient and patient-centered care. The key challenge is to ensure that these workflows can be effectively adopted across practices of all sizes and resource levels, without compromising the quality of care provided.

Equipping a practice with powerful computers, software licenses, 3D printers, and devices needed for post-processing (such as ultrasound cleaners, UV light curers, and polishers of various sorts) adds up and the final cost may be too high, especially for practices that do not use this technology on a regular basis. Furthermore, not all 3D printing equipment is suitable for dental offices, e.g., printers for metallic appliances require much space and the workflow may pose health hazards for the dental team [321]. The "in-house laboratory" needs to meet specific requirements and specific protocols need to be followed [324]. The printing room should be separated from the rest of the clinic and patient care, and proper ventilation needs to be ensured. Many materials used for 3D printing or post-processing are toxic and non-biocompatible, including the release of volatile organic compounds (VOCs) and ultrafine particles during the printing and post-processing stages. To mitigate these hazards, it is crucial to ensure proper ventilation in printing areas, use biocompatible and non-toxic materials, and adhere to established safety guidelines. Special attention should be dedicated to making sure that all personnel understand the health risks they are exposed to when ignoring prescribed protocols.

When it comes to the limitations of this scientific field, as a new and rapidly advancing area, it would benefit from more research about material safety and clinical efficiency. Possible future directions in this field include more of an evidence base for the clinical efficiency of DPA**,** making 3D printing cheaper and available to any dentist, and ensuring the materials used are of no harm even in the long term for either patient (even with extended time in the oral cavity) or doctor and the technician manufacturing it[128]**.** All materials that are intended for intraoral use need to be rigorously tested, and international standards and guidelines regarding laboratory tests would be beneficial [130,325]

Last but definitely not least, it is crucial to focus further scientific endeavors on specific 3D-printed materials from the luting perspective. Different materials require different cements, and this could be of double importance for novel materials and the way of their fabrication. In other words, together with the development of new fabrication methods and novel materials, all necessary measures need to be taken to ensure their ease of use and no immediate or delayed complications. The available studies are rather scarce [326]. The ideal progression in this field could be the development of the direct 3D printing of orthodontic accessories made from shape memory materials, which has the potential to revolutionize the entire orthodontic landscape. Such orthodontic accessories made from shape memory materials could combine the advantages of directly printed resin devices—such as excellent adhesion to tooth structures and superior aesthetics—with the benefits of directly printed metal devices, including strength and biocompatibility. Moreover, directly printed aligners could incorporate accessory devices within their structure. If these materials can also be produced in a cost-effective manner, ensuring financial accessibility for a broader population, they could significantly transform orthodontic treatments, making advanced technology available to practices and patients worldwide. The AI could address the complexity of designing custom-made orthodontic accessories by utilizing automated tools that evaluate patient scans and suggest optimal biomechanical treatment methods, streamlining the planning process and improving precision. In addition, recent research has outlined the potential of AI in setting orthodontic treatment goals based on the enhancement of faces using deep learning algorithms [172]. Figure 20 illustrates a comparison of 3D-printed resin, metal, and shape memory orthodontic devices, detailing their advantages, disadvantages and future potential.

5. Conclusions

The integration of AI software, 3D printing and facial scanning and AI assistance into orthodontics is leading to a paradigm shift in the field. These technologies are transforming the way dentistry and 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 assistance 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 assist in diagnosis, treatment planning and predicting possible 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. The profession and society must pick up the mettle and formulate best practices and regulations to ensure safety of AI. Orthodontics should embrace the power of AI and pave the way for a new era of personalised data-driven care. However, we must not forget the limitations of AI, and the continued necessity for appropriate oversight by a specialist doctor.

In our scoping review we showed that face-guided (facially driven) orthodontics is on the rise and is part of a complex AI assistance revolution in the field, possibly leading to an unprecedented paradigm shift. AI support will likely make it possible to handle difficult tasks, such as analysing complex facial features and simulations, to better assist orthodontists. We are currently at the beginning of incorporating AI into daily orthodontic practice.

In our research we focused on the intersection of artificial intelligence (AI) and facial aesthetics, demonstrating the potential of AI-powered face enhancement in orthodontics. Our results confirms that AI can successfully enhanced images. The modified ones are consistently rated as more attractive than originals, with the greatest modifications observed in the lower facial third, including lip fullness, eye size, position, and chin height. Our findings suggest that AI may serve as a valuable tool for visualizing treatment outcomes, improving patient communication and decision-making. While AI has significant potential in personalized orthodontic care, several ethical, technical, and clinical limitations must be addressed. AI models remain opaque ("black box" problem), possibly prone to bias and hallucinations, and dependent on data quality. Furthermore, AI-enhanced images may create unrealistic expectations among patients, necessitating clear communication regarding the biological limitations. The role of orthodontists remains indispensable, ensuring that AI serves as an augmentative tool rather than a replacement for clinical expertise. Future research could focus on integrating AI into orthodontic workflows responsibly, ensuring safety, data security, transparency. Additionally, the long-term validity of AI-driven aesthetic assessments should be explored through clinical trials and real-world applications. With continued advancements, AI assistance has the potential to redefine orthodontic treatment planning, to help orthodontists offer greater precision, efficiency, and personalization, ultimately enhancing both patient outcomes and the workflow of the doctor.

An area of emphasis in our research was 3D printing. The advancement of three-dimensional printing technology has revolutionized the creation and fabrication of tailor-made orthodontic devices, transforming diagnostic and treatment approaches in orthodontics. A wide range of appliances can be directly 3D-printed in-office or produced by specialized laboratories. While direct printing offers advantages like improved precision, treatment predictability, and shortened chair time, limitations such as extended manufacturing times and post-processing requirements must be considered. Additional investigations into the physical, chemical, and biological characteristics of 3D-printable materials are necessary. Further research should also focus on overcoming high costs and steep learning curve for dental practitioners, followed by further long-term clinical evaluations. However, advancements in 3D-printing speed, AI automation, and memory shape materials could address these barriers, paving the way for the broader adoption of 3D-printing technology in orthodontics in the future.

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7. Afterword

AI is indeed already reshaping our life, and how it evolves and what further changes it enacts is something we should all think about. We should also never forget, that we as society have the power and it's imperative to steer its progression. It is a huge chance to empower us and a huge responsibility.

As final thought let me quote Frederick Brown's 1954 a short story titled "Answer". In this tale all the computers of almost 100 billion planets were connected to a central supercomputer. Right after making the final connection is when we join the story:

""The honor of asking the first question is yours, Dwar Reyn."
"Thank you," said Dwar Reyn. "It shall be a question which no single cybernetics machine has been able to answer."
He turned to face the machine. "Is there a God?"
The mighty voice answered without hesitation, without the clicking of a single relay.
"Yes, now there is a God."
Sudden fear flashed on the face of Dwar Ev. He leaped to grab the switch.
A bolt of lightning from the cloudless sky struck him down and fused the switch shut. "

Fredric Brown, "Answer", 1954

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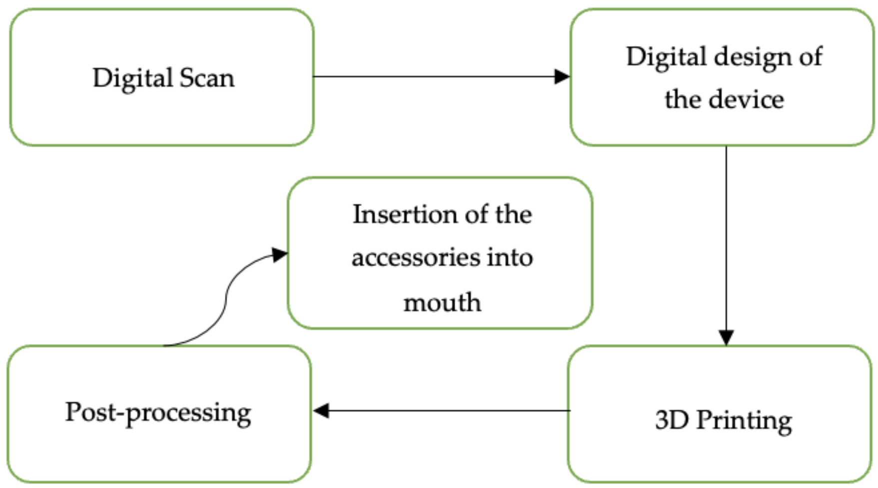
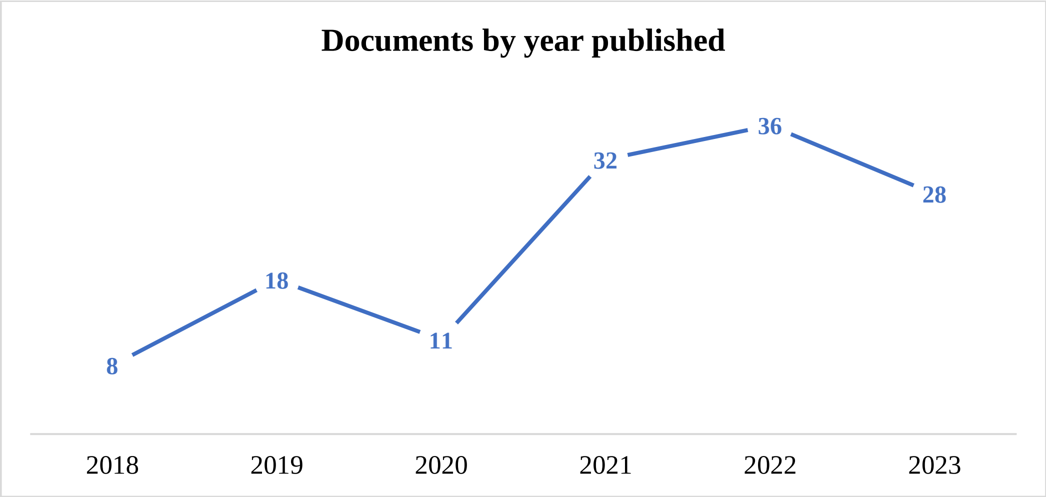


Figure 1. A simple scheme of manufacturing steps of customized 3D-printed orthodontic accessories.



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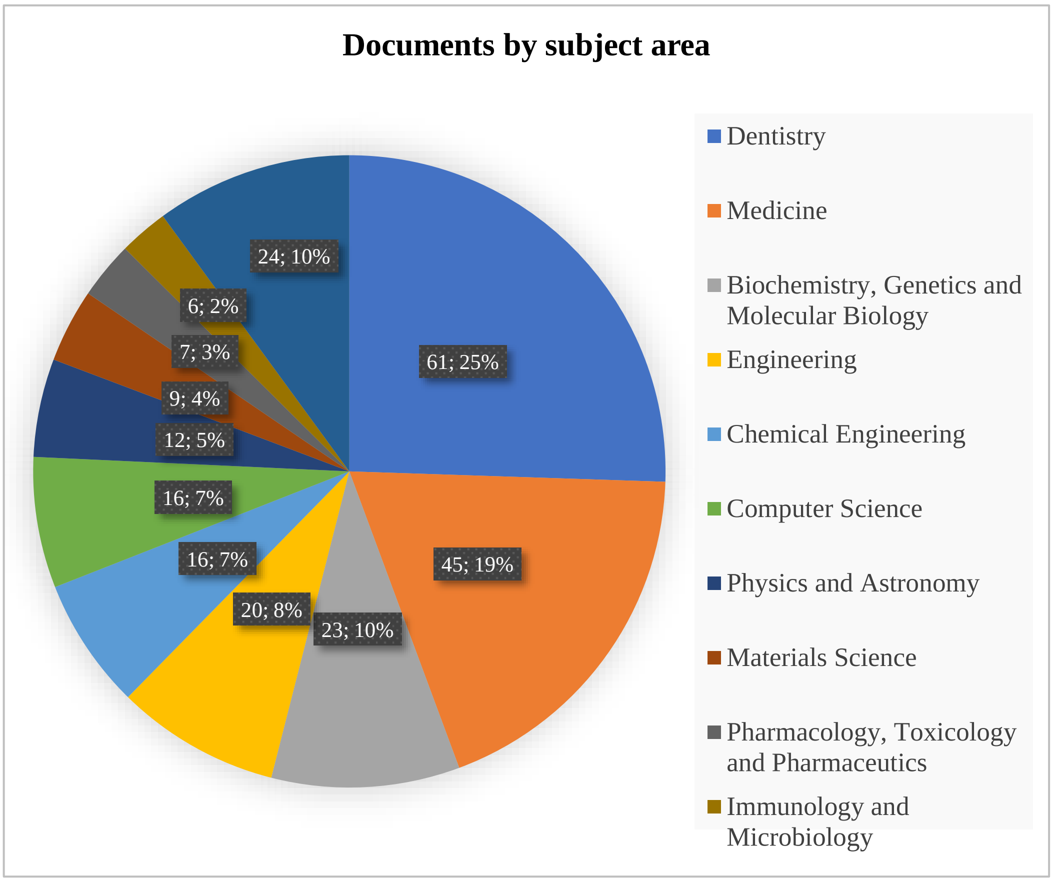

Figure 3. Distribution of searched documents within various subject areas in our scoping review.

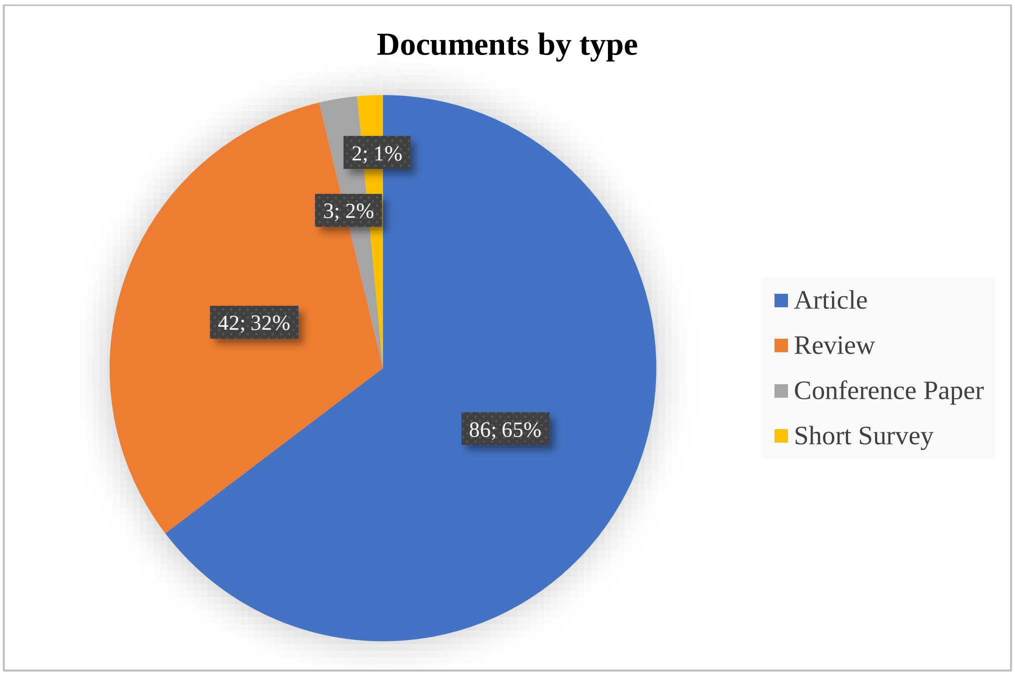

Figure 4. Proportion of various types of searched documents in our scoping review.

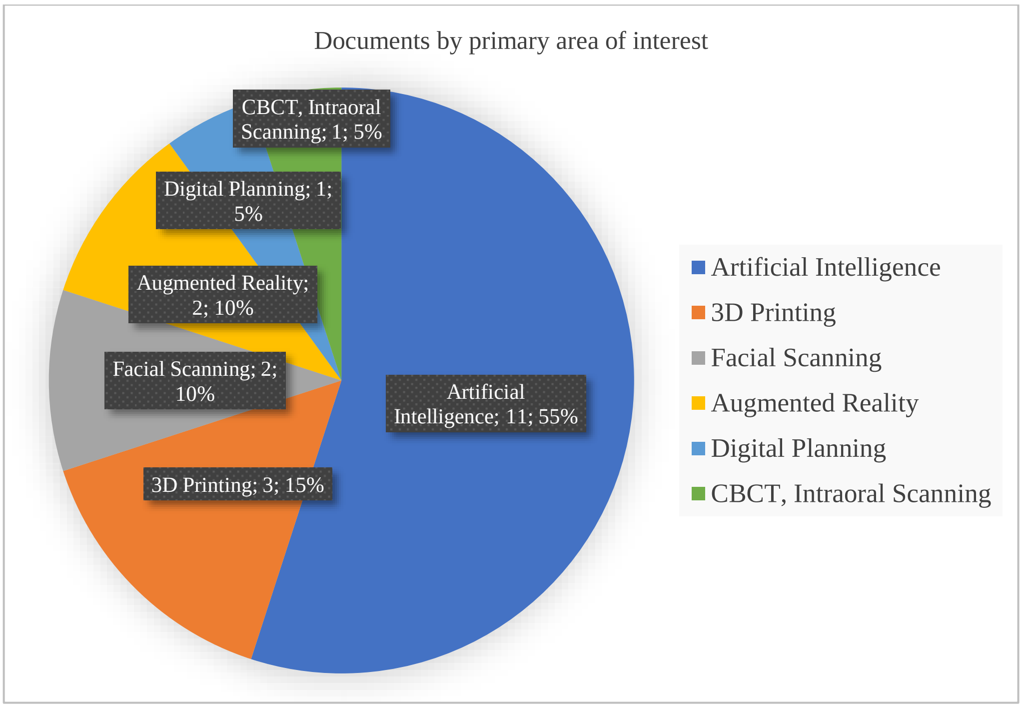

Figure 5. Number of most-cited documents by their primary area of interest in our scoping review.

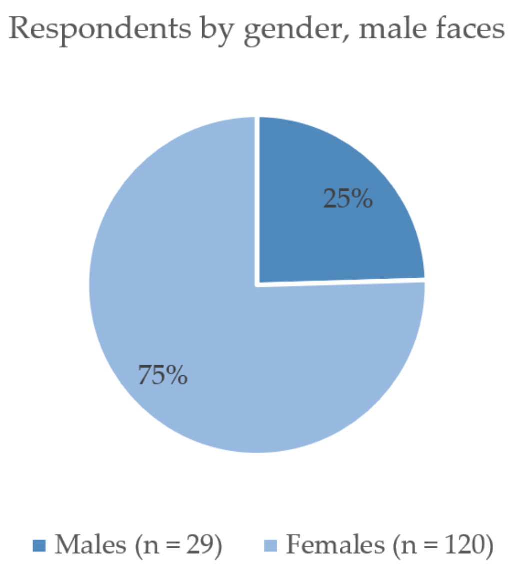

Figure 6. Respondents to the “Male faces” questionnaire by gender.

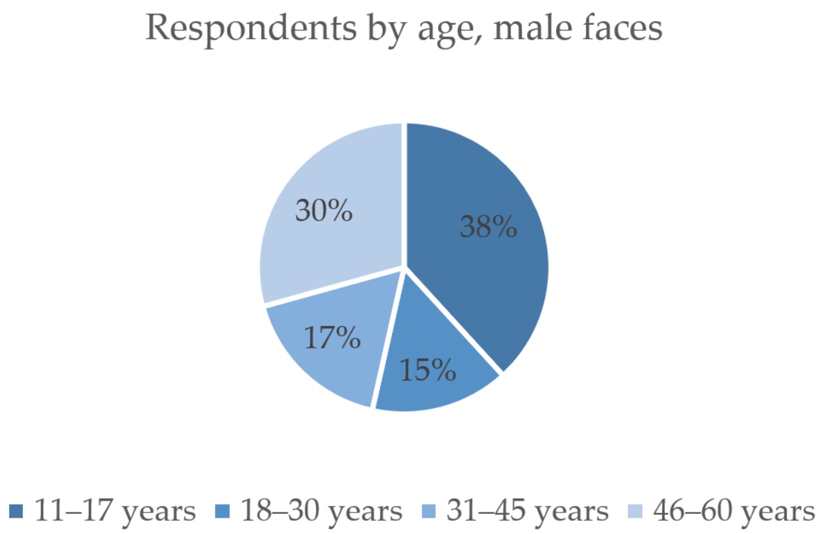

Figure 7. Respondents to the "Male faces" questionnaire by age.

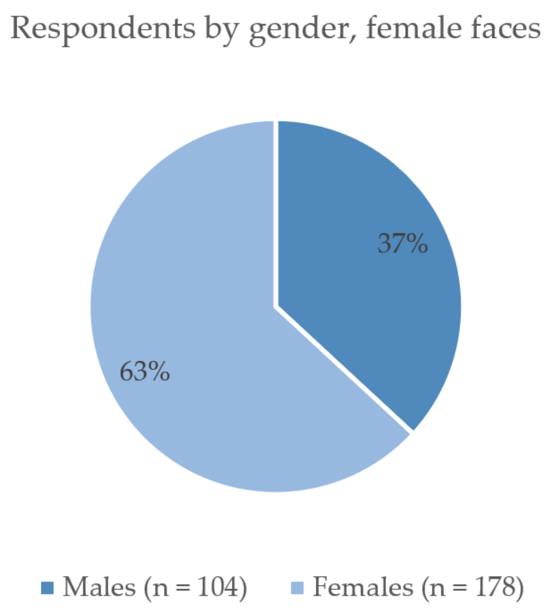

Figure 8. Respondents to the “Female faces” questionnaire by gender.

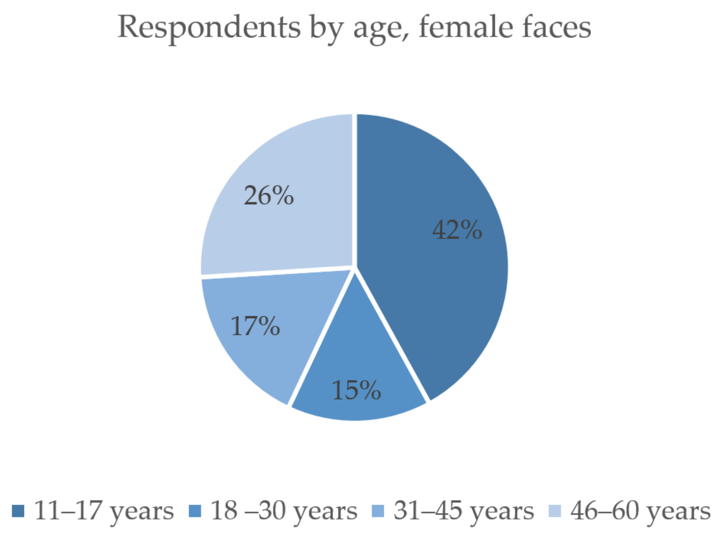

Figure 9. Respondents to the “Female faces” questionnaire by age.

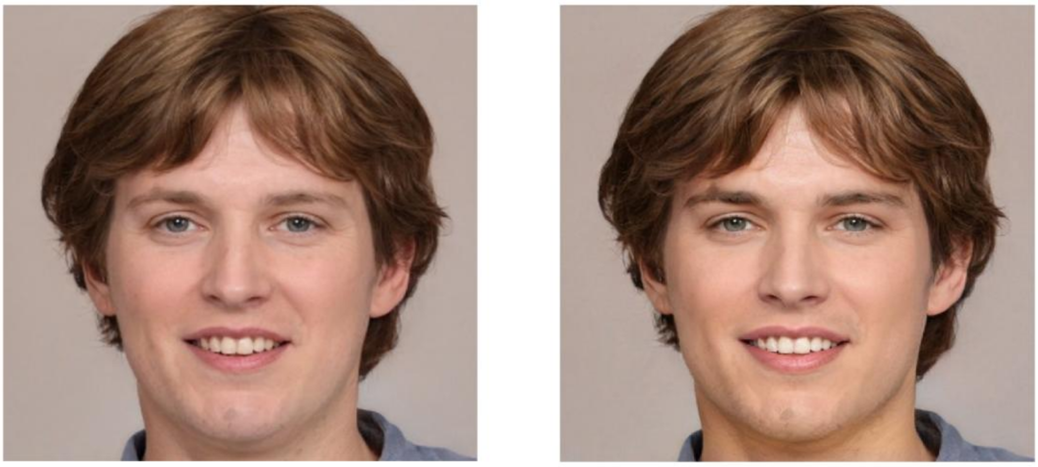

Figure 10. Left—original, right—FaceApp-enhanced. This AI-enhanced picture (Male face 19) was voted as the more attractive one of the pair by the highest percentage of respondents (90.57%).

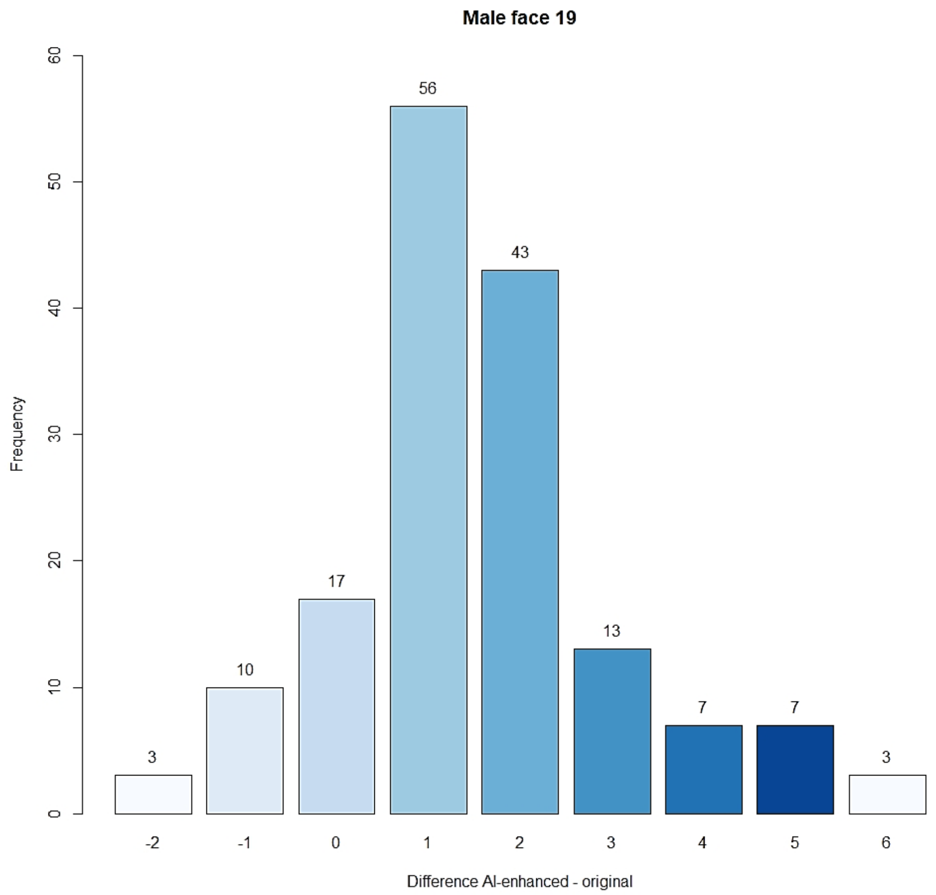

Figure 11. The difference between the attractiveness score (from 1 to 10, 10 being the most attractive) between the AI-enhanced and original version of the male picture, of which the latter one was judged most frequently as the more attractive one (Male face 19).

Figure 12. Left—original, right—FaceApp-enhanced. This AI-enhanced picture (Female face 25) was selected as the more attractive one of the pair by the highest percentage of respondents (92.91%).

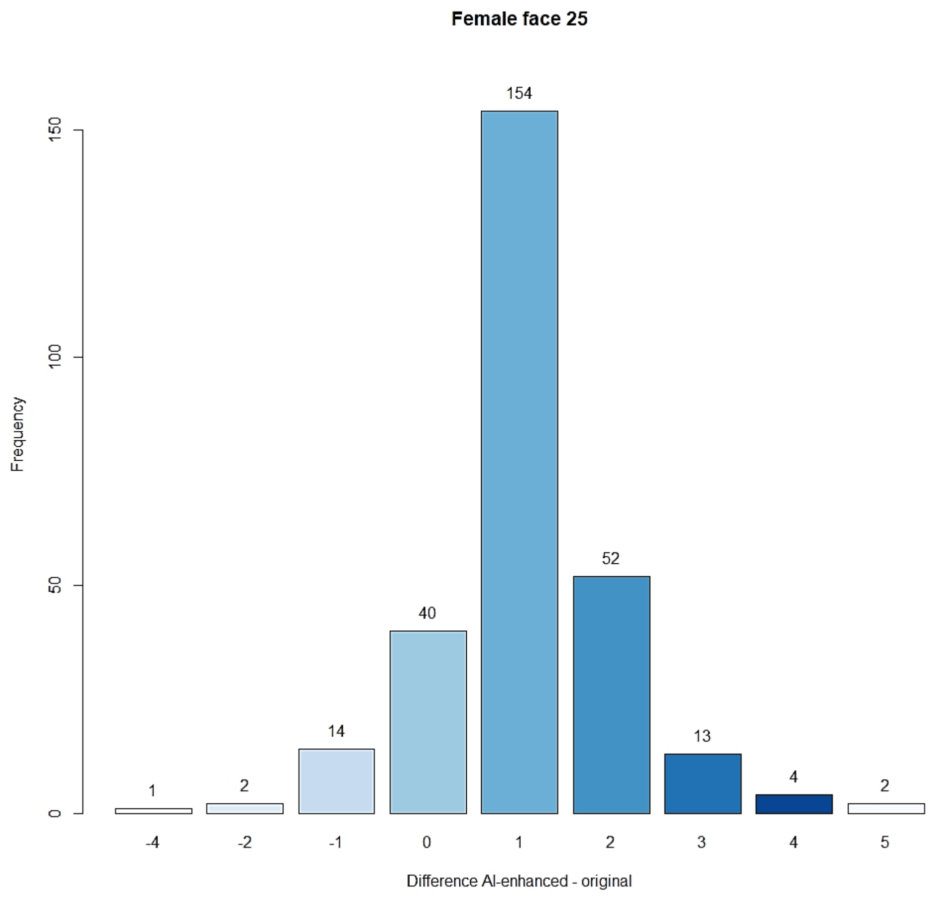

Figure 13. The difference between the attractiveness score (from 1 to 10, 10 being the most attractive) between the AI-enhanced and original version of the female picture, of which the latter one was judged most frequently as the more attractive one (Female face 25).

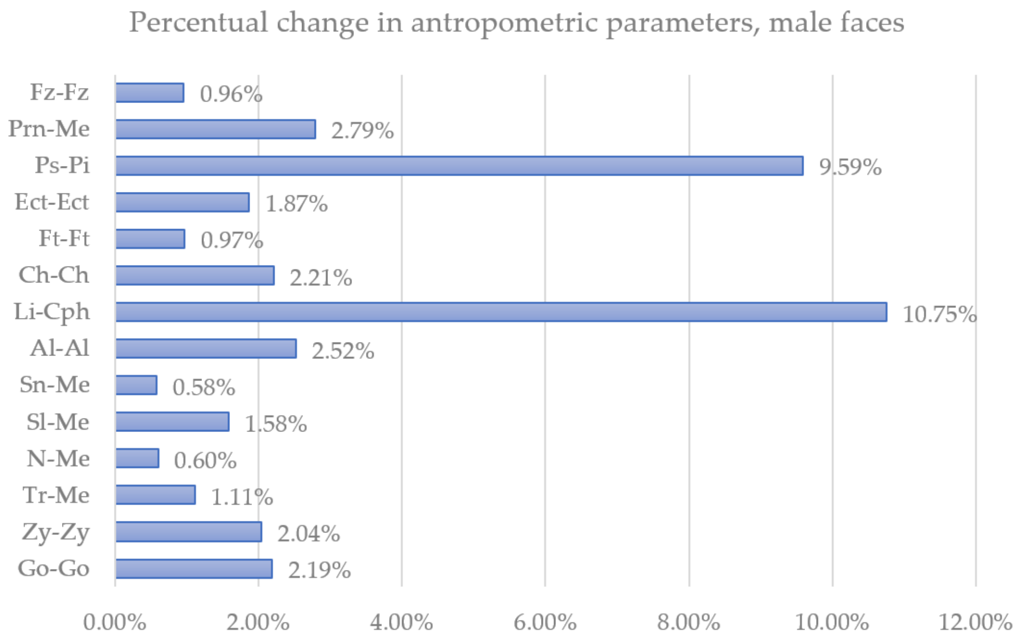

Figure 14. The changes in selected anthropometric distances on the male face, resulting from AI enhancement of the pictures.

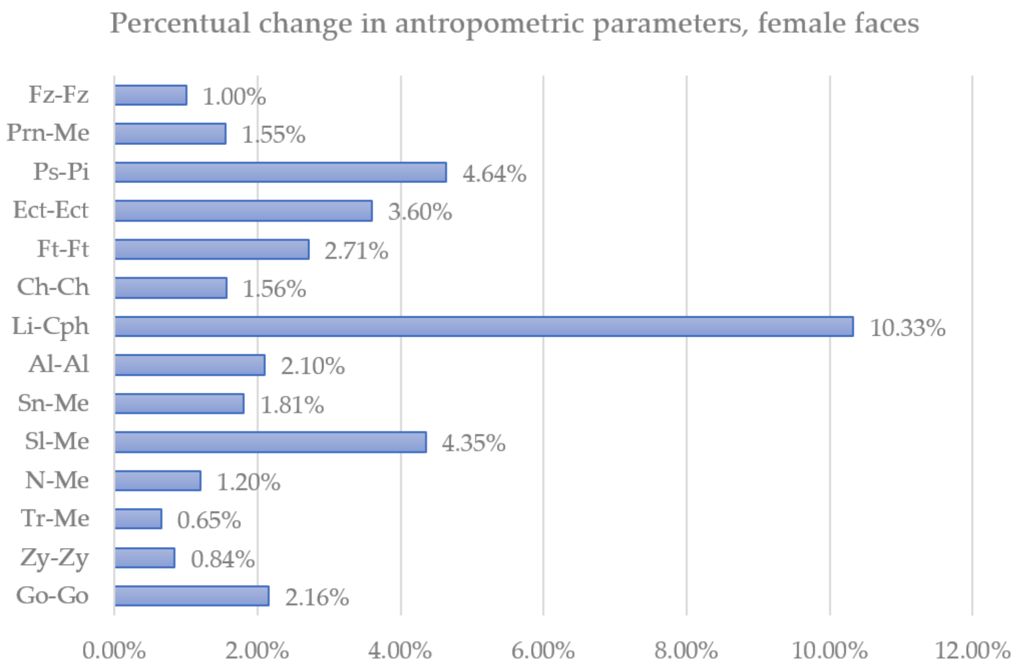

Figure 15. The changes in selected anthropometric distances on the female face, resulting from AI enhancement of the pictures.

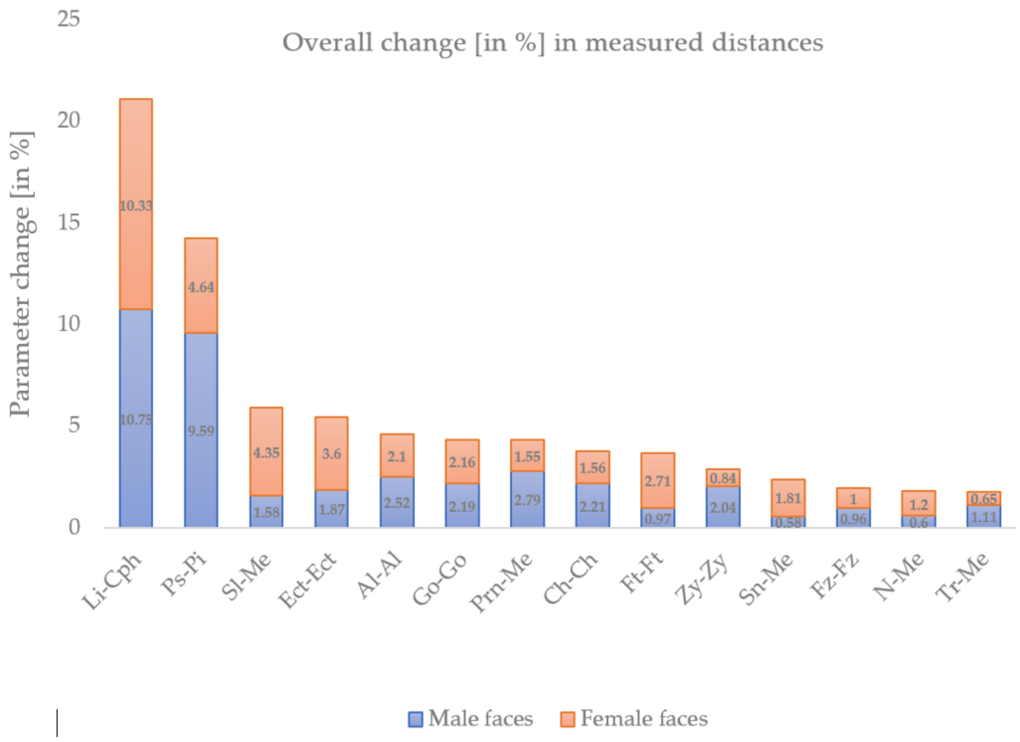

Figure 16. Percentual changes in measured distances (from highest to lowest overall value).

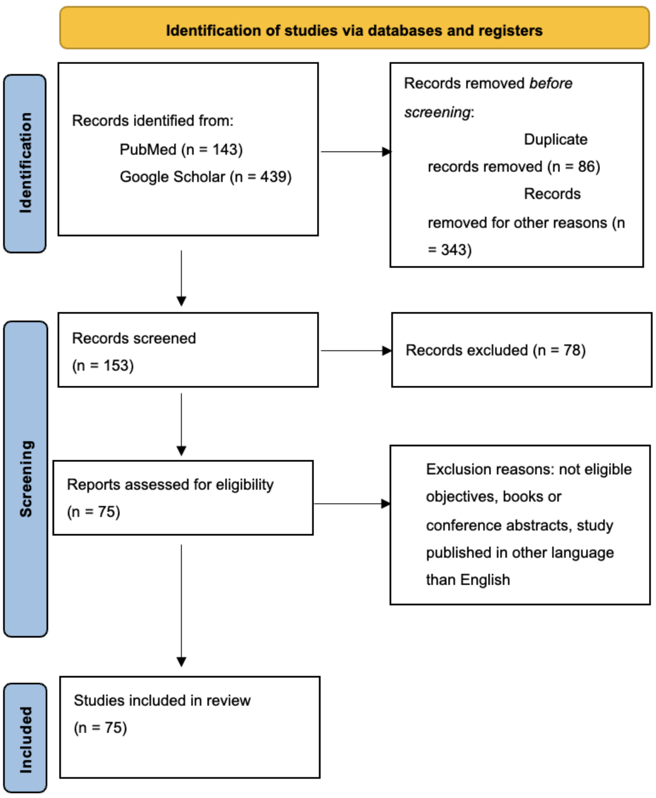

Figure 17. Prisma scheme for the identification of studies of the 3D printing topic.

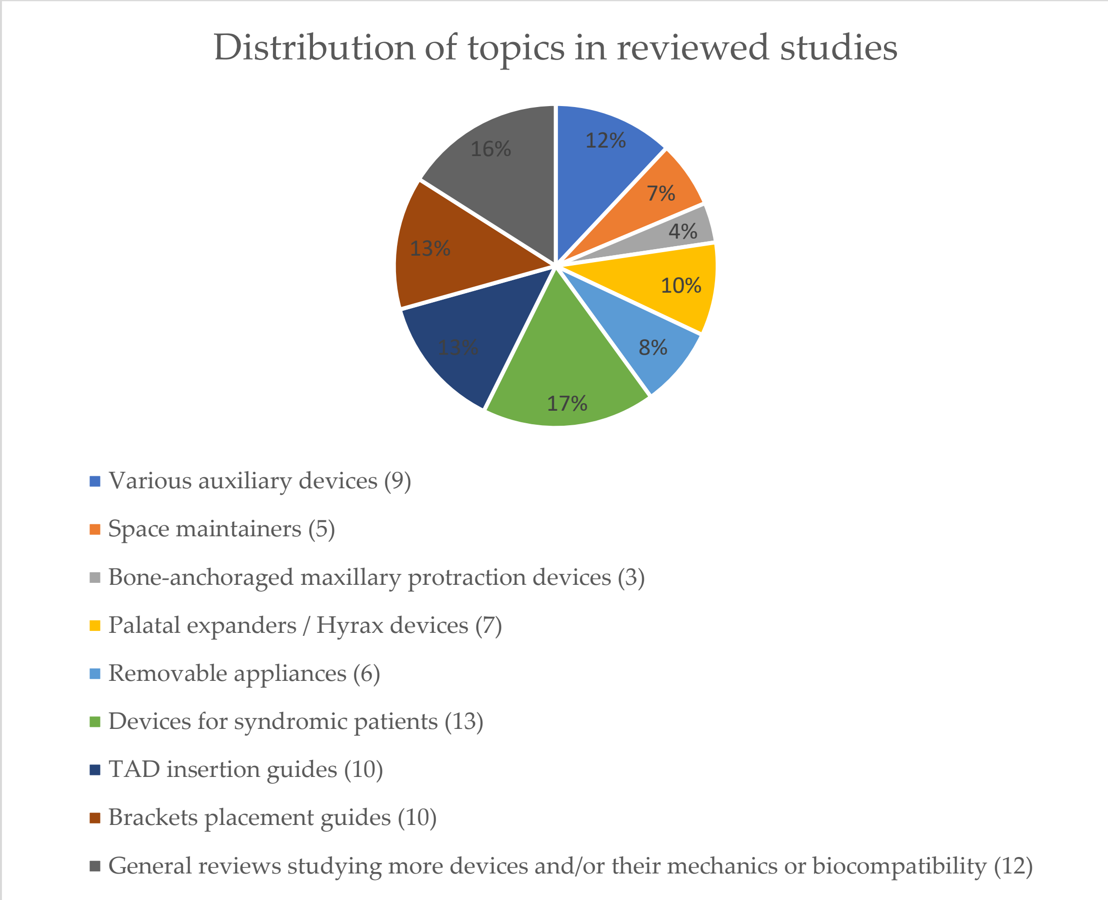

Figure 18. Distribution of topics in the reviewed studies of the 3D printing topic.

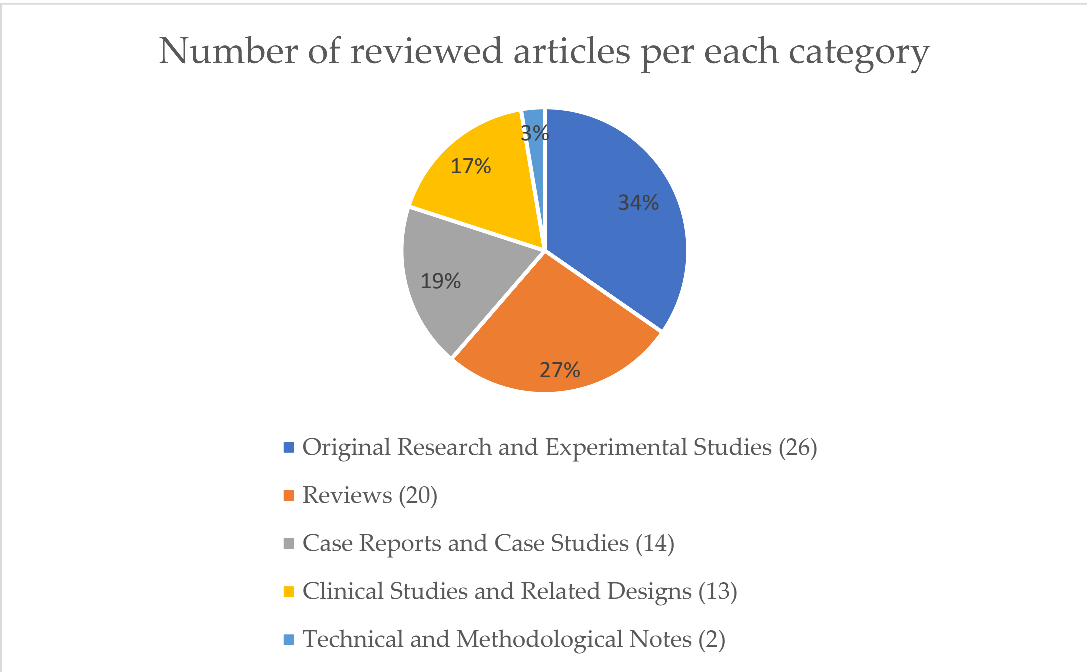

Figure 19. Number of reviewed articles per category of the 3D printing topic.

Type of Device	Advantages	Disadvantages	Potential of Shape Memory Devices
Resin Devices	*Good adhesion to tooth structures*	*Limited strength*	*Combines adhesion of resin with the strength of metal*
	Superior aesthetics	*Biocompatibility concerns for some materials*	*Potentially biocompatible and safe for extended intraoral use*
Metal Devices	*High strength and durability*	*Difficult to process in dental offices* (e.g., *large printers, ventilation required)*	*Provides strength and resilience while being more affordable*
	Biocompatibility for most alloys	*Expensive equipment and materials*	*Affordable in-house printing*
	Reliable for long-term orthodontic treatments	*Less aesthetically pleasing*	*Can combine strength with aesthetic properties*
Shape Memory Devices	*Potentially combine the adhesion, aesthetics, and customization of resin devices*	*Currently in development, with limited availability*	*Could represent a paradigm shift in orthodontics by integrating best characteristics from resin and metal devices*
	Offer the strength and durability of metal devices	*Unknown long-term biocompatibility*	*Could provide both flexibility and resilience*
	Cost-effective production		*Enhance accessibility to advanced orthodontic treatments*

Figure 20. Comparison of 3D-printed resin, metal, and shape memory orthodontic devices: advantages, disadvantages, and future potential.

Equations:

$Sample\ size = \dfrac{\dfrac{z^2 \times P \times (1-P)}{E^2}}{1 + \dfrac{z^2 \times P \times (1-P)}{E^2 \times N}}$	Equation (1)
$Sample\ size = \dfrac{\dfrac{1.96^2 \times 0.9 \times (1-0.9)}{0.05^2}}{1 + \dfrac{1.96^2 \times 0.9 \times (1-0.9)}{0.05^2 \times 1800}} = 128.43$	Equation (2)

Tables:

Table 1. The facial anthropometric points selected to compare the pairs of pictures.

Abbreviation	Craniometric Points	Significance
Ch-Ch	Ch—cheilion	Mouth width
Go-Go	Go—gonion	Mandible width
Zy-Zy	Zy—zygion	Middle face width
Tri-Me	Tri—trichion, Me—menton	Face height
Sl-Me	Sl—sublabiale, Me—menton	Chin height
Sn-Me	Sn—subnasale, Me—menton	The distance from the nose to chin
N-Me	N—nasion, Me—menton	Anterior face height
Al-Al	Al—alare	Nose width
Ft-Ft	Ft—frontotemporale	The distance of the most outer points of superciliary arches on the frontozygomatic suture
Fz-Fz	Fz—frontozygomaticus	The distance of the most outer points of superciliary arches
Ps-Pi	Ps/i—palpebrale superius/inferius	Eye height
Ect-Ect	Ect—exocanthion	Eye width
Li-Cph	Li—labrale inferius, Cph—crista philtri	The distance between the upper and lower lip lines
Prn-Me	Prn—pronasale, Me—menton	The distance between the nose tip and chin

Table 2. 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	D'Ettorre, Giorgio; Farronato, Marco; Candida, Ettore; Quinzi, Vincenzo; Grippaudo, Cristina	2022	Face scanning	15.68

	technology for three-dimensional face scanning [205]				
2	Deep convolutional neural network-based automated segmentation and classification of teeth with orthodontic brackets on cone-beam computed-Tomographic images: A validation study [159]	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 [40]	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 [327]	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 [74]	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 [328]	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 [329]	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 [330]	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 [173]	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 [195]	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
11	Scope and performance of artificial intelligence technology in orthodontic diagnosis, treatment planning, and clinical decision-making—A systematic review [160]	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 [161]	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! [331]	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 [175]	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 [23]	Staderini, Edoardo,; Guglielmi, Federica; Cornelis, Marie A.; Cattaneo, Paolo M.	2019	CBCT, intraoral scanning	3.46
16	Augmented reality in dentistry: a current perspective [332]	Kwon, Ho-Beom; Park, Young-Seok; Han, Jung-Suk	2018	Augmented reality	2.83

17	Decoding Deep Learning applications for diagnosis and treatment planning [333]	Retrouvey, Jean-Marc; Conley, Richard Scott	2022	AI	2.35
18	Smartphone-Based Facial Scanning as a Viable Tool for Facially Driven Orthodontics? [206]	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 [198]	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 [153]	Leite, André Ferreira; Vasconcelos, Karla de Faria; Willems, Holger; Jacobs, Reinhilde	2020	AI	2.05

Table 3. The percentage of respondents selecting the given picture (male and female face, original and AI-enhanced) as more attractive from the pair.

	Original	**FaceApp**	***p*-value**		**Original**	**FaceApp**	***p*-value**
Male face 1	30.82	69.18	0.000013	Female face 1	13.48	86.52	< 0.000001
Male face 2	36.48	63.52	0.000649	Female face 2	51.06	48.94	0.7209
Male face 3	24.53	75.47	< 0.000001	Female face 3	26.60	73.40	< 0.000001

Male face 4	15.72	84.28	< 0.000001	Female face 4	12.06	87.94	< 0.000001
Male face 5	28.30	71.70	< 0.000001	Female face 5	36.17	63.83	0.000003
Male face 6	15.72	84.28	< 0.000001	Female face 6	14.89	85.11	< 0.000001
Male face 7	13.21	86.79	< 0.000001	Female face 7	26.95	73.05	< 0.000001
Male face 8	15.72	84.28	< 0.000001	Female face 8	34.04	65.96	< 0.000001
Male face 9	19.50	80.50	< 0.000001	Female face 9	9.93	90.07	< 0.000001
Male face 10	15.72	84.28	< 0.000001	Female face 10	17.38	82.62	< 0.000001
Male face 11	22.64	77.36	< 0.000001	Female face 11	24.11	75.89	< 0.000001
Male face 12	23.27	76.73	< 0.000001	Female face 12	26.60	73.40	< 0.000001
Male face 13	39.62	60.38	0.008869	Female face 13	20.21	79.79	< 0.000001
Male face 14	18.87	81.13	< 0.000001	Female face 14	20.21	79.79	< 0.000001

Male face 15	22.64	77.36	< 0.000001	Female face 15	19.50	80.50	< 0.000001
Male face 16	17.61	82.39	< 0.000001	Female face 16	22.70	77.30	< 0.000001
Male face 17	29.56	70.44	< 0.000001	Female face 17	43.26	56.74	0.02364
Male face 18	35.85	64.15	0.000359	Female face 18	12.77	87.23	< 0.000001
Male face 19	9.43	90.57	< 0.000001	Female face 19	23.76	76.24	< 0.000001
Male face 20	11.95	88.05	< 0.000001	Female face 20	30.85	69.15	< 0.000001
Male face 21	11.95	88.05	< 0.000001	Female face 21	19.86	80.14	< 0.000001
Male face 22	16.35	83.65	< 0.000001	Female face 22	39.72	60.28	0.000553
Male face 23	26.42	73.58	< 0.000001	Female face 23	22.34	77.66	< 0.000001
Male face 24	10.69	89.31	< 0.000001	Female face 24	9.93	90.07	< 0.000001
Male face 25	33.96	66.04	0.000052	Female face 25	7.09	92.91	< 0.000001

Table 4. 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