applied sciences

Review

3D-Printed Accessories and Auxiliaries in Orthodontic Treatment

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Abstract: The integration of 3D printing has transformed orthodontics, allowing for the creation of highly customized intraoral devices that support traditional orthodontic treatments. This review examines the innovations and applications of 3D-printed accessories in orthodontics, focusing on customization, precision, and workflow improvements. In-office 3D printing enables reduced dependence on external labs, enhancing efficiency and potentially lowering costs. Key topics include material properties, biocompatibility, and clinical applications, alongside an evaluation of both successes and limitations highlighted in recent studies. Unlike prior research focused on aligners and braces, this review centers on auxiliary devices, demonstrating how 3D printing can revolutionize these less-studied accessories in orthodontics. The rise of 4D memory shape materials signals a potential breakthrough in "smart orthodontics", where directly printed devices can adapt over time. This innovation could lead to a new era of personalized dynamic orthodontic solutions with 3D-printed auxiliaries, providing unprecedented customization and expanding the scope of orthodontic care. Further research is essential to address challenges related to durability, biocompatibility, and long-term clinical performance to optimize 3D printing's role in orthodontic treatments.

Keywords: additive manufacturing in dentistry; biocompatible materials; digital workflow in orthodontics; 4D printing; smart orthodontic devices; DPA; customized devices

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1. Introduction

Digital technologies and their advancements have completely changed dentistry, including orthodontics. Among these technologies, three-dimensional (3D) printing has emerged as a particularly transformative tool, offering 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 [1]. Three-dimensional printing creates objects by overlaying material layer by layer [2,3]. This powerful technology began its ascension when Charles Hull discovered stereolithography (SLA) and developed the first three-dimensional (3D) printing system in 1986. In that same year, he introduced the first 3D printer. Four years later, in 1990, Scott Crump introduced fused deposition modeling (FDM) [4,5]. 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) [4]. Due to its precision, SLA printing technology gained widespread popularity [6]. However, several different types of 3D printing are able to produce acceptable results for orthodontic treatment [4].

SLA is based on photosensitive liquid, a resin that is polymerized and cured layer by layer by localized light. It can be used to print large precise objects but it can only use one material in a model and often needs to incorporate sacrificial support structures. On the other hand, FDM is a method where molten plastic is extruded. This process is simple and fast and can combine various materials [2].

Thanks to recent progress in biomaterials and CAD-CAM technology, new polymers and metals are emerging as viable alternatives to traditional materials in orthodontics [7,8]. Advances in printable dental materials are accelerating, with ongoing research to optimize additive manufacturing (AM) printing parameters to enhance mechanical characteristics [9]. Printable materials can be categorized into synthetic polymers, metals, and ceramics [10]. A key aspect to keep in mind is biocompatibility: ensuring the biocompatibility of 3D printing materials is crucial for their application in dentistry [9,11,12]. Materials used in 3D printing for dental applications must meet strict biocompatibility standards due 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 resistance to wear [13].

Recently, thanks to gaining significant popularity, AM also grew in market value and in areas of applications. The Wohlers Report 2024 shows that the AM and 3D printing industry grew by 11.1% in 2023, pushing the industry's market value beyond USD 20 billion. Improvements in printer speed and reductions in material costs are expected to lower production costs. This may expand the use of AM for high-volume production and make 3D printing more economical. Three-dimensional printing spread into all industrial sectors, with dentistry and medicine covering 16% of the total volume [14,15]. According to the Grand View Report, in 2023, orthodontics held the largest share of the dental 3D printing market, accounting for 39% of the revenue. As described in Figure 1, the demand in this segment is expected to continue growing significantly, highlighting its critical role in driving advancements in dental 3D printing technologies, even though implantology might potentially surpass orthodontics in total market share in the next years.

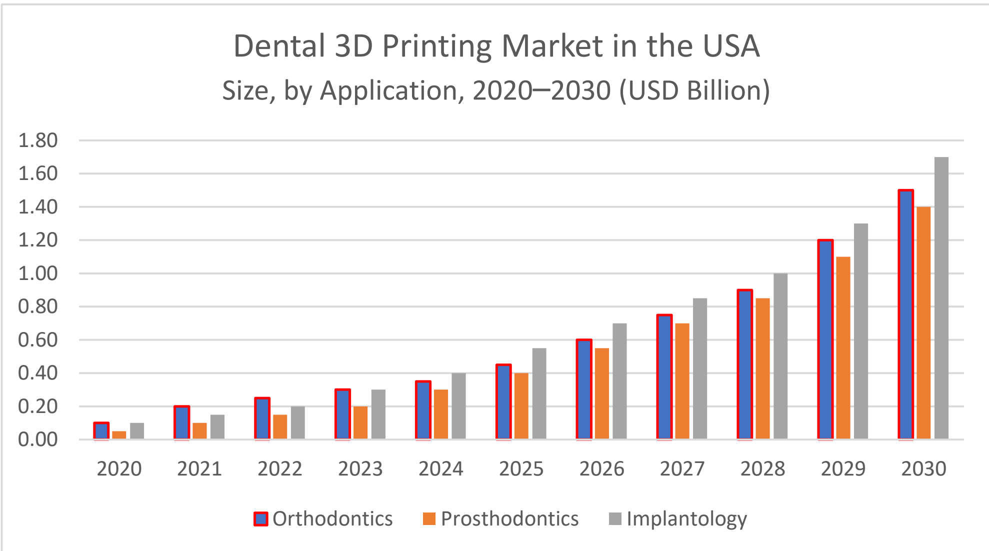

Figure 1. Dental 3D printing market in the USA (2020–2030) by application, in USD billion. Data from Grand View Research [16].

One of the first and increasingly popular uses of 3D printing in orthodontics was the manufacturing of anatomic study models. In some orthodontic practices, 3D-printed models replaced conventional stone casts. Numerous studies evaluated the precision, accuracy, and reproducibility of orthodontic models created using 3D printing technology. Almost all studies considered them highly accurate and suitable for use in clinical practice [17]. However, according to a recent study by Knode et al., it is recommended to use these models immediately in orthodontic applications to avoid inaccuracies in retainers and appliances over time due to the shrinkage of 3D-printed models, which occurs regardless of material type or storage conditions [18]. Three-dimensional printing technologies can be also used to customize the size, shape, and prescription of brackets. The mechanical characteristics of 3D-printed brackets were evaluated by indentation testing and found to be superior to available plastic brackets [19]. The frictional resistance of 3D-printed self-ligating brackets was compared with 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 [19].

The most studied use of 3D printing in orthodontics is the production of aligners [19]. Directly printed aligners (DPA), introduced in 2021 [20], 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 [20]. Utilizing 3D printing technology enables the personalization of aligner features, such as material thickness, surface textures, and overall design, providing greater precision in controlling tooth movements [21]. The capacity to adjust the thickness of the aligners is a promising approach to enhance the effectiveness of intended orthodontic movements while reducing unintended tooth movements, thus improving the predictability and accuracy of tooth movements [22]. Furthermore, if we bypass creating printed models and thermoforming, it is possible to reduce the accumulation of errors during the production process. While the design of the aligners and treatment is time-consuming, the manufacturing is faster due to the reduced supply chain: the DPAs can be printed immediately and in the practice [23]. Importantly, directly printed aligners present an eco-friendly option by reducing or even eliminating the need for resin models and plastic sheets traditionally used for thermoforming [21]. Obviating the need to 3D print resin models decreases the costs as well [20]. It has been shown that the traditional aligner fabrication method has a considerable environmental toll [23]. However, some authors are skeptical about DPAs. Sayahpour et al. in their study showed that thermoformed aligners might still have better mechanical properties compared to some directly printed aligners [24]. When it comes to the clinical effectiveness of DPAs, there is still further research needed as of now. 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) [25] 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. Despite that, the final product is more susceptible to moisture, impairing the ability to deliver forces in the oral cavity [20].

These technological advancements allowed healthcare professionals to offer more personalized medical devices to each patient. Three-dimensionally printed appliances are crafted specifically for an individual's anatomy, utilizing imaging data and 3D models to design and manufacture medical appliances [10]. The manufacturing workflow for customized 3D-printed orthodontic accessories is illustrated in Figure 2.

This review explores 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 crucial roles in the management and modification of tooth movement. 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 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 paper aims to provide a comprehensive overview of its impact on orthodontic practices and its 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.

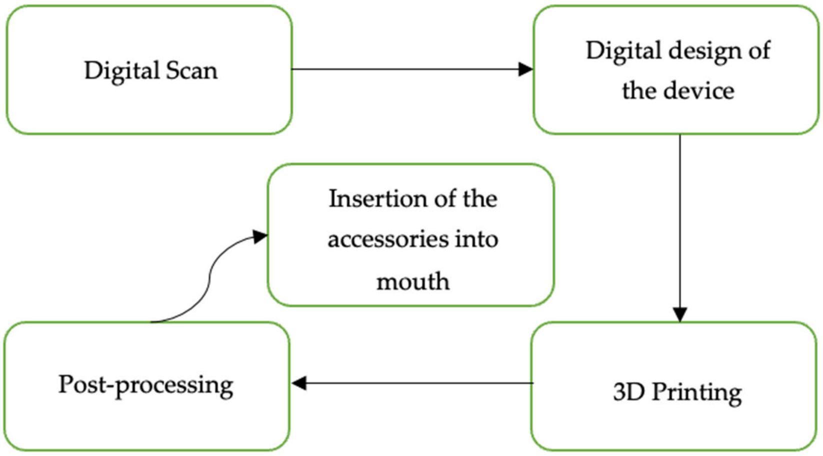

Figure 2. A simple scheme of manufacturing steps of customized 3D-printed orthodontic accessories.

2. Materials and Methods

In conducting this 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 this 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.

Two of the authors (M.P., J.T.) screened all of the identified articles against the inclusion criteria, resolving discrepancies through discussion. 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 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

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 3 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 4.

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 5.

In the reviewed articles, 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 instances, and DLP, used in 9 instances. 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%).

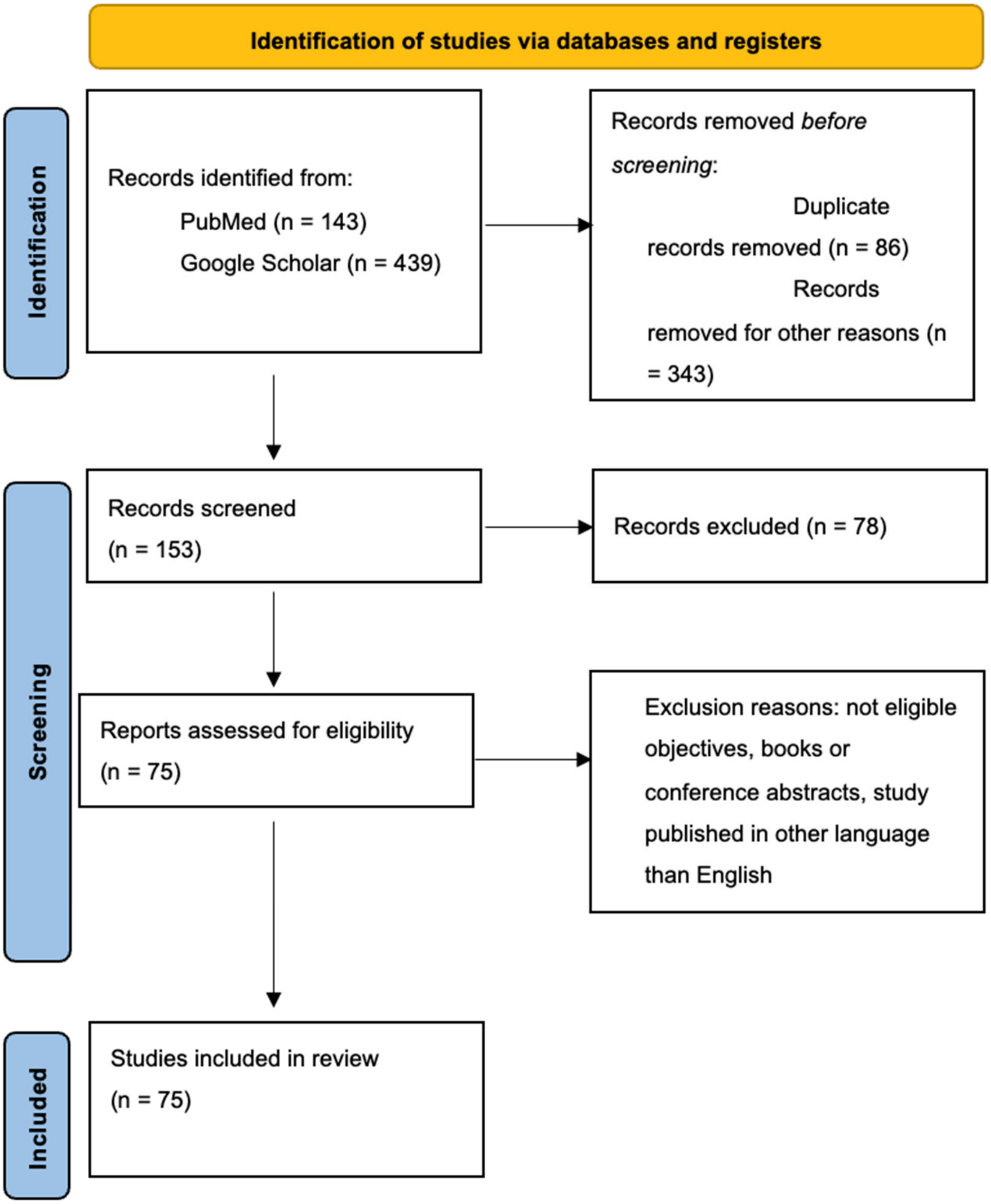

Figure 3. Prisma scheme for the identification of studies.

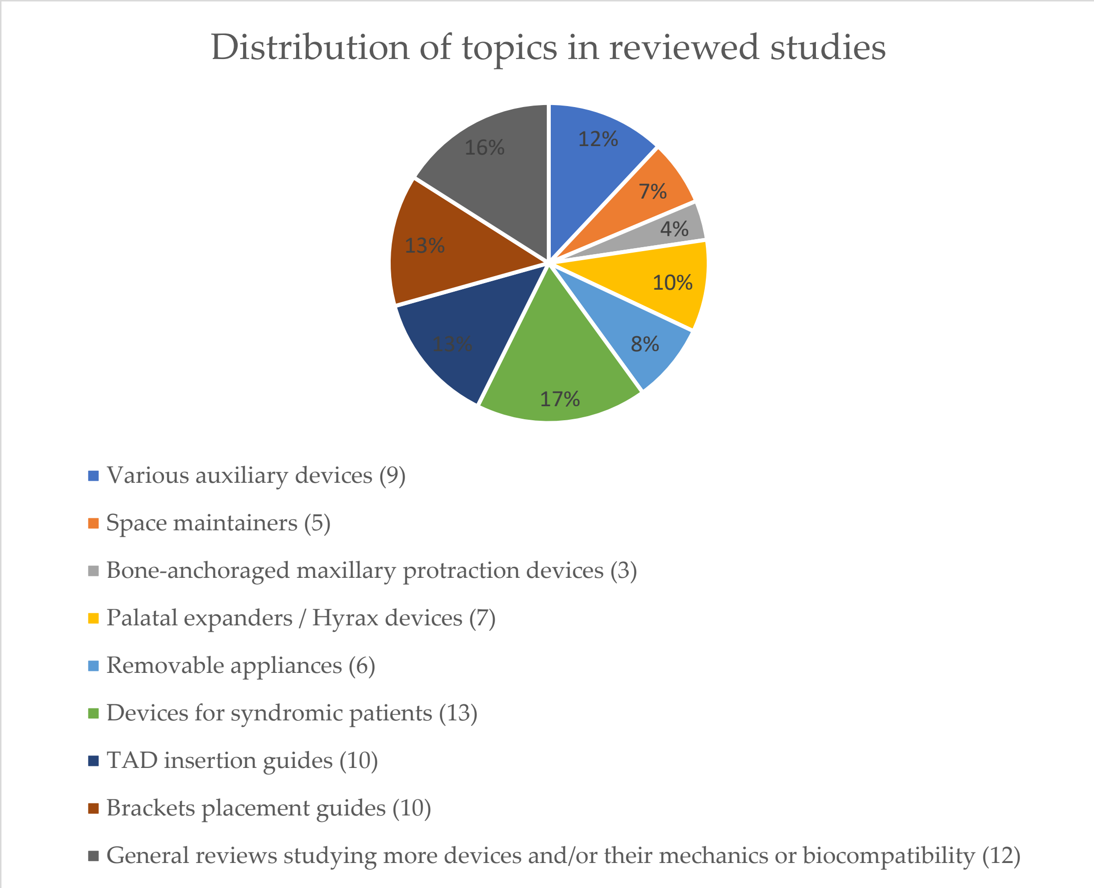

Figure 4. Distribution of topics in the reviewed studies.

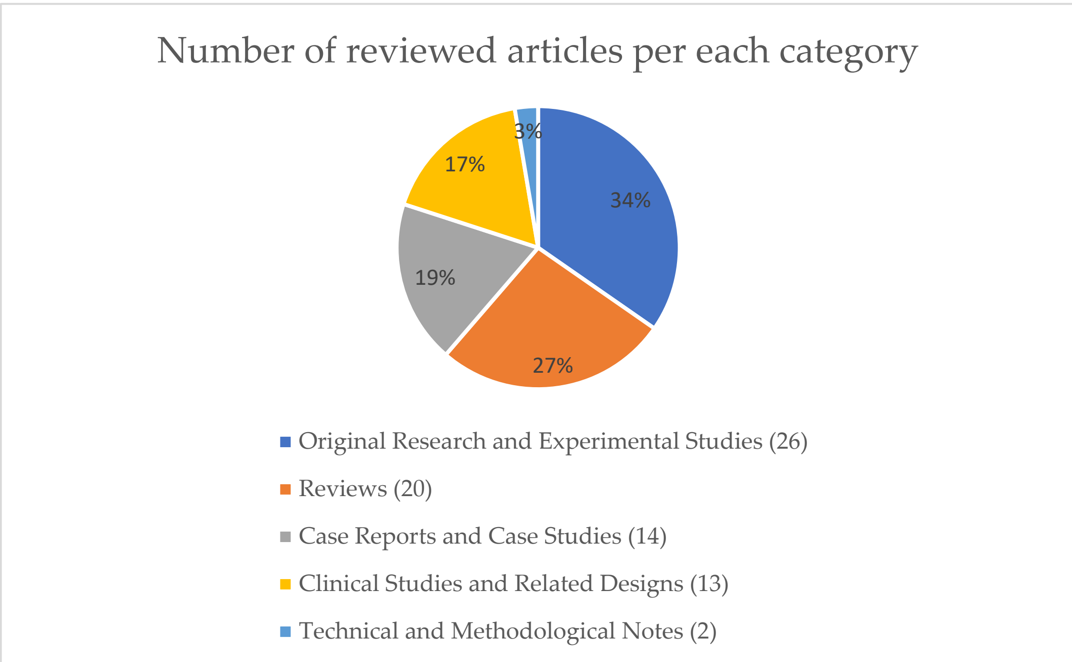

Figure 5. Number of reviewed articles per category.

4. Discussion

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. 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. 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.

4.1. 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. 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.

4.1.1. Various Auxiliary Devices

A variety of personalized orthodontic accessories, such as distalizers [26,27], power arms [28], powerchains [29], or support devices for impacted teeth [30–33] can be fabricated using 3D printing technology.

One such example is a biocompatible individualized distalizer made from photopolymeric 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 [26]. 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 [27].

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 [28].

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 [29]. 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 [31,34].

4.1.2. 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 [34]. Digitally designed space maintainers can also be beneficial for non-compliant pediatric patients to avoid gag reflex via the elimination of conventional impressions [35]. 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 [34,36–39]. 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 [36]. 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 [34]. 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 [37]. Another advantage is that with 3D design, we can print more periodontally friendly versions of bands [38]. 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 [39].

4.1.3. 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 [40]. This can be performed with simultaneous rapid palatal expansion (RPE) [40–42]. 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 [43]. 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 [40–43].

4.1.4. 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 [44]. Bone-borne maxillary expansion [44,45] appliances enable skeletal expansion while minimizing the side effects associated with tooth-anchored palatal expanders [46–48], especially undesired teeth movement [45]. 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 [49]. 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 [45]. 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 [44]. Another study also described the use of a digital laser-sintered palatal expander, with satisfying results [46].

4.1.5. 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 [50]. Several studies described the manufacturing of variable removable orthodontic appliances by 3D printing [50–55].

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 toward more integrated CAD/CAM processes in dental manufacturing [52]. Kujirai et al., in their study, demonstrated successful manufacturing of myofunctional appliance by implementing the 3D-printed protocol [53].

Mandibular advancement devices (MADs) are widely used for mild to moderate obstructive sleep apnoea (OSA). OSA is a prevalent and potentially life-threatening condition, primarily treated medically with continuous positive airway pressure [54]. 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 [55].

4.1.6. 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 [56]. Treatment strategies involve a comprehensive approach, incorporating both nonsurgical and surgical interventions to promote the most natural development possible for infant patients with CDF [57]. 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 [58]. Digital scans provide a safer alternative to conventional impressions for infant patients with craniofacial disorders and the production of clinically relevant devices is possible [59].

The utilization of computer-aided design in the presurgical 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 presurgical alignment of the alveolar ridge while minimizing the time spent in the dental chair and the number of appointments. CAD/NAM treatment was claimed to be a more effective method that lessens the overall demand for patient care [60–64]. 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 [56,57,59,65,66].

4.1.7. 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 [67]. Their usage enhances the biomechanics and procedures in orthodontics [30].

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 [17]. Several studies provided evidence of the successful implementation of 3D-printed TAD insertion guides in their practices [30,68–71]. The key benefits of using a digital workflow in guide production include reducing the risk of complications, minimizing chair time, and enhancing patient comfort [72].

4.1.8. Brackets Placement Guides

The effectiveness of orthodontic treatment with fixed appliances depends on precise bracket positioning [73]. Advanced direct and indirect bonding techniques are continuously investigated, highlighting the effectiveness of different technologies and techniques in achieving precise bracket placement [73–81]. 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 [74]. 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 [74].

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 [75]. 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 [76]. 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 [77]. 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 [78].

4.2. Artificial Intelligence and 3D Printing and 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 [2]. 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 [82].

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 [2]. Given that AI is already used in other areas of orthodontics or 3D printing as a powerful problem-solving tool [2,83]. 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 [84]. We can expect further uses empowering the specialist orthodontists [1]. 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 [82]. In orthodontics, 3D applications are expected to overtake 2D applications in the future [85], 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 [85–87]. Even after rigorous polymerization and cleaning, leads to some unpolymerized monomers are left over and these molecules can escape from the plastic [86].

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 [88]. 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 [89], 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 [90]. 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 [91].

4.3. 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 [92–94]. 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 [95,96]. 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 [97]. 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 [98].

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 [1].

4.4. 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 [99]. 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 [26,100]. 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 [101]. 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 postprocessing (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 [99]. The "in-house laboratory" needs to meet specific requirements and specific protocols need to be followed [102]. 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 [20]. All materials that are intended for intraoral use need to be rigorously tested, and international standards and guidelines regarding laboratory tests would be beneficial [19,103].

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 [104]. 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 [105]. Figure 6 illustrates a comparison of 3D-printed resin, metal, and shape memory orthodontic devices, detailing their advantages, disadvantages and future potential.

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

5. Conclusions

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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