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Advanced orthodontic materials: From current clinical strategies to emerging applications

Jiaxi Zhang[1,§], Tingting Sun[1,§], Jiasheng Jiang[1], Hongpan Rong[2], Gaoshan Huang[3], Zhe Zhao[1]✉, and Xuanyong Liu[1,4]✉

[1] *Shanghai Engineering Research Center of Nano-Biomaterials and Regenerative Medicine, College of Biological Science and Medical Engineering, Donghua University, Shanghai 201620, China*
[2] *Beijing Key Laboratory of Construction-Tailorable Advanced Functional Materials and Green Applications, School of Materials Science & Engineering, Beijing Institute of Technology, Beijing 100081, China*
[3] *International Institute for Intelligent Nanorobots and Nanosystems, College of Intelligent Robotics and Advanced Manufacturing, and State Key Laboratory of Photovoltaic Science and Technology, Fudan University, Shanghai 200438, China*
[4] *State Key Laboratory of High Performance Ceramics, Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 200050, China*
§ *Jiaxi Zhang and Tingting Sun contributed equally to this work.*

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ABSTRACT: Progress in biomedicine has long been driven by materials innovation, an impetus now profoundly reshaping the field of orthodontics. The discipline has undergone a pivotal evolution: where early efforts primarily targeted mechanical performance and aesthetic enhancement, the contemporary focus has shifted toward intelligent, multifunctional materials that seamlessly integrate diagnosis with therapeutic intervention. Today, propelled by breakthroughs in microelectronics, additive manufacturing, and artificial intelligence, orthodontic materials are being fundamentally re-engineered. They are no longer passive corrective appliances but have evolved into core components of interactive biomedical platforms. These advanced systems are designed not only to achieve precise tooth movement but also to enable real-time monitoring of intraoral forces, biofilm activity, and even systemic health biomarkers. Along this review,we trace the progression from material (including alloys, polymers, ceramic materials) and manufacturing advances to the integration of smart sensing, responsive coatings, and artificial intelligence.

Representative examples illustrate the synergistic integration of materials, processing strategies, and intelligent systems, facilitating the evolution of orthodontics toward personalized and intelligent care. Finally, we summarize the current research status and outline prospective directions, foreseeing an intelligent, minimally invasive, and fully personalized paradigm for orthodontic treatment.

KEYWORDS: orthodontic materials, surface treatment, intelligent orthodontics, biomedical materials

1 Introduction

With the prosperity of the global economy, the popularity of social networks and the pursuit of aesthetics, the proportion of people receiving orthodontic treatment has increased year by year. The basic idea of orthodontics first appeared in the 17th century, far before the establishment of a systematic clinical framework. However, it was not until Delabar invented the bow wire technology that the field really entered the modern orthodontic era [1]. According to the World Health Organization, malocclusion is the third most significant oral health concern worldwide, with a prevalence of 39%–93% [2]. This significant clinical demand has been a major driver for the continuous refinement of orthodontic techniques and appliances. With the progress in materials science, increasing dissatisfaction with the aesthetic limitations and discomfort of metal brackets spurred the gradual adoption of transparent archwires and ceramic alternatives. Although the aesthetics have significantly improved, issues such as cleaning

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✉Address correspondence to Zhe Zhao, zhezhao@dhu.edu.cn; Xuanyong Liu, xuanyong@dhu.edu.cn

difficulty and mechanical friction remain clinical challenges to be addressed [3]. The "bracket-free" invisible orthodontic technology of the last century brought about revolutionary changes. Clear aligners have gradually become the treatment of choice. They offer the dual advantages of aesthetics and comfort. However, clear aligner treatment relies on good patient compliance. Longer intervals between follow-up visits may result in clinical issues not being detected in time [4]. Therefore, there is a significant clinical demand for advanced smart materials with integrated sensing, feedback, and responsiveness. Such timely feedback is of great significance to clinical practice.

Advanced orthodontic materials belong to the emerging interdisciplinary fields of orthodontics, materials science, engineering, and biomedical sciences. Through innovative design and precise manufacturing, these materials are endowed with intelligent capabilities such as sensing, responding, adapting, and even actively executing. A search of the Web of Science Collection database shows that over the past decade, the number of research articles related to "smart materials" and "orthodontics" has steadily increased each year. The latest research directions indicate that interdisciplinary collaboration is promoting the development of smart materials. For example, orthodontic appliances integrated with microsensors can track orthodontic forces in real time [5–7]. Continuous monitoring of oral pH fluctuations can assist in the diagnosis of dental caries [8, 9], Metabolite analysis in saliva provides a method for non-invasive health screening [10–12]. The application of antimicrobial coatings improves the performance of materials [6]. Additive manufacturing (AM) greatly enhances the personalization and precision of orthodontic devices. Four-dimensional (4D) printing creates materials that can change their properties or shape in response to specific stimuli (such as mechanical, chemical, thermal, or electrical stimuli) [13, 14]. The integration of artificial intelligence with these advanced technologies has led to greater progress in smart orthodontic systems [15]. In summary, the ultimate goal of developing advanced orthodontic materials is to establish an intelligent, precise, and functional treatment system to improve orthodontic outcomes and maintain long-term oral health.

Here, this review systematically analyzes the progress of advanced orthodontic materials. As shown in Fig. 1, we have comprehensively sorted out the latest progress of current advanced orthodontic materials through systematic retrieval. At the end, we have detailed the main challenges at present and looked forward to the future development direction of this field.

2 Urgent demands of advanced functional orthodontic materials

Orthodontic products have been continuously developing. However, the transition to fully intelligent and personalized treatment protocols remains an ongoing challenge. Up to now, fixed orthodontic appliance therapy remains the preferred choice for many cases. Relevant technological developments have mainly targeted brackets and archwires, improving their aesthetic and functional properties. As substitutes for metal ones, the introduction of transparent archwires represent one such response to aesthetic demands. Many researches addressed the lack of real-time force feedback in clinical practice. Micro-sensors integrated at the bracket-archwire interface now enable direct force

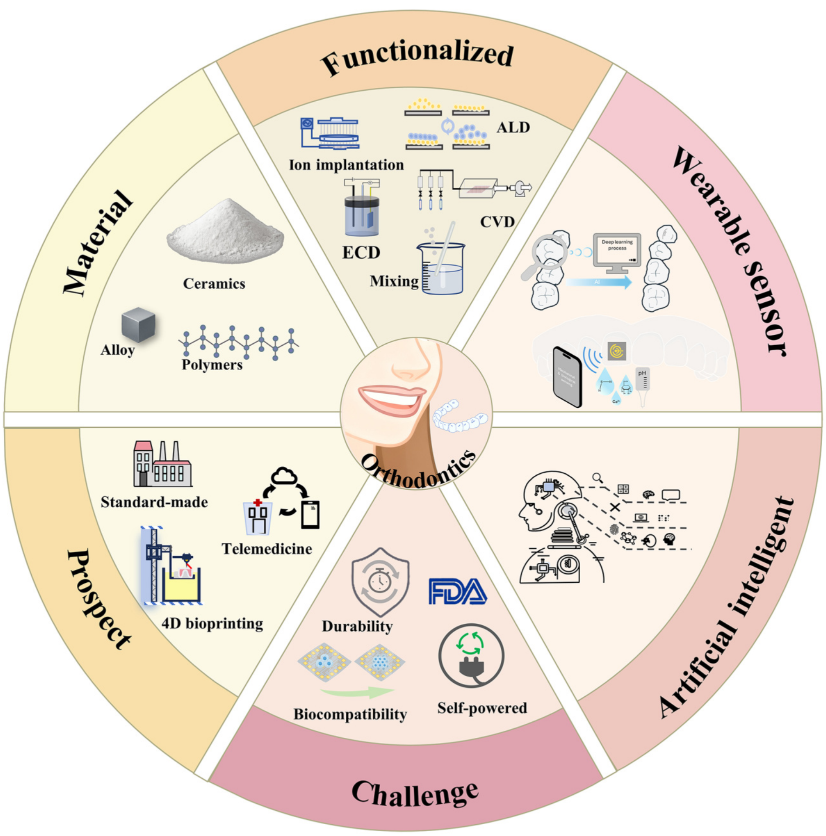

Figure 1 This diagram illustrates the evolution of orthodontic materials (ceramics, metals, polymers) into intelligent, multifunctional platforms. Overcoming persistent challenges in durability, biocompatibility, and regulatory approval is essential to advance standardized production and achieve the goal of intelligent orthodontics.

measurement [16], while other sensing modalities permit early detection of bond failures [17]. Apart from these mechanical considerations, surface engineering approaches were utilized to create antibacterial bracket surfaces [18]. Current strategies include titanium dioxide nanotube arrays on metal brackets for controlled chlorhexidine release to three-dimensional (3D)-printed bioceramic brackets incorporating zinc ions. Although these designs can reduce plaque accumulation to some degree, they still face unresolved technical challenges—including the durability of antimicrobial efficacy, the risk of biofilm resistance development, and the preservation of mechanical strength—and such limitations, along with the opportunities for functional expansion, become even more pronounced in the increasingly popular clear aligners, whose water ripples on the inside of the invisible braces made of thermoplastic polyurethane (TPU) or polyethylene terephthalate (PETG) base, which aims to form a visual hidden effect, but provides an ideal substrate for microbial adhesion [19]. Recent research confirmed that these water ripples could significantly enhance bacterial biofilm formation [19]. The limited self-cleaning effect of saliva further aggravates the risk and increases the incidence of complications such as enamel demineralization and tooth coloring. From a biomechanical perspective, clear aligner therapy is a goal-oriented technology. Although it relies on increasingly sophisticated 3D modeling and AI algorithms for treatment planning, it lacks a crucial real-time feedback mechanism. The single-day wearing time has a significant impact on the efficiency of treatment, but there is no objective data feedback on it. The lack of feedback between these designs and executions still brings a lot of trouble to doctors and patients, and increases unnecessary communication costs, which is not conducive to establishing a relationship of trust between doctors and patients. Paradoxically, the requirement for more than 22 h of intimate daily contact positions the clear aligner as a unique platform for multifunctional integration, and emerging innovations in drug delivery and biosensing are progressively transforming it from a passive mechanical appliance into an active health-management platform [20].

Saliva emerges as a diagnostically significant biofluid, containing a complex milieu of DNA, RNA, proteins, microorganisms, and metabolites that positions it as an ideal medium for non-invasive monitoring [21], upon which recent engineering advances have enabled the direct integration of microfluidic chips into orthodontic aligners to achieve picomolar-level detection sensitivity for periodontal biomarkers and to allow real-time oral health monitoring during treatment.

To conclude, we strongly believe that the advancement of next-generation orthodontic materials will be grounded in improvements in aesthetics and mechanical performance, while moving toward greater intelligence and personalization.

3 Design and fabrication of orthodontic materials

As clinical demands continue to rise, researchers have not only focused on enhancing the mechanical properties of orthodontic materials but have also integrated aesthetic considerations, striving to balance clinical requirements with aesthetics. Orthodontic materials can be classified into three main categories: metal alloys, ceramics, and polymers. Metal materials are widely used for their excellent mechanical strength and low friction coefficient, but they face challenges such as corrosion risks and aesthetic concerns. In contrast, ceramics have good biocompatibility and a tooth-like appearance, making them highly favored by patients with high aesthetic demands; however, their inherent brittleness and high surface friction limit their clinical use. Polymers such as polyurethane (PU) and polyetheretherketone (PEEK) have gained growing attention due to their design flexibility and compatibility with 3D printing technology [22, 23], motivating ongoing efforts to develop next-generation polymer systems with enhanced functional performance and intelligent, stimulus-responsive capabilities. This section reviews the research progress of these three types of materials [24, 25].

3.1 Alloy for orthodontic materials

The demand for mechanical properties, biocompatibility, and functional diversity in clinical treatment drives the development of orthodontic metal materials. The development of oral medicine is inseparable from materials science. The development of dental metal materials can be divided into four stages: the era of precious metals, the era of stainless steel, the era of nickel-titanium alloys (NiTi), and the era of metal surface biofunctionalization (Fig. 2(a)). This evolution reflects a shift in treatment concepts, as clinical demands gradually move from basic mechanical requirements toward intelligent and personalized designs.

Orthodontic archwires are an important force application device in orthodontic treatment. Archwires need to exhibit different mechanical properties at different treatment stages. The earliest orthodontic archwires can be traced back to gold archwires discovered on Egyptian mummies (Fig. 2(a)) [26]. Gold alloys are favored for their excellent biocompatibility and ductility [27, 28]. Among them, gold-palladium alloys are the most representative materials. They possess chemical stability, antioxidant properties, and good biocompatibility. Gold-palladium alloys can release non-precious metal ions such as Cu^{2+} and Ag^{+}. These ions attach to the bacterial surface, disrupt enzyme systems, and inhibit microbial growth and adhesion [29, 30]. However, the high cost of gold significantly restricts its widespread clinical application. Semi-precious metal materials, such as silver-palladium alloys, offer a cost-effective alternative. These alloys primarily consist of silver, with small proportions of palladium, gold, and copper. Compared to non-precious metal materials, this alloy shows superior antioxidant properties, corrosion resistance, and biocompatibility [30]. The Ag^{+} ions released by silver-palladium alloys have broad-spectrum antibacterial activity but exhibit low toxicity to human cells [31]. These properties render silver–palladium alloys particularly suitable for the oral cavity, an open environment rich in microbial activity.

Precious metal alloy archwires are relatively soft, preventing them from delivering continuous orthodontic force, and their high cost further limits clinical application, although they have excellent biocompatibility and antibacterial advantages [37], indicating that future research should focus on optimizing alloy compositions to achieve a balance among biocompatibility, mechanical performance, and economic feasibility, thereby overcoming current constraints and fully realizing their clinical potential.

Stainless steel wire appeared in the early 20th century and was quickly applied in the field of orthodontics [38]. Its excellent strength, corrosion resistance, as well as its low friction coefficient, good formability and cost-effectiveness make stainless steel an important material for manufacturing orthodontic brackets, archwires, and mini-implants [39]. To date, stainless steel brackets remain the most widely used choice in clinical practice.

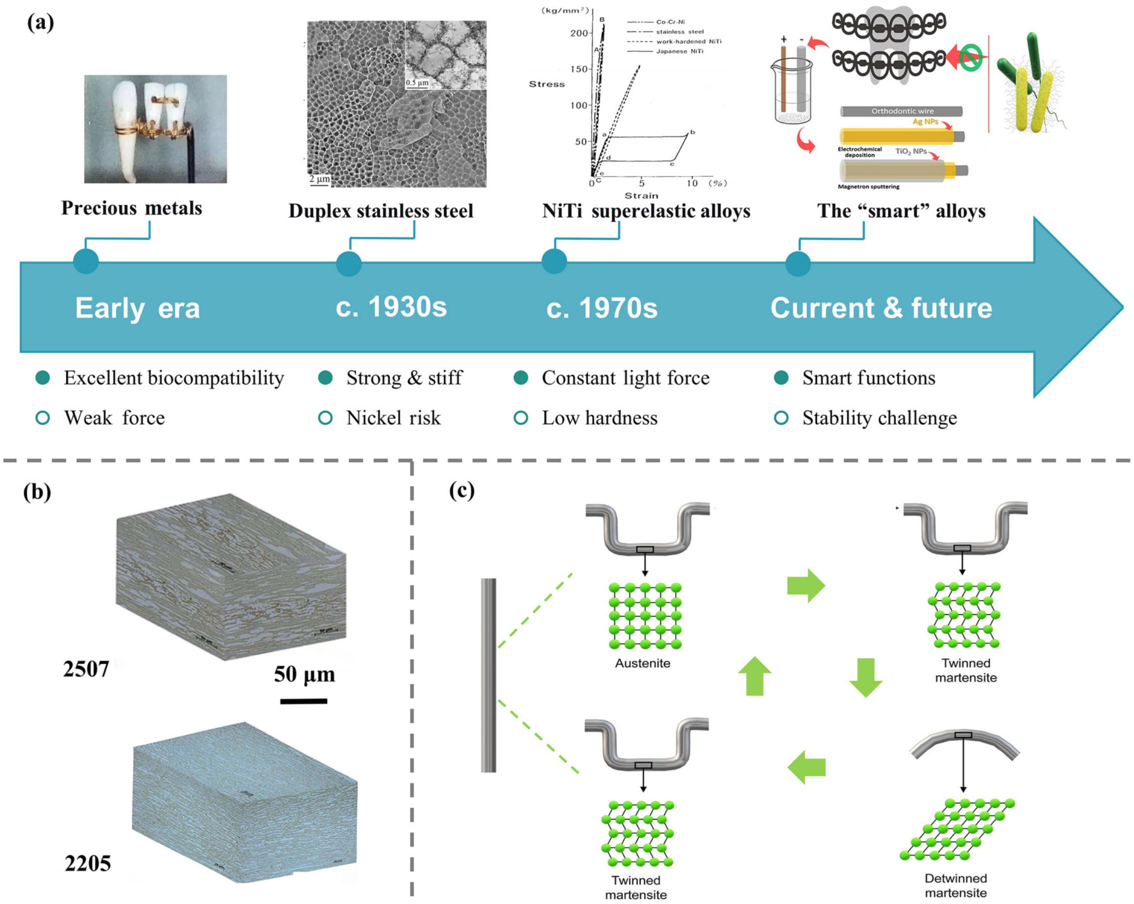

Figure 2 (a) Timeline of orthodontic alloy development, ranging from noble metals and stainless steel to nickel–titanium and modern smart alloys [26, 32–34]. Reprinted with permission from Ref. [26], © American Dental Association 1947; Ref. [32], © Acta Materialia Inc. 2020; Ref. [33], © Mosby, Inc. 1986; Ref. [34], © Elsevier B.V. 2023. (b) The Optical micrographs of 2507 and 2205 DSS, respectively. The bright regions are austenite, and the dark regions are ferrite. Reprinted with permission from Ref. [35], © Springer Science Business Media, LLC 2017. (c) Simplified overview of the shape memory effect and the phase transitions. Reprinted with permission from Ref. [36], © Karabuk University 2022.

316 stainless steel is the mainstream material for orthodontic brackets, with a composition of 16%–18% chromium, 10%–14% nickel, and 2%–3% molybdenum [40]. Nickel is the primary element that stabilizes the metallic austenite structure. It allows the material to form a face-centered cubic (FCC) crystal lattice structure. This structure imparts excellent ductility and toughness to the material, making it highly suitable for the manufacture of complex orthodontic devices [40]. Additionally, 316L stainless steel exhibits strong corrosion resistance in chloride-containing environments [41]. This property has been confirmed in studies using simulated physiological solutions [42] and artificial saliva [43]. 316L stainless steel remains non-magnetic under most conditions [40]. This characteristic makes it highly compatible in situations where imaging examinations are required. Although 316L stainless steel meets the performance requirements for most orthodontic treatments, its strength and hardness may still be insufficient under certain harsh conditions [44]. As a result, researchers have explored various methods to enhance its mechanical properties. For example, doping with niobium (Nb) and combining solution heat treatment can significantly improve mechanical properties, particularly elongation [45]. The incorporation of TiN into the material can increase hardness by over 30% [46]. However, the complexity of the oral environment presents unique challenges for metallic materials. Fluctuations in temperature, pH, mechanical load, and microbial activity all accelerate material degradation. The performance of 316L is significantly impaired under acidic conditions or when exposed to fluoride ions [47, 48].

To overcome these issues, duplex stainless steel (DSS) is composed of nearly equal proportions of austenite and ferrite. This structure combines the advantages of both, exhibiting unique properties (Fig. 2(b)) [49]. Studies have shown that by adjusting the ratio of the two phases through heat treatment, the corrosion resistance of DSS can be precisely controlled. For example, treatment at 900 °C for 2 min significantly improves its corrosion resistance [35]. The appropriate addition of nitrogen can synergistically enhance the strength and corrosion resistance of stainless steel. Sintering in an N_2–H_2 gas atmosphere allows precise control of nitrogen absorption, enabling the tensile strength of stainless steel to exceed 500 MPa [50].

In summary, DSS presents higher yield strength [49] and superior mechanical properties [51] compared to austenitic stainless steel. Furthermore, DSS exhibits excellent corrosion resistance. In standard pitting corrosion tests using a 6% $FeCl_3$ solution, DSS outperforms 316L in terms of corrosion resistance [52]. Due to the scarcity and high cost of nickel, researchers have successfully developed low-alloy duplex stainless steel (LDSS). By partially replacing nickel and molybdenum with manganese and nitrogen

[53]. At the same time, it retains mechanical properties comparable to conventional duplex stainless steel, making LDSS an ideal alternative to 316L [54].

As orthodontic treatment paradigms continue to evolve, materials science has developed in parallel. Influenced by the BEGG light force philosophy, there has been an increasing clinical demand for archwires with superelastic properties. In late 1971, George Andreasen from the University of Iowa first introduced NiTi alloys into the field of orthodontics, demonstrating through experiments that it outperformed stainless steel archwires in terms of elastic limit, load-deflection ratio, and working range [33, 55]. Shortly thereafter, Unitek (now 3M Unitek) commercialized the NiTi alloy under the brand name "Nitinol" [56]. The core characteristic of NiTi alloys arises from their thermoelastic martensitic phase transformation: under external force, the high-temperature austenite phase (parent phase) transforms into the martensite phase, and this transformation is reversible upon unloading or heating, which imparts superelasticity and shape memory effect to the material (Fig. 2(c)) [36]. Recent studies on the microphase transformation mechanisms of NiTi alloys have revealed that, in addition to the common austenite (A) and martensite (M) phases, the R-phase, an intermediate transition phase, plays a crucial role in enhancing alloy fatigue life and reducing mechanical hysteresis [57].

To improve the mechanical properties of NiTi alloys, researchers have explored various material enhancement strategies. For example, the introduction of elements such as copper (Cu) can significantly reduce the width of the superelastic hysteresis loop, while the addition of cobalt (Co), iron (Fe), or chromium (Cr) can effectively regulate the transformation temperature [58–60]. In addition to introducing other elements, processing techniques also influence the performance of NiTi alloys. For example, heat treatment can promote the formation of precipitates, thereby enabling precise control of plateau stress and residual strain [60]. Additionally, the design of graded-force archwires allows different segments of a single archwire to release varying levels of stress. This feature allows it to accommodate differences in both the distance and direction of tooth movement [61].

The flexible use of these methods meets the diverse needs of orthodontic treatments. However, it is important to note that the nickel element in NiTi alloys poses a risk of nickel ion release. Under certain conditions, this release may even exceed that of stainless steel [62]. Researchers have attempted to optimize the performance of NiTi alloys through compositional modifications. For example, the incorporation of Cu not only raises the transformation temperature but also alters the precipitation behavior and phase morphology, affecting the mechanical properties and superelastic range [55]. The addition of noble metals such as palladium (Pd) and platinum (Pt) helps form a more stable passive film on the alloy surface, effectively inhibiting the release of nickel ions [63]. Recent studies have focused on applying coatings to the surface of NiTi archwires to enhance their aesthetic appeal and improve biological safety. However, the long-term durability of such coatings is questionable. The relevant technologies will be further discussed in subsequent chapters. The fundamental solution is to develop nickel-free alloys. Titanium and its alloys have excellent biocompatibility and corrosion resistance. They are used in orthodontic archwires and mini-implants. Among them, β-titanium alloys have an elastic modulus close to that of bone tissue. Its ultra-low elastic modulus allows it to exert gentler and more physiologically appropriate forces, reducing root resorption and patient pain. This characteristic is crucial for reducing orthodontic complications [64]. β-Titanium alloys also have good strength and toughness. It can maintain stability without significant permanent deformation under complex therapeutic stresses [65]. Nevertheless, their relatively high friction coefficient cannot be overlooked. Studies have shown that Ti-Nb-based wires, such as Gummetal®, generate greater frictional forces compared to other orthodontic alloys [66, 67], and this effect becomes more pronounced after acid immersion due to corrosion-induced surface roughening [68]. While elevated friction hinders tooth sliding during the initial alignment phase, it can be advantageous in the finishing stage by facilitating precise tooth control. Beyond Ti-Nb systems, other β-titanium alloys have also been investigated for orthodontic use. For example, Wang et al. [69] reported a high-performance Ti-Ni-B alloy in which tensile properties and mechanical anisotropy were improved by controlling columnar prior-β grains and α-Ti morphology. Unfortunately, these alloys are prone to surface oxide formation, which increases friction [66, 67] and thus impedes tooth movement. Outside of archwire applications, commercially pure titanium (cp-Ti) and Ti-6Al-4V alloys have become the primary materials for orthodontic micro-implants [70]. Their excellent biocompatibility, corrosion resistance, and mechanical stability provide reliable osseointegration and anchorage, forming the foundation for modern precision orthodontics.

Significant improvements have been made in the mechanical properties of orthodontic alloys. With the refinement and integration of various processes, orthodontic alloys are now evolving towards more intelligent and personalized designs, which will be further discussed in the following sections. However, it is important to note that inherent issues such as imaging artifacts and aesthetic concerns in orthodontic alloys have yet to be resolved. Moving forward, while focusing on intelligence and progress, these issues must also be addressed.

3.2 Polymers for digital orthodontics

Polymer materials are the foundation for enabling the functionality of digital orthodontic devices, As their properties directly influence the efficiency, accuracy, and safety of clinical treatment. This chapter provides a systematic overview of polymers applied in digital orthodontics. They are classified into four main categories based on processing techniques and primary functions: thermoforming polymers, polymer blends, directly 3D printed polymers, and bioactive or smart polymers. Clear aligner therapy (CAT) made from thermoforming polymers has expanded rapidly over the past decade [71]. The number of clear aligners worldwide has experienced significant growth [72]. Currently, most clear aligners are still produced using traditional vacuum thermoforming technology. Thermoplastic sheets are directly formed over physical models [73, 74], which makes the process relatively complex. Emerging trends indicate a shift toward the implementation of direct 3D printing technologies, thereby obviating the requirement for physical models. However, direct printing imposes strict requirements on materials, including excellent biocompatibility, mechanical properties, and optical transparency [74–77]. Tera Harz TC-85 material from Graphy, South Korea, has received FDA approval and offers customizable colors to meet specific needs [78]. Currently, no other direct 3D printing materials fully meet the performance standards (Refer to: https://itgraphy.com/en/dental). A comparative summary of their advantages and disadvantages is provided in Table 1.

Clear aligners are generally made from several types of polymers,

Table 1 Performance evaluation and comparison of thermoplastic versus directly 3D-printed clear aligners

The fabrication of clear aligners	Advantage	Disadvantage	References
Thermoplastic	Mature technology and low cost	Limited accuracy and quality control	[77, 79]
	Short production cycle	Potential degradation of mechanical properties	[80, 81]
	Diverse materials	Material waste and adverse environmental impact	[82]
3D printing	Highly customized	High equipment cost	[83]
	Environmentally friendly	Limited material choices	[78, 84, 85]
	Material performance improvement	Complex manufacturing process	[83, 86]
	Minimization of material waste	Inaccurate printing direction	[87, 88]

including polyesters, polyurethanes, polypropylene, and various copolymers [89–91]. Polyethylene terephthalate (PET) and its amorphous copolymer, polyethylene terephthalate glycol-modified (PETG), exhibit excellent mechanical strength and optical clarity, making them the preferred material choices [92].

PET is synthesized from ethylene glycol and terephthalic acid, and it exists in both amorphous and crystalline forms. The amorphous form is transparent and highly ductile, while the crystalline form appears opaque white and exhibits superior hardness, rigidity, and strength [93]. These two forms determine the material's properties [94]. To ensure that PET-based clear aligners provide stable orthodontic forces, research primarily focuses on improving tear resistance, flexural strength, and stiffness. One effective approach is the introduction of functional inorganic fillers to bulk-modify PET. Li et al. [95] demonstrated that epoxy resin chain extender-modified pyrophyllite (A-Prl) significantly improved the crystallization rate and impact toughness of both PET and PET/PETG blends.

PETG is a copolyester derivative of PET. It is modified by introducing 1,4-cyclohexanedimethanol (CHDM) as a comonomer. Compared with PET, PETG exhibits higher toughness, lower crystallinity, and superior thermoforming ability [96–98]. PETG has become an excellent material for clear aligners and retainers [96]. Current research focuses on further improving its mechanical performance and forming capabilities [97, 99]. Improvement methods such as adjusting the CHDM content or blending PETG with other polymers can achieve better flexibility, higher impact resistance, and more uniform stress distribution. This ensures the precise and effective transmission of orthodontic forces. With the rapid advancement of 3D printing technologies, PETG has shown satisfactory printability. However, the precise identification of optimal printing parameters still requires extensive investigation and confirmation [100].

The PU main chain contains unique isocyanate groups, exhibiting excellent toughness, elasticity, wear resistance, and biocompatibility. Its performance remains stable under X-ray exposure, which is particularly important in orthodontic treatments, as radiographic examinations are often required [101]. Align Technology upgraded its clear aligner material from the single-layer polyurethane Exceed 30 to SmartTrack™—a multilayer aromatic thermoplastic polyurethane/copolyester composite [102]. This material has better elasticity and can provide more stable orthodontic forces, making it widely recognized by doctors [91]. On a microscopic level, the performance of PU is due to its micro-phase separation structure.underscoring the significant potential of PU in orthodontic applications. The hard segments provide strength and rigidity, while the soft segments impart flexibility and elasticity. Its performance can be finely tuned by adjusting the types and ratios of isocyanates, polyols, and chain extenders. This structural configuration establishes PU as a strong alternative to conventional materials such as PETG, as it more effectively accommodates diverse mechanical and deformation requirements [103]. Moreover, PU performs better than PETG in terms of microbial adhesion and aggregation [104]. Similar to PETG, PU has also become a potential material for direct 3D printing [22, 23, 105]. The printing parameters, like those for PETG, remain unclear. Polycarbonate (PC) has excellent impact resistance, rigidity, and transparency. Its relatively high rigidity may exert excessive stress on the periodontal tissue. Therefore, PC is seldom used as a standalone material. Mixing PC with other polymers can effectively reduce this risk while improving its mechanical properties. Studies have shown that mixing PETG/PC/TPU in specific proportions can achieve a good balance between toughness and rigidity [90]. The PETG/PC2858 blend performs better in tensile strength, impact resistance, and elongation at break [106]. Additionally, PC is also a potential material for direct 3D printing.

In summary, an optimal material for clear aligners should provide sufficient rigidity to reliably transmit orthodontic forces, while maintaining adequate elasticity to ensure patient comfort. Achieving a balance between these properties within a single polymer presents significant challenges. Polymer blending is a practical solution. Mixing different materials such as PETG, PC, and TPU can optimize their properties. For example, mixing PETG with TPU retains PETG's rigidity and thermoformability while incorporating TPU's flexibility and comfort [107]. The mechanical properties of blended polymers are significantly influenced by the blending ratio [90]. A blend of PETG/PC/TPU in a 70/10/20 ratio outperforms other blending ratios in terms of performance [90]. Additionally, incorporating nanofillers or short carbon fibers into the polymer blend can significantly enhance its mechanical properties [108, 109].

Although the main method for producing clear aligners is thermoforming technology, the thermoforming process has inherent limitations. The complexity of personalized structures, high mold costs, and the difficulty of achieving fine geometric shapes limit its clinical application range. Direct 3D printing technology directly produces the final product, greatly simplifying the manufacturing process. This method not only improves the accuracy of the aligners and optimizes their mechanical design but also avoids material property changes that may occur during the thermoforming process [23, 110].

However, direct 3D printing of orthodontic devices is still limited because there are few printable polymer materials suitable for orthodontics. Among the existing materials, PEEK has excellent mechanical strength, chemical stability, and biocompatibility. Its elastic modulus is close to that of bone tissue and dentin, effectively reducing the "risk of stress shielding" [111]. This performance profile makes it highly suitable for manufacturing various dental prostheses and orthodontic devices [25]. Research demonstrated that PEEK can be effectively applied to NiTi archwires as coatings or sleeves, where it exhibited excellent flexibility, preserves the core wire's mechanical properties, improves biocompatibility, and significantly reduces sliding friction [112–114]. The alternative approach involves using PEEK as a complete replacement for metal archwires. However, studies by Maekawa et al. [25] and Tada et al. [24] comparing the mechanical properties of PEEK wires with NiTi wires found that while friction forces in self-ligating bracket systems showed no significant difference, the PEEK wires exhibited undesirable permanent deformation and stress relaxation. In the long term, the clinical adoption of PEEK archwires remained limited. This is primarily due to performance gaps, such as permanent deformation and stress relaxation, alongside a lack of standardized studies comparing them to commercial orthodontic wires. Nonetheless, PEEK archwires generally offer better aesthetics than metal wires, eliminate the risk of allergies associated with metallic materials, and are compatible with MRI [115]. Furthermore, CAD/CAM technology has enhanced the accuracy, reliability, and efficiency of PEEK fabrication, while reducing production time [116, 117].

To further optimize the long-term performance of PEEK in orthodontic clinical applications—particularly in the microbe-rich oral environment—surface functionalization has become a prominent direction in current research. Although current research on antibacterial modification of PEEK has mainly focused on orthopedic and maxillofacial implants, these modification strategies provide valuable insights for orthodontic applications, such as mini-implant anchorage and removable orthodontic appliances. Active antibacterial and osteo-promotive surface engineering is expected to become a critical development direction for improving treatment success and reducing complications, including gingivitis and mucosal irritation. To enhance the antibacterial properties of PEEK, some studies have explored functionalizing the PEEK surface with antimicrobial peptides or antibiotics to achieve long-lasting antibacterial effects. For example, one study loaded murine β-defensin-14 onto a three-dimensional porous PEEK surface. This modification not only provides the material with long-lasting, broad-spectrum antibacterial activity but also significantly promotes the osteogenic differentiation of bone marrow-derived mesenchymal stem cells [118]. In infectious animal models, this approach achieved both effective antibacterial action and bone integration. Another strategy involves loading small-molecule drugs, such as simvastatin, to modulate the local immune microenvironment, thereby achieving combined antibacterial and osteogenic effects [119]. A further research direction focuses on designing smart responsive coatings that can dynamically adapt to the complex in vivo environment, thereby achieving therapeutic outcomes that integrate both antibacterial activity and bone regeneration [120–123].

In brief, PEEK demonstrates promising yet challenging application prospects in orthodontics, particularly for composite archwires and retainers [114, 124]. It is crucial to emphasize that achieving this potential in clinical applications will necessitate substantial progress in both the material's performance and its long-term stability [115]. As discussed, although the application of digital polymers in orthodontics is rapidly expanding, inherent limitations remain to be addressed. Future progress must not only focus on overcoming these challenges but also move toward the development of intelligent orthodontic appliances with bio-responsive capabilities.

3.3 Ceramic materials

Metal brackets are not aesthetically pleasing in the oral cavity. Ceramic brackets significantly solve this problem. Early ceramic brackets were mainly made from single-crystal alumina, also known as sapphire brackets. This ceramic has high translucency, allowing it to blend perfectly with natural tooth color, resulting in excellent aesthetic effects. Polycrystalline alumina ceramics, in addition to their aesthetics, also possess sufficient strength and biocompatibility, and their production cost is relatively low [125]. However, ceramic brackets present inherent limitations. Relative to their metallic counterparts, they possess lower fracture toughness while exhibiting comparatively higher bonding strength [126, 127].This may lead to bracket fracture or damage to the teeth [126, 128].

Moreover, ceramic materials generally exhibit higher frictional resistance than metal brackets [129, 130]. The frictional resistance of polycrystalline ceramic brackets is higher than that of single-crystal brackets. This is the fatal flaw of ceramic brackets, as it greatly affects the efficiency of tooth movement [131, 132]. Therefore, researchers have developed new ceramic materials and processing techniques to enhance their mechanical properties and biocompatibility [133, 134]. For example, the new generation of polycrystalline ceramic brackets has significant improvements in frictional performance compared to previous products [135]. Silicon nitride ceramics exhibit excellent biocompatibility [136]. To meet higher aesthetic demands, researchers have developed a standardized manufacturing technology for customized ceramic brackets (CCB) [137]. It enables personalized design, with improvements in both aesthetics and mechanical properties. Clinical experience indicates that many practitioners are dissatisfied with the high frictional resistance associated with ceramic brackets. In comparison, biocompatibility seems less important in orthodontic treatment. Therefore, reducing the friction of ceramic brackets remains very important.

4 Functional treatments for orthodontic materials

Orthodontic treatment relies on various materials, including fixed brackets, removable appliances, and auxiliary devices. These appliances create a unique microenvironment in the oral cavity. The appliances are exposed to saliva containing enzymes and electrolytes, which facilitates the adhesion of pathogens such as Streptococcus mutans and the formation of dental plaque. This is a direct cause of orthodontic clinical complications such as enamel demineralization and gingivitis [129]. Metal orthodontic appliances are susceptible to corrosion by saliva, releasing ions such as Ni^{2+}, which may cause oral allergies. Researchers have begun exploring novel strategies to address these challenges. This chapter reviews innovations in orthodontic appliance materials, mainly including surface modification for functionalization, incorporation of antimicrobial nanoparticles, and the addition of coatings that release bioactive agents.

4.1 Antibacterial surface coatings

Improving the performance of orthodontic devices relies on surface modification. Techniques such as atomic layer deposition (ALD), physical vapor deposition (PVD), and sol–gel dip coating are used to improve wear resistance, bioactivity, and antimicrobial functions. The functional layers formed by these methods enable the materials to cope with the complex and variable oral environment. These coating methods can be classified into physical and chemical coatings.

PVD transforms solids or liquids into vapor in a vacuum. The vapor then condenses on the substrate, forming films with thicknesses ranging from nanometers to micrometers. It is capable of producing multilayered, hierarchical structures or thick deposits, even with specialized designs. Studies show that these PVD-derived coatings can optimize surface properties, including roughness, hardness, and elastic modulus. At the same time, they can enhance the material's wear resistance and corrosion resistance [138, 139]. Thermal evaporation is the core method of PVD, using heat to evaporate materials and effectively deposit single or composite films. Research indicates that silver-based nanocoatings produced by this method can significantly improve the antimicrobial properties of stainless steel brackets over the long term [140, 141].

Unlike thermal evaporation, which relies on heating, magnetron sputtering uses radio-frequency or direct-current power along with a magnetic field to control plasma, as shown in Fig. 3(a). This method allows for higher deposition rates and excellent film quality. Its outstanding process adaptability and low-temperature operability make it an excellent deposition method [142]. As a result, magnetron sputtering technology has been widely applied in orthodontic material research [143–147]. As shown in Fig. 3(b), Sun et al. [142] used this method to deposit antimicrobial coatings on archwires and confirmed that nitrogen-doped TiO_2 composite archwires exhibited higher antimicrobial activity than pure TiO_2 coatings.

Differing from physical methods, CVD generates coatings through chemical reactions. The precursor gases react on a heated substrate, directly forming a thin film on the surface, which includes techniques such as electrochemical vapor deposition (EVD) [148]. The target surface acts as the cathode in an electrochemical cell (Fig. 3(c)). Using this method, Shimaa El-Hadad et al. [149] fabricated a hydroxyapatite coating on a Ti50-

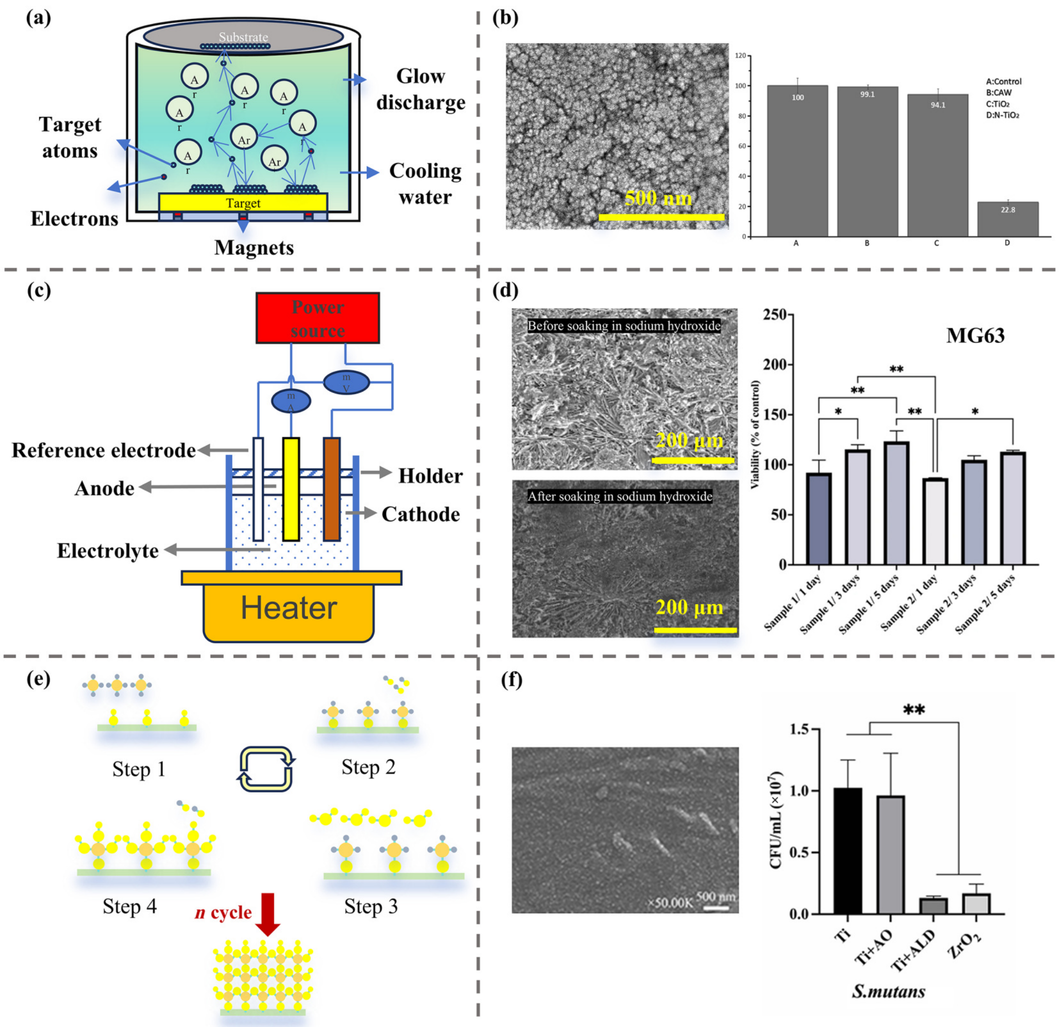

Figure 3 (a) Schematic of the reactive magnetron sputtering process. Reproduced with permission from Ref. [153], © Maurya, D. K. et al. 2014. (b) An antibacterial orthodontic archwire doped with N-TiO_2. Reproduced with permission from Ref. [142], © Royal Society of Chemistry 2017. (c) The typical configuration of an electrodeposition setup. Reproduced with permission from Ref. [154], © Saha, S. et al. 2020. (d) A Ni-Ti memory alloy coated with hydroxyapatite. Reproduced with permission from Ref. [149], © Springer Nature 2022. (e) A schematic ALD process for depositing multi-ZnO layers using DEZ and water as the precursors on substrate with reactive OH* sites. Reproduced with permission from Ref. [155], © Guan, C. et al. 2016. (f) Preparation of titanium dioxide film on titanium dental table. Reproduced with permission from Ref. [151], © Pan, Y. et al. 2024.

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Ni50 shape memory alloy that exhibited favorable biocompatibility, as evidenced by nickel ion release remaining within safe limits (Fig. 3(d)). ALD synthesizes inorganic thin films and coatings through sequential reactions between vapor-phase precursors and substrate surface functional groups, and as shown in Fig. 3(e) its defining feature is self-limitation—where reactions cease once surface sites are consumed and are subsequently regenerated in the next cycle—thus enabling atomic-scale thickness control. ALD is widely applied to deposit uniform antibacterial nano-coatings on medical devices, ALD-derived materials simultaneously enhance friction reduction, antibacterial activity, corrosion resistance, and inhibit undesired adhesion in the oral environment for orthodontic applications [150]. Hui Cheng et al. [151] demonstrated in a comparative study that ALD produces nano-TiO_2 coatings on titanium abutments with antibacterial properties equivalent to ZrO_2 and superior to anodic oxidation (AO) in reducing bacterial and biofilm adhesion, while additional investigations confirm that ALD-derived coatings can effectively limit harmful ion release from orthodontic materials, as evidenced by the markedly improved resistance to nickel leaching in Al_2O_3-coated NiTi alloys immersed in SBF (Fig. 3(f)) [152].

4.2 Blending modifications

Although surface modification technologies have been shown to effectively improve the performance of orthodontic materials, they still face some inherent limitations, including insufficient long-term adhesion between the coating and the substrate, uneven crystallinity, and inconsistent composition [156]. A plausible solution strategy is to directly mix functional nanomaterials into orthodontic materials, thereby achieving long-lasting and stable performance.

Recent advances in nanoparticle synthesis and functionalization have opened new avenues for enhancing the antibacterial performance and biocompatibility of orthodontic materials. Green synthesis strategies utilizing plant extracts or biomolecules have enabled the preparation of various nanoparticles with low toxicity and high biocompatibility [157]. Functionalization approaches—including polymer coating, surface modification, encapsulation and ligand addition—have further enhanced the stability and antibacterial efficacy of nanoparticles under complex oral conditions [158]. For example, the use of nanoparticles for antibacterial drug delivery and targeting can markedly enhance the stability, permeability, and efficacy of antibiotics, while passive or active mechanisms effectively overcome drug resistance, intracellular infections, and biofilm barriers, thereby offering new strategies for the treatment of bacterial infections[159]. These functionalized nanoparticles can be integrated into orthodontic adhesives, archwires, or aligner matrices to provide long-term antimicrobial protection, promote remineralization, and even enable responsive drug release.

Incorporating antibacterial nanoparticles into dental matrices or applying them as surface coatings on orthodontic appliances represents a reliable strategy for enhancing antimicrobial performance [160]. Depending on their origin and mechanism, they are typically categorized into three types: inorganic nanoparticles, organic nanoparticles, and nanoparticles from composite materials derived from natural polymers. Inorganic nanoparticles comprise metals, metal oxides, their doped forms, and novel surface-modified types, including silver nanoparticles [161], gold nanoparticles [162], and copper nanoparticles [163], as well as metal oxide nanoparticles [164], fluoride nanoparticles [165, 166], and graphene oxide nanoparticles [167]. Silver nanoparticles were the most widely used blending additive, demonstrating remarkable antibacterial efficacy both when applied alone and in combination with other agents (Fig. 4(a)). *In situ*-formed silver nanoparticles demonstrated pronounced antibacterial efficacy through mechanisms involving oxidative stress and the release of silver ions [168, 169]. Several novel orthodontic materials have been developed using silver nanoparticles. Marco et al. [170] incorporated different concentrations of silver nanoparticles into the commercial orthodontic adhesive Transbond XT and found that the modified adhesive exhibited significantly enhanced antibacterial properties and effectively reduced enamel demineralization. Zhang et al. [171] applied 4,6-diamino-2-pyrimidinethiol-modified gold nanoparticles (AuDAPT) onto clear aligners, and these coatings displayed antibacterial activity against *P. gingivalis* suspensions, influenced the adjacent material environment, slowed biofilm development, and exhibited favorable biocompatibility (Fig. 4(b)).

In addition, researchers have investigated the direct modification of nanoparticles to accommodate diverse and complex orthodontic environments, including nitrogen, sulfur, and various metal doping strategies. For example, Shweta Nagesh et al. [172] synthesized SrCuHA nanoparticles by incorporating strontium and copper ions into hydroxyapatite, which markedly enhanced their antimicrobial activity. Although further studies are needed to evaluate bonding strength, biocompatibility, and long-term antimicrobial performance, they show great potential in orthodontic applications. While silver nanoparticles provide outstanding antibacterial efficacy, they may also darken composite resins, leading to aesthetic concerns. Recent investigations have focused on orthodontic composites incorporating two or more types of Nanoparticles (NPs) to enhance antibacterial performance while maintaining aesthetic quality, and Mahdiyeh et al. developed an Ag/ZnO nanocomposite resin that exhibited strong antibacterial activity against diverse oral pathogens, high shear bond strength, and excellent biocompatibility, without the aesthetic drawbacks commonly linked to silver nanoparticles [173]. Alongside inorganic nanoparticles, research has also examined organic and natural polymer-based NPs, with representative examples including quaternary ammonium compounds as broad-spectrum cationic antibacterial agents and natural polymer-based systems such as chitosan NPs, curcumin NPs, and curcumin-doped PLGA NPs. The antibacterial function of cationic quaternary ammonium salts (QAS) mainly occurs through an extracellular mechanism in which they are attracted to negatively charged bacterial membranes, penetrate them, and cause disruption, a process confirmed by Tatiana's group whose study showed that incorporating quaternary ammonium methacrylate (QAM) into resin formulations markedly reduced bacterial metabolic activity [174].

Compared with natural polymer-based NPs, the use of metal NPs may weaken shear bond strength [175], cause undesirable enamel discoloration when incorporated into orthodontic resins. [176], and increase the cytotoxic potential of the material [177]. Current research on natural polymer-based NPs have largely focused on chitosan NPs, a biopolymer obtained through chitin deacetylation which have been investigated for enhancing the mechanical and antibacterial properties of orthodontic materials [178], whose derivatives can inhibit *Streptococcus mutans*, *Streptococcus sanguinis*, and fungi [179], and owing to their non-toxic, biodegradable, and biocompatible nature,

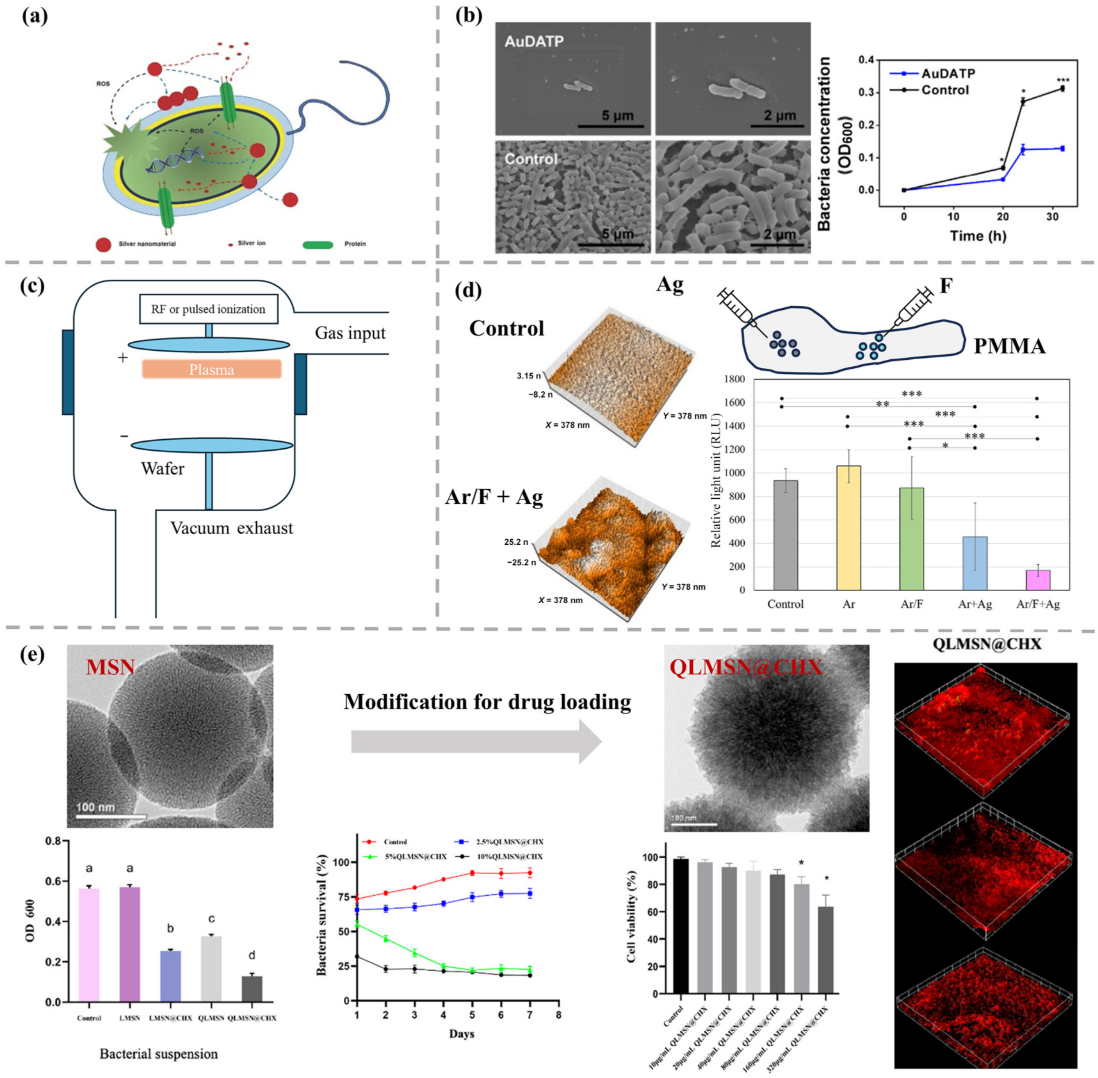

Figure 4 (a) Antibacterial mechanism of NPs applied in orthodontic materials. Reproduced with permission from Ref. [186], © WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 2018. (b) A clear aligner doped with gold nanoparticles. Reproduced with permission from Ref. [171], © American Chemical Society 2020. (c) Plasma immersion ion implantation scheme. Reproduced with permission from Ref. [187]. (d) Antimicrobial ion modification in orthodontic adhesive. Reproduced with permission from Ref. [188], © Kagami, K. et al. 2020. (e) Implementation method of a dual-mode antimicrobial orthodontic adhesive. Reproduced with permission from Ref. [189], © Teng, X. T. et al. 2025.

these polysaccharide materials have attracted significant attention as promising alternatives to metal NPs for overcoming the latter's limitations [180].

Orthodontic materials can be functionalized through blending with various inorganic non-metallic or organic compounds. Bioactive glass (BAG), an inorganic bioceramic material known for strong antibacterial activity and outstanding remineralization capacity under physiological conditions [181], has been further advanced through fluoride doping to create resin adhesives capable of intelligently releasing fluoride ions in response to the acidic environment of early caries [182], while a strontium- and calcium phosphate-doped BAG system (Sr/CaP-BAG) offers another promising strategy by simultaneously delivering Ca^{2+}, Sr^{2+}, phosphate ions, and andrographolide to achieve both enamel remineralization and effective antibacterial effects [183]. In terms of organic compounds, 1,3,5-triacryloylhexahydro-1,3,5-triazine (TAT) has been recognized as an antibacterial agent with photosensitizing potential, while montmorillonite (Mont) and nanoporous silica (NPS) serve as carriers in long-lasting antimicrobial resins that, when loaded with cetylpyridinium chloride (CPC), enable autopolymerizing systems to sustain drug release and reloading for up to 14 days to inhibit *Streptococcus mutans*, though this improvement compromises mechanical strength and induces discoloration [184]. Moreover, evidence from a randomized clinical trial confirms that incorporating quaternary ammonium methacryloxy silicate (QAMS) into acrylic resin provides strong anti-biofilm activity against dental plaque [185], with the modified resin remaining appropriate for removable denture fabrication and thus offering notable clinical potential.

4.3 Ion immersion implantation and drug loading/delivery

Beyond surface coatings and bulk blending, ion implantation and drug-loading systems offer more targeted functionalization. The former embeds ions at the atomic scale to create a stable surface layer that resists biofilms and improves corrosion resistance and biocompatibility, without affecting bulk properties (Fig. 4(c)). The latter integrates agents such as chlorhexidine or nanoparticles into resins or coatings, enabling sustained and controlled antimicrobial release.

Since their introduction to dentistry in the mid-1980s [190], titanium nitride (TiN) coatings and nitrogen ion implantation have served as effective surface modification strategies. Early studies revealed that implanting nitrogen, fluoride, or silver ions into orthodontic materials markedly improved antibacterial activity, wear resistance, and corrosion resistance. For example, nitrogen ion implantation converts the NiTi archwire surface into a TiN layer by replacing allergenic nickel with inert nitrogen and thereby producing the lowest ion release compared to uncoated or rhodium-coated wires as shown in Fig. 4(d) [191], while a comparable strategy of embedding fluoride or silver ions into polymethyl methacrylate (PMMA) enhanced material hydrophobicity, decreased bacterial adhesion, and effectively inhibited Streptococcus mutans growth [188].

Plasma immersion ion implantation and deposition (PIIID), developed as an advancement over conventional plasma techniques, was first applied to orthodontic brackets and demonstrated antibacterial performance comparable to physical vapor deposition (PVD) and silver electroplating, while achieving stronger bactericidal effects without altering surface roughness [18]. In drug delivery, chlorhexidine (CHX)—a widely used cationic antiseptic—prevents caries by interfering with plaque formation and bacterial adhesion to the acquired pellicle [192], and recent progress has introduced dual-mode antibacterial composites containing CHX-loaded quaternary ammonium-modified mesoporous silica nanoparticles (QLMSN@CHX) as functional fillers, which eradicate biofilms within 24 hours while sustaining antibacterial efficacy, mechanical strength, and biocompatibility comparable to commercial orthodontic resins (Fig. 4(e)) [189]. Furthermore, cinnamaldehyde—a naturally occurring compound extracted from cinnamon essential oil with proven antibacterial properties [193]—has been integrated into cellulose-based thermoplastic clear aligners, enabling these modified materials to delay biofilm development by cariogenic bacteria while maintaining the biocompatibility and mechanical strength required for orthodontic performance [194].

In summary, this section focuses on the main methods of orthodontic material modification. These methods have promoted smarter and more personalized orthodontic treatments. Unfortunately, clinical translation remains challenging, especially due to issues such as long-term biocompatibility, coating durability, and controlled release of compounds.

5 Integration of sensor and orthodontic material

Orthodontic treatment still heavily relies on the clinical experience of practitioners. The main reason is the lack of real-time, objective mechanical and physiological feedback. Microelectromechanical systems (MEMS) and flexible hybrid electronics enable miniature sensors to be directly integrated into orthodontic devices. These embedded systems allow for continuous, non-invasive clinical monitoring, providing objective data to clinicians without affecting oral function or treatment outcomes. Although these developments are promising, many challenges remain in clinical applications. Sensors placed in the oral cavity must withstand repetitive chewing forces, be able to endure prolonged exposure to the saliva environment, and cope with complex microbial ecosystems. This places stringent demands on the sensor's biocompatibility, structural durability, and chemical stability. In this section, we review typical case studies that showcase the latest advancements in the integration of wearable sensors with orthodontic devices, while also highlighting the key obstacles faced in this field and future directions for development.

5.1 Force sensing

The precise application of orthodontic force is the foundation for achieving ideal tooth movement. In clinical practice, determining the optimal orthodontic force largely depends on the subjective judgment of the orthodontist. Although finite element analysis can simulate the application of force, it is difficult to accurately replicate the real mechanical environment of the oral cavity. Therefore, real-time visualization of orthodontic forces is particularly important. It not only helps in clinical decision-making but also enhances patient engagement. Wearable sensing technology, by integrating sensor modules, enables the visualization of orthodontic treatment, laying the foundation for precision orthodontics.

Fixed appliances remain the gold standard in orthodontics [195]. However, their mechanical system is extremely complex. The forces and moments generated by the appliance are the primary driving forces for tooth movement. However, this process is usually in a "black box" state. The application of embedded force sensors has successfully addressed this issue. Depending on the integration method, force sensor systems can be divided into external and embedded systems. In external measurement systems, force sensors are used as independent devices placed on experimental platforms outside the dental arch, avoiding conflicts between sensor size and the limited oral space. The application of such systems has been validated [196–199]. For instance, studies by Lai [200] and Midorikawa [201] rigidly connected six-axis sensors to artificial dental models, effectively avoiding spatial constraints within the dental arch. This device not only achieved high measurement accuracy but also enabled the visualization of orthodontic forces. Although these external measurement systems are still far from being "wearable" devices in a clinical sense, they have laid an important methodological foundation.

Clearly, in vitro measurement systems are unable to replicate the complex mechanical conditions within the oral cavity. As a result, researchers have sought to integrate force sensors directly into orthodontic brackets, with one of the key challenges being the issue of wireless signal transmission [202–204]. Kuhl's team pioneered a wireless stress monitoring system for orthodontic brackets by integrating 24 piezoresistive field-effect transistors (FETs) with planar microcoils on a CMOS chip through electroplating [205]. The resulting 2 mm × 2.5 mm × 0.73 mm module achieved the first demonstration of wireless power delivery and data transmission for embedded sensors using the 13.56 MHz medical RFID band. Building on this foundation, the research team of Hafner, Lapatki, and Paul achieved the ultimate leap in system integration and clinical applicability, developing the first telemetric smart orthodontic bracket suitable for clinical therapy [202]. This bracket integrated an optimized CMOS stress-sensing chip with a custom micro-coil directly beneath the slot component of a standard ceramic bracket, enabling completely wireless telemetric operation.

With continuous progress in precision manufacturing, sensor accuracy has been further improved. Although a wired device was employed, Xie et al. [203] made a crucial breakthrough in measurement precision (Fig. 5(a)): By employing an ultra-miniature MEMS pressure sensor array, they successfully achieved, for the first time, three-dimensional in vivo quantification of orthodontic forces, with a monitoring error of less than 0.01 N. This achievement lays a solid foundation for clinical decision-making.

Monitoring the three-dimensional orientation of orthodontic forces represents an advanced capability of smart brackets, extending beyond the conventional assessment of force magnitude. In fixed appliance therapy, inappropriate torque is a common cause of treatment failure. By monitoring torque forces in real time, smart brackets can provide clinicians with direct evidence of whether teeth are moving according to the predetermined 3D plan. For this purpose, As shown in Fig. 5(b), Hu et al. [206], inspired by the ancient Chinese architectural mortise–tenon joint structure, fabricated a pressure-sensing device that connects upper and lower structures through interlocking concavities and convexities. Integrated with the orthodontic appliance, this device can analyze the magnitude and direction of orthodontic forces, offering significant potential to enhance an orthodontist's control over force values and vectors.

Sensing technology is now being applied to the bonding interface. One study proposed a wireless microsystem that detects humidity changes between the bracket and tooth surface, enabling early assessment of bonding stability. Another developed a sensor-integrated bracket positioning device that quantifies vertical pressure during bonding in real time, helping to standardize adhesive thickness and shift the procedure from an experience-based to a digitally-guided process [17]. It is evident that the integration of sensing technology and orthodontics is a powerful strategy for eliminating “areas of experiential uncertainty” in clinical practice.

With the widespread adoption of clear aligner technology, the need for mechanical monitoring has extended from fixed appliances to this bracket-free domain. Given that clear aligners must closely fit the tooth surfaces to deliver effective and continuous force, researchers were dedicated to developing ultra-thin, flexible force sensors for integration onto the inner surface of the aligners. For example, the work by Sun et al. [207] made significant progress in visualizing the distribution of orthodontic forces. By integrating an iontronic sensor and electrode array into the inner surface of the aligner, they achieved real-time, 3D mapping of orthodontic force distribution. Wired connections make the device very complex. Wireless sensing technology has become the frontier research direction in this field [207, 208]. In 2025, Guo et al. [208] developed an orthogonal force sensing system (OFAS) integrated into clear aligners. The system combines foldable circuits with an iontronic sensor array, seamlessly integrating them into the clear aligner (Fig. 6(a)). It can precisely measure three-dimensional forces and moments, and the mechanical data is highly reliable. After 15 days of in vivo testing, the system showed a certain degree of performance stability. This

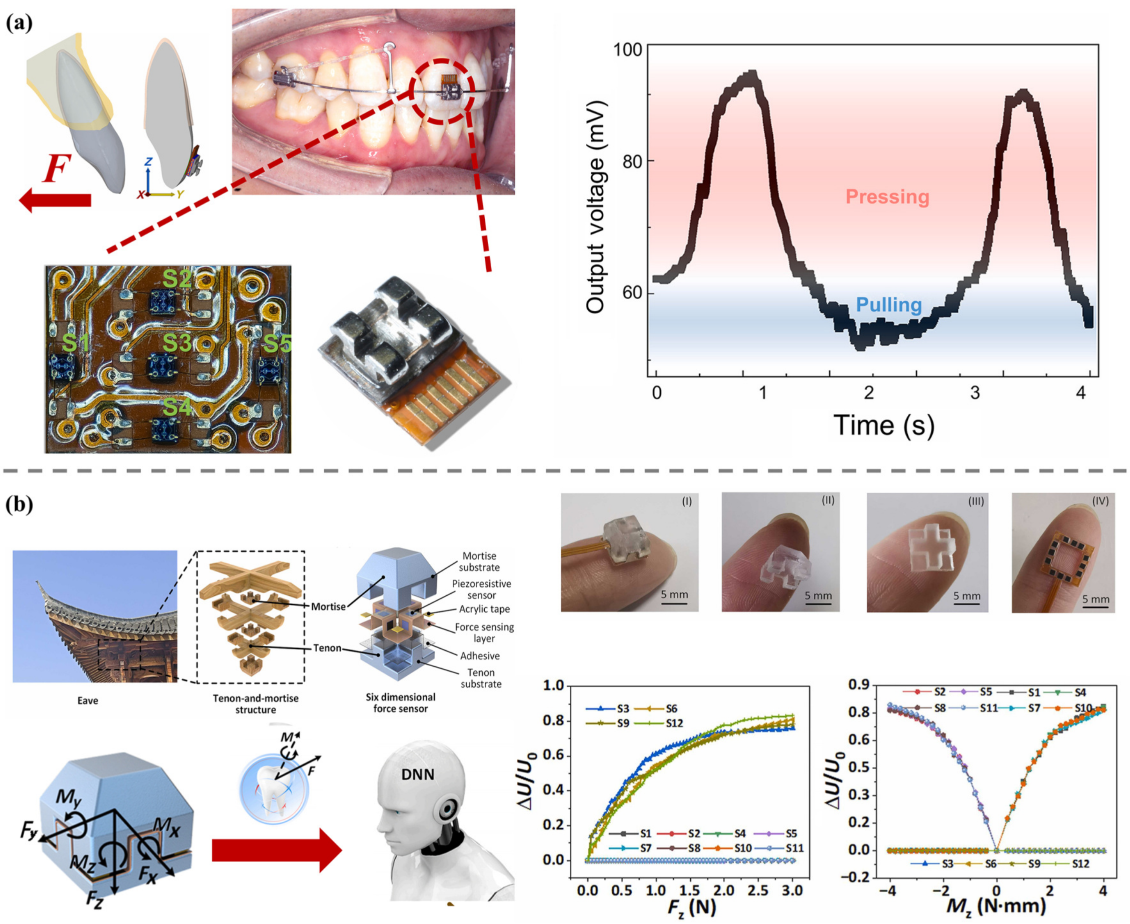

Figure 5 (a) The force-detecting bracket was designed and fabricated, followed by clinical trials. Reproduced with permission from Ref. [203], © Xie, Q. Y. et al. 2023. (b) A flexible six-axis force sensor inspired by mortise-tenon architecture, enabling multi-directional force measurement. Reproduced with permission from Ref. [206], © Elsevier Ltd. 2022.

wireless sensing system is more streamlined, intelligent, and miniaturized.

In contrast to the above-mentioned sensing methods, Feng et al. [209] proposed a method based on visual signals. The device directly converts orthodontic forces into optical image outputs (Fig. 6(b)). By combining artificial intelligence for image analysis, this system achieves flexible integration of monitoring and intelligent diagnostics.

Orthodontic treatment depends not only on the magnitude of the applied force but also on the control of the force direction. Therefore, sensors capable of precisely measuring the direction of force have significant clinical importance. The miniature sensor by Shi et al. [210] , while innovative in design, proves unsuitable for routine clinical use due to its rigid structure and reliance on wired power and data connections. In contrast, the system developed by Song et al. [211] employs a polyelectrolyte-based iontronic sensor with an inductor–capacitor (LC) resonant circuit. Their approach uses a low-creep, ion-leakage-free polyelectrolyte elastomer as the core sensing material, which maintains excellent long-term stability with minimal signal drift (< 2%) under sustained static pressure (Fig. 6(c)).

Bite force monitoring is crucial for assessing masticatory function and the effectiveness of orthodontic treatment. Professor Yang's team developed a flexible piezoresistive sensor by directionally freezing an MXene/bacterial cellulose composite into a 3D porous aerogel, achieving a sensitivity of 210.21 kPa^{-1} within a bite force range of 420 kPa [212]. Building on this, Lin et al. [213] combined multilayer ceramic capacitors with polyimide components to achieve static and functional monitoring of occlusal forces. Yu et al. [214] proposed a self-powered flexible sensor array based on the principle of triboelectric nanogenerators (TENG). This array can convert the distribution of occlusal forces into an intuitive electrical signal image, providing an objective method for evaluating occlusal reconstruction outcomes (Fig. 7(a)). The advantage of this

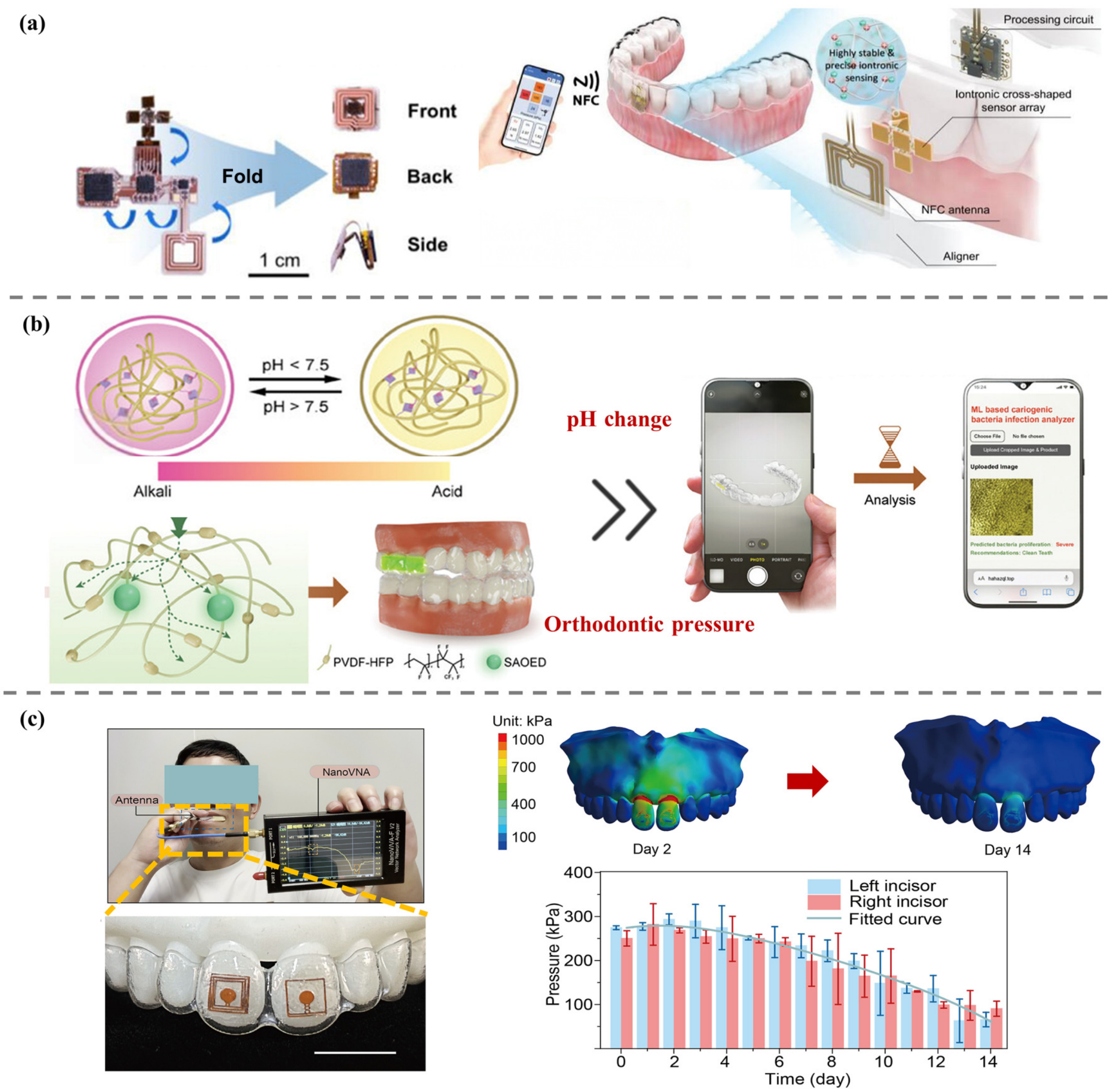

Figure 6 (a) Real-time monitoring of tooth movement trajectory and force distribution via 3D orthodontic force signals acquired by a passive cross-shaped sensor array. Reproduced with permission from Ref. [208], © Guo, J. H. et al. 2025. (b) Principles and future applications of bimodal non-interfering visual detection in the context of orthodontic force monitoring and bacterial infection detection. Reproduced with permission from Ref. [209], © Wiley-VCH GmbH 2024. (c) An iontronic sensing platform for orthodontics, enabled by polyelectrolytes to achieve wireless and drift-free operation. Reproduced with permission from Ref. [211], © Song, J. et al. some rights reserved; exclusive licensee American Association for the Advancement of Science 2025.

device is that it eliminates the limitations of active power supplies. Liu et al. [215] fabricated a piezoelectric sensor using regenerated silk fibroin. Its biodegradability is very eco-friendly, but its lifespan is a concern. Of course, the integration of artificial intelligence with sensors has greatly promoted the development of digital orthodontics. A notable example is the work of Feng et al. [216], who introduced ARIA, a fully integrated smart clear aligner system. By applying machine learning algorithms to large-scale clinical datasets, ARIA achieved accurate classification of malocclusion types (accuracy > 95%) and automated detection and tracking of harmful oral habits. This innovation represents a significant step forward in orthodontics, transitioning from conventional mechanical sensing to a new era of intelligent, integrated treatment systems (Fig. 7(b)).

Neuromuscular dysfunction has a significant impact on oral function [217, 218]. For example, unilateral chewing may lead to facial developmental asymmetry. Wang et al. [219] designed a detection system that track muscle bulges and cranial vibrations caused by temporalis muscle contractions, indirectly identifying unilateral chewing behavior, with a detection accuracy of 84.8%. In contrast, surface electromyography (sEMG) can directly record the action potentials of muscle fibers. This offers a greater advantage in studying the fundamental mechanisms of neuromuscular function [220, 221]. However, the bulky equipment of traditional sEMG limits its application in daily monitoring. Therefore, the miniaturization of its equipment may be the next direction for research.

The effectiveness of orthodontic treatment highly depends on patient compliance. Therefore, monitoring the wear time of the orthodontic appliance is crucial. It not only provides reliable evidence but also reduces communication barriers between doctors and patients. The wearable technology of miniaturized temperature sensors (such as TheraMon®) solves this problem [222, 223]. This technology has been validated in orthodontic clinical trials [224]. The results revealed a significant difference between self-reported and actual usage by the patients. It is evident that the key research

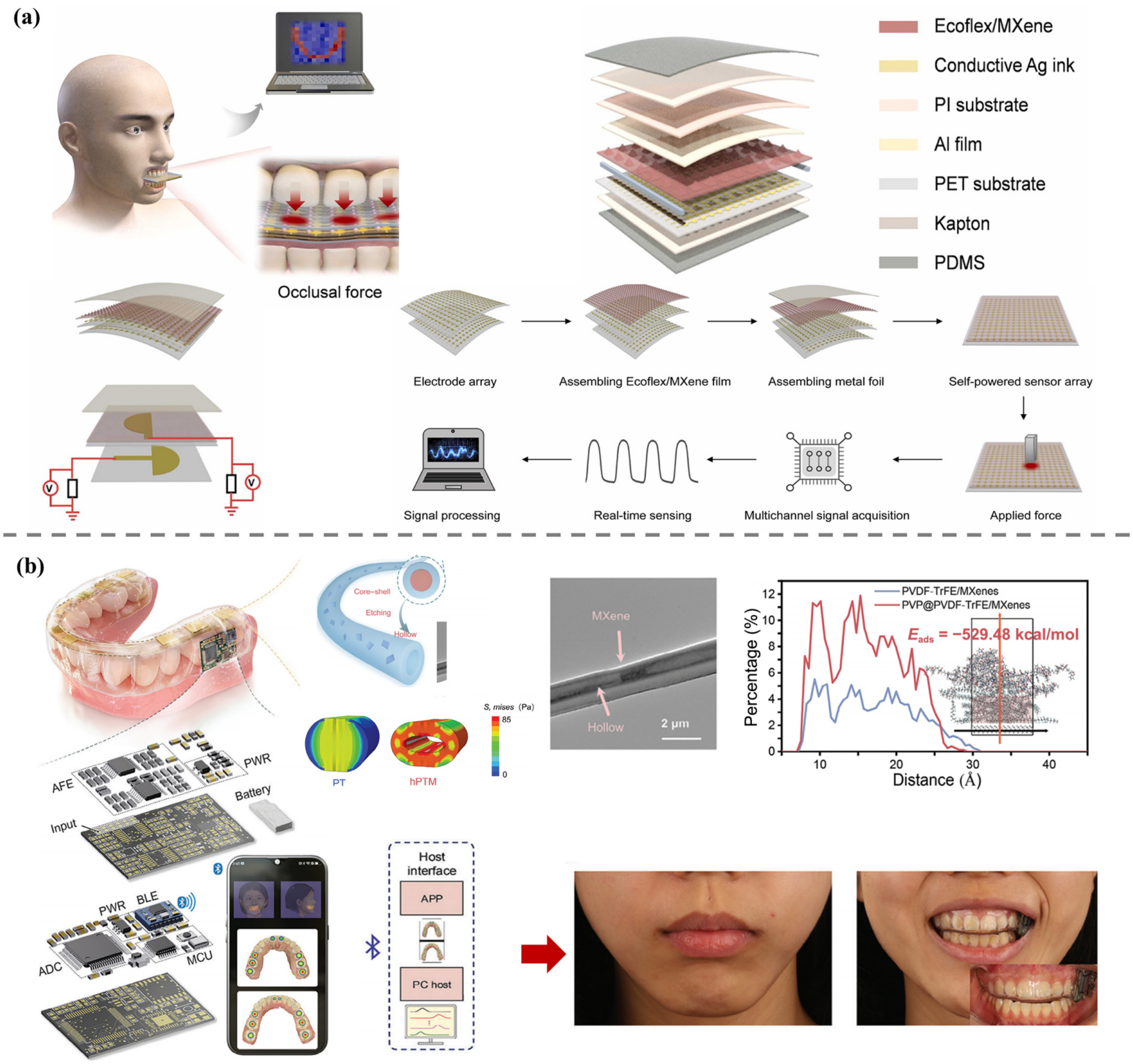

Figure 7 (a) A flexible self-powered sensor array enabling real-time monitoring and visualization of occlusal force distribution. Reproduced with permission from Ref. [214], © Elsevier Ltd. 2024. (b) Flexible integrated aligner with piezoelectric sensors for real-time occlusal force monitoring and AI-based detection of harmful oral habits. Reproduced with permission from Ref. [216], © Feng, H. et al. 2024.

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direction in advancing digital orthodontics lies in the integration of these monitoring systems, coupled with real-time data for intelligent management and feedback.

5.2 Biomolecular sensors

Tooth movement relies on the remodeling of periodontal tissues. Healthy periodontium is the cornerstone of successful orthodontic treatment. In recent years, biosensor technology has made it possible to conduct non-invasive, continuous biomarker monitoring in oral fluids (such as saliva and gingival crevicular fluid) [225, 226]. This method can detect inflammation, metabolic activity, and hormone levels, providing new approaches for assessing periodontal and overall health [227]. Monitoring periodontal health indicators provides important references for evaluating orthodontic outcomes [228, 229].

Unlike the single-time-point sampling method used in previous periodontal monitoring, wearable systems enable continuous, non-invasive monitoring and support long-term dynamic tracking. It can monitor changes in plaque, mineral dissolution, pH levels, metabolites, and bone metabolism markers [230, 231]. This long-term monitoring has irreplaceable advantages in the ever-changing oral environment.

Oral pH serves as a primary environmental determinant of the microbial community's structure and activity, and represents one of the most critical indicators for assessing microbial metabolic activity and caries risk. Tseng et al. [232] introduced a millimeter-scale, conformable radio-frequency trilayer sensor for tooth enamel, establishing a versatile platform for wireless, battery-free monitoring of the oral environment. As illustrated in Fig. 8(a), when the pH-responsive PNIPAM hydrogel functions as the sensing layer, its volume changes accordingly with variations in oral pH. The volumetric changes in the sensing layer affect the dielectric constant of the sensor, which in turn causes a shift in the resonant frequency, enabling real-time pH feedback. It should be noted that the sensor can be engineered to respond to multiple stimuli, including calcium ions and temperature, thereby making it applicable for monitoring a variety of biochemical parameters [233, 235–237].

Colorimetric methods have gained increasing attention for their low cost and intuitive readout. Matzeu et al. [233] developed a fully edible colorimetric pH sensor, using pH indicators derived from natural fruits like blueberries and nectarine peels. This choice ensured both biocompatibility and reduced production costs. When exposed to saliva at different pH levels, the sensor exhibited distinct color changes. By comparing the results with a color chart, salivary

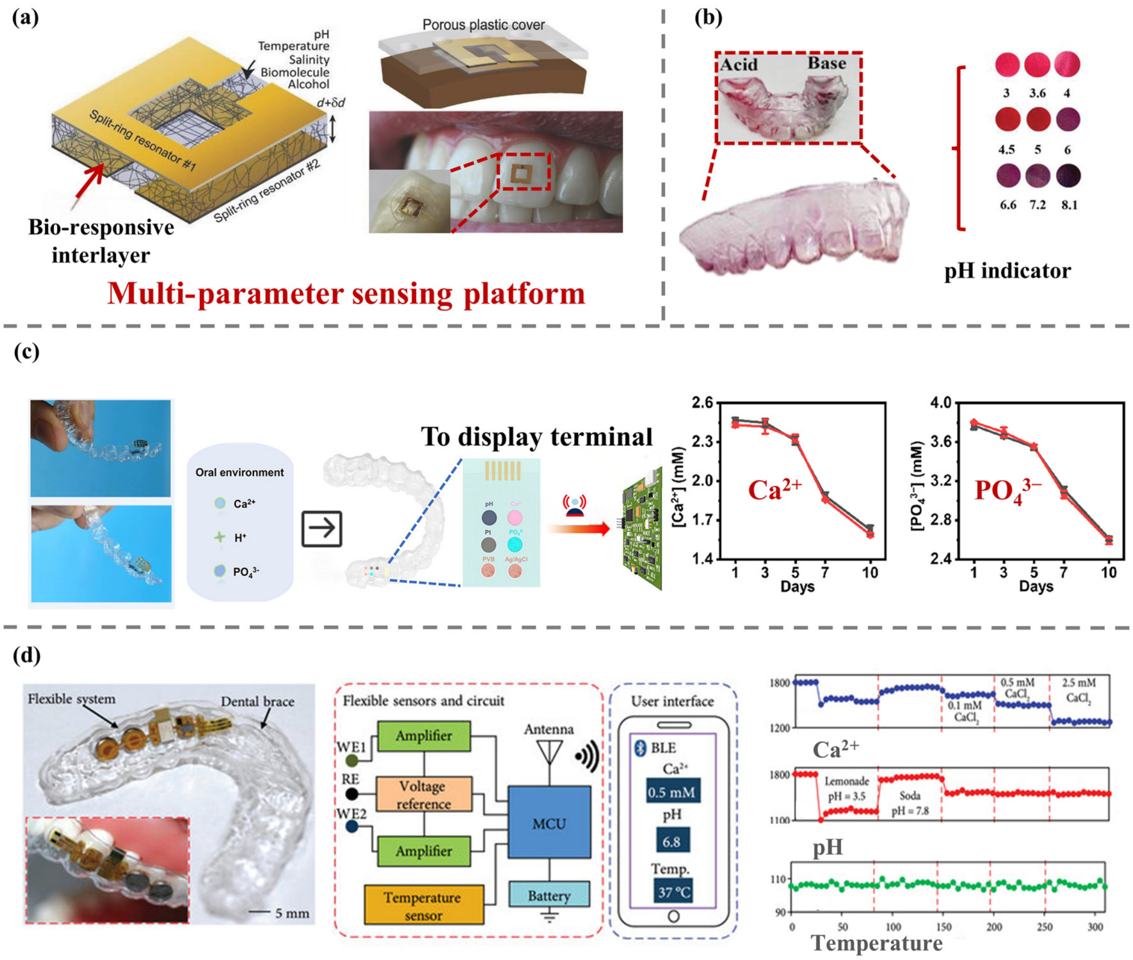

Figure 8 (a) Wireless RF sensing platform using a functional interlayer to convert environmental changes into frequency responses. Reproduced with permission from Ref. [232], © WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 2018. (b) A mouthguard-based colorimetric sensor for the determination of intraoral pH variations. Reproduced with permission from Ref. [233], © Matzeu, G. et al. 2021. (c) Integrated Multiplexed Sensing Clear Aligner (IMSCA) for monitoring enamel demineralization indicators during orthodontic treatment. Reproduced with permission from Ref. [8], © American Chemical Society 2023. (d) Schematic diagram of a modular flexible electronic system for real-time monitoring of salivary Ca^{2+}, pH, and temperature. Reproduced with permission from Ref. [234], © Ling, W. et al. 2022.

pH could be directly observed by the naked eye. However, the biggest problem with this sensor is its inability to continuously monitor the pH change of saliva in real time (Fig. 8(b)).

The development of wireless, battery-free, miniaturized monitoring systems is crucial for advancing the practical deployment of wearable technologies. Mondal et al. [238] developed a miniaturized passive wireless pH sensor based on direct electrochemistry. This pH sensing system used a custom solid-state electrode to achieve 49.5 mV/pH linear response. Its integrated ADC-RF architecture enables fully passive operation through backscatter communication, providing interference-resistant digital output that surpasses colorimetric methods. Successful oral validation establishes a pathway to reliable implantable chemical sensors.

Monitoring oral calcium and phosphate ions is essential in orthodontics for assessing enamel demineralization risk, as they directly regulate the demineralization-remineralization balance. Miniaturized sensing strategies for this purpose are actively being explored [234, 239, 240], among which one study developed a multiplexed sensor array integrated into a clear aligner. This system achieved the first synchronous, wireless, and real-time monitoring of pH, Ca^{2+}, and PO_4^{3-}. In both simulated demineralization experiments and tests on human teeth, it accurately captured the release of Ca^{2+} and PO_4^{3-} in response to acidic challenge (Fig. 8(c)), providing early warning of enamel demineralization.

To confirm the stability and reliability of the sensor in clinical settings, Ling et al. [234] innovatively combined a Ca^{2+} sensor (based on the ionophore ETH 129) with a pH sensor (based on polyaniline) and a temperature sensor to create a dual-sensor system. They cleverly incorporated the temperature sensor to compensate for signal drift in the electrochemical measurements. Experimental results demonstrated that the Ca^{2+} sensor showed a linear response within the 0.25 to 4 mM range, with a sensitivity of 30.3 $mV{\cdot}dec^{-1}$, while the pH sensor displayed linearity across the pH range of 4 to 8, with a sensitivity of 60.6 $mV{\cdot}dec^{-1}$, thus fully covering the concentration windows required for clinical applications. Additionally, the device incorporated polyvinyl butyral (PVB) to enhance stability, while gold nanoparticles (AuNPs) were electroplated onto the electrodes to improve sensor performance, with a lifespan exceeding 20 days (Fig. 8(d)).

Diabetes has become a major global health challenge, with its prevalence steadily increasing. The number of people affected is projected to rise from 422 million in 2014 to 552 million by 2030 [241]. The disease disrupts bone metabolism through the accumulation of advanced glycation end-products and persistent inflammation, thereby impairing the bone healing process [242]. In orthodontics, such disruption can influence alveolar bone remodeling, ultimately affecting treatment outcomes [243]. Consequently, monitoring glucose levels becomes particularly critical, and this demand can be met by biosensors capable of non-invasive oral glucose detection, offering dual benefits for diabetes management and real-time orthodontic guidance [11, 244].

Since salivary glucose concentrations are markedly elevated during the early stages of diabetes [245]. Arakawa et al. [10] incorporated a glucose oxidase (GOD)-based enzymatic sensor into a wireless telemetry system embedded in a customized mouthguard, creating a "cavity sensor" for real-time salivary glucose monitoring (Fig. 9(a)). This device achieved accurate detection within the physiologically relevant range of 5–1000 $\mu mol{\cdot}L^{-1}$. To improve resistance against interference, the same group later applied a cellulose acetate (CA) coating to the sensor. This anti-fouling membrane effectively minimized disturbances from electroactive species in human saliva, such as ascorbate and urate, thereby enhancing selectivity and stability, and making the sensor highly suitable for short-term intraoral monitoring (Fig. 9(b)) [11]. Nevertheless, enzymatic sensors face inherent drawbacks, including limited operational stability and complex fabrication processes, which remain significant obstacles. To address these issues, recent studies have shifted toward non-enzymatic alternatives. For instance, Lu et al. [244] developed a mouthguard sensor using robust platinum metal hydrogel (PMH) as the electrocatalyst (Fig. 9(c)). This non-enzymatic sensor offers a wide linear detection range, maintains strong performance in real saliva, and, importantly, has lower maintenance costs, which is another key advantage. Notably, recent studies have conferred active antibacterial properties to hydrogel-based glucose sensors. The constructed superhydrophilic sensing interface effectively inhibits the adhesion and biofilm formation of various oral pathogens, significantly enhancing the reliability and durability of the sensors in complex oral environments [246].

Lactate, the final product of glycolysis [247], can lower local pH, increasing the risk of enamel demineralization. In addition, it acts as a signaling molecule, stimulating gingival fibroblasts to release pro-inflammatory factors that may exacerbate periodontal inflammation and tissue damage. Liu et al. [248] employed an electrochemical approach combining enzymatic reactions with electrode processes to detect uric acid (UA) concentrations in saliva. The detection was achieved through electron transfer, where reduction at a Prussian Blue-modified electrode generated current corresponding to salivary UA levels. Considering the complexity of saliva, the researchers introduced electropolymerized o-phenylenediamine to protect the electrode from biofouling and interference caused by electroactive substances. The device was further integrated with a Bluetooth low energy chipset, enabling wireless connectivity with smartwatches, mobile phones, or computers. Similar sensing platforms have also been adapted to monitor salivary cholesterol [249], providing potential utility for assessing systemic bone metabolism (Fig. 9(d)).

Urea is an endogenous basic substrate, and its metabolism plays a key role in maintaining periodontal health [251, 252]. Researchers have designed sensors based on cross-linking methods to detect urea levels. These sensors exhibit high specificity and a linear response over a wide concentration range. Additionally, a miniature Bluetooth module enables real-time wireless transmission of data to smart devices [253].

Gas signaling molecules produced by microbial metabolism play a significant regulatory role in normal human metabolism. Ammonia (NH_3) is a key metabolic product of oral microbes and is significantly associated with caries activity [254]. As shown in Fig. 10(a), Jin et al. [255] designed a multifunctional flexible sensor platform based on bacterial cellulose/MXene (BC/MXene) bio-aerogel. With its unique three-dimensional porous structure, the platform can selectively detect NH_3 at carious sites. Volatile sulfur compounds (VSCs) are another important oral metabolic product. Their dynamic fluctuations are closely related to periodontal tissue health. Sensing detection technologies for these biomarkers provide strong support for early, non-invasive diagnosis of periodontitis and caries [256–259]. The transparent fluorescent dental braces developed by Li et al. [260] integrate ZnO-PDMS nanocomposite materials inside (Fig. 10(b)). Its working principle is based on the

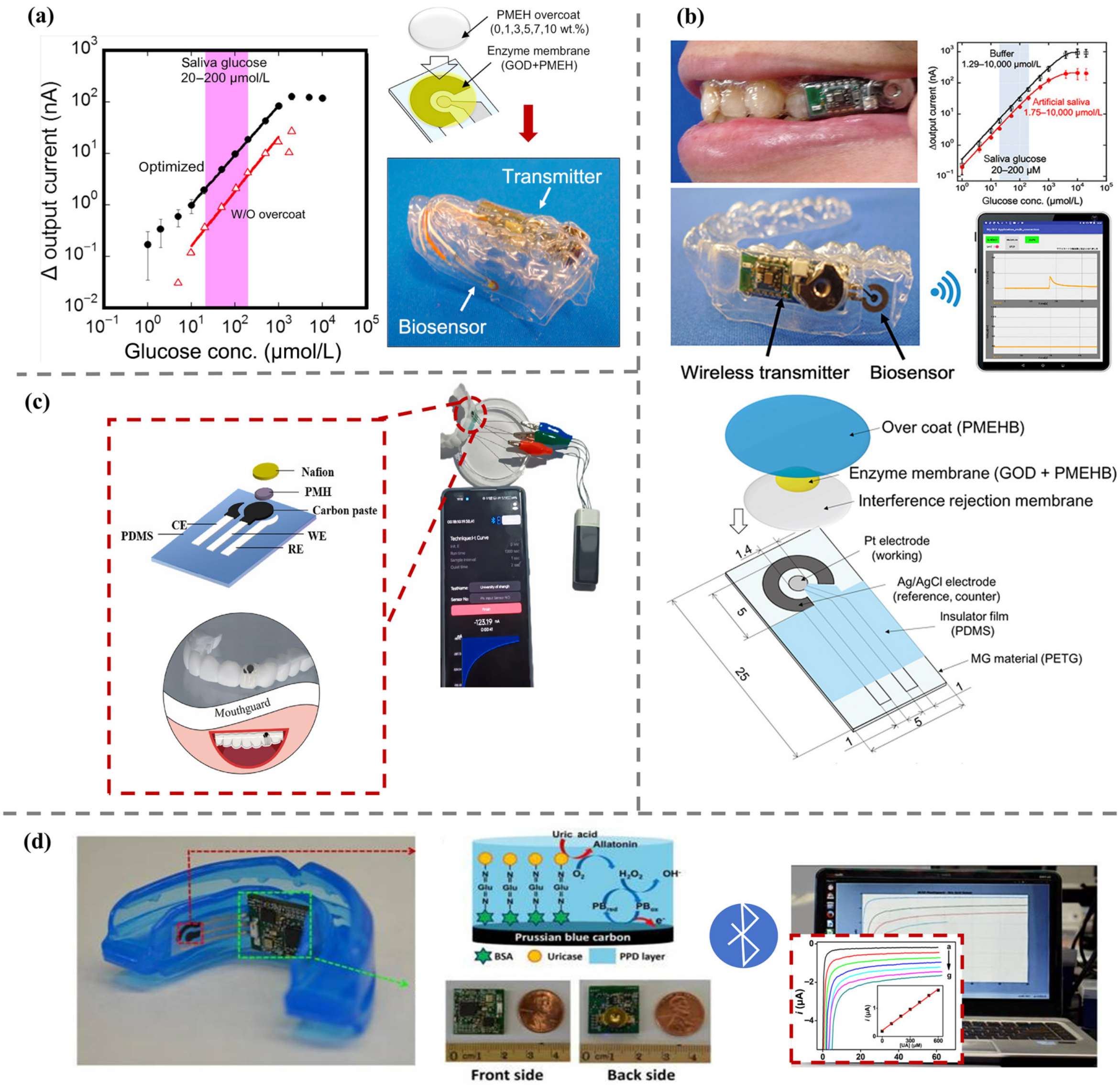

Figure 9 (a) A cavity sensor measuring salivary glucose. Reproduced with permission from Ref. [10], © Elsevier B.V. 2015. (b) A cavity sensor for glucose detection with a cellulose acetate coating. Reproduced with permission from Ref. [11], © American Chemical Society 2020. (c) Non-enzymatic electrochemical sensor for detecting salivary glucose, utilizing a platinum-based metallic hydrogel. Reproduced with permission from Ref. [244], © Elsevier B.V. 2024. (d) A screen-printed biosensor was developed on a PET-based mouthguard for monitoring salivary uric acid, employing the uricase enzyme as the active component. Reproduced with permission from Ref. [250], © Elsevier B.V. 2015.

fluorescence quenching effect of ZnO quantum dots when exposed to VSCs (especially H_2S), enabling intuitive and precise localization of hidden caries, which was validated in clinical trials. Ma et al. [261] introduced a colorimetric detection system based on gold@silver nanorods (Au@Ag NRs) This material has localized surface plasmon resonance (LSPR) properties (Fig. 10(c)). When exposed to H_2S, this sensor exhibits a distinct color change. This method is simpler to operate and suitable for large-scale screening.

Unlike the monitoring of bacterial metabolic products, monitoring of oral pathogens is more direct [252, 262, 263]. Li et al. [263] developed a portable electrochemical sensor that enables specific detection of *Streptococcus mutans*, the primary cariogenic bacterium, in saliva. This sensor can convert bacterial capture events into quantifiable changes in current signals, thereby enabling bacterial monitoring. The system has high sensitivity, a wide detection range, and significant clinical application value. In conclusion, biosensors have shown great potential for application in oral healthcare, but most research remains at the laboratory stage. Issues such as long-term operational stability and biocompatibility still need to be addressed.

5.3 Integrated sensing for diagnosis and treatment

The application of sensors should not be limited to a single diagnostic or therapeutic function, but should integrate both functions. Integrated diagnostic and therapeutic orthodontic devices represent a new development direction, aiming to build a multifunctional system that combines sensing, decision-making, and intervention to achieve intelligent orthodontic treatment.

The design of integrated diagnostic and therapeutic systems relies on hardware platforms that can support sensing, decision-making, and execution functions. From this perspective, the occlusion-activated electromechanical synergistic orthodontic

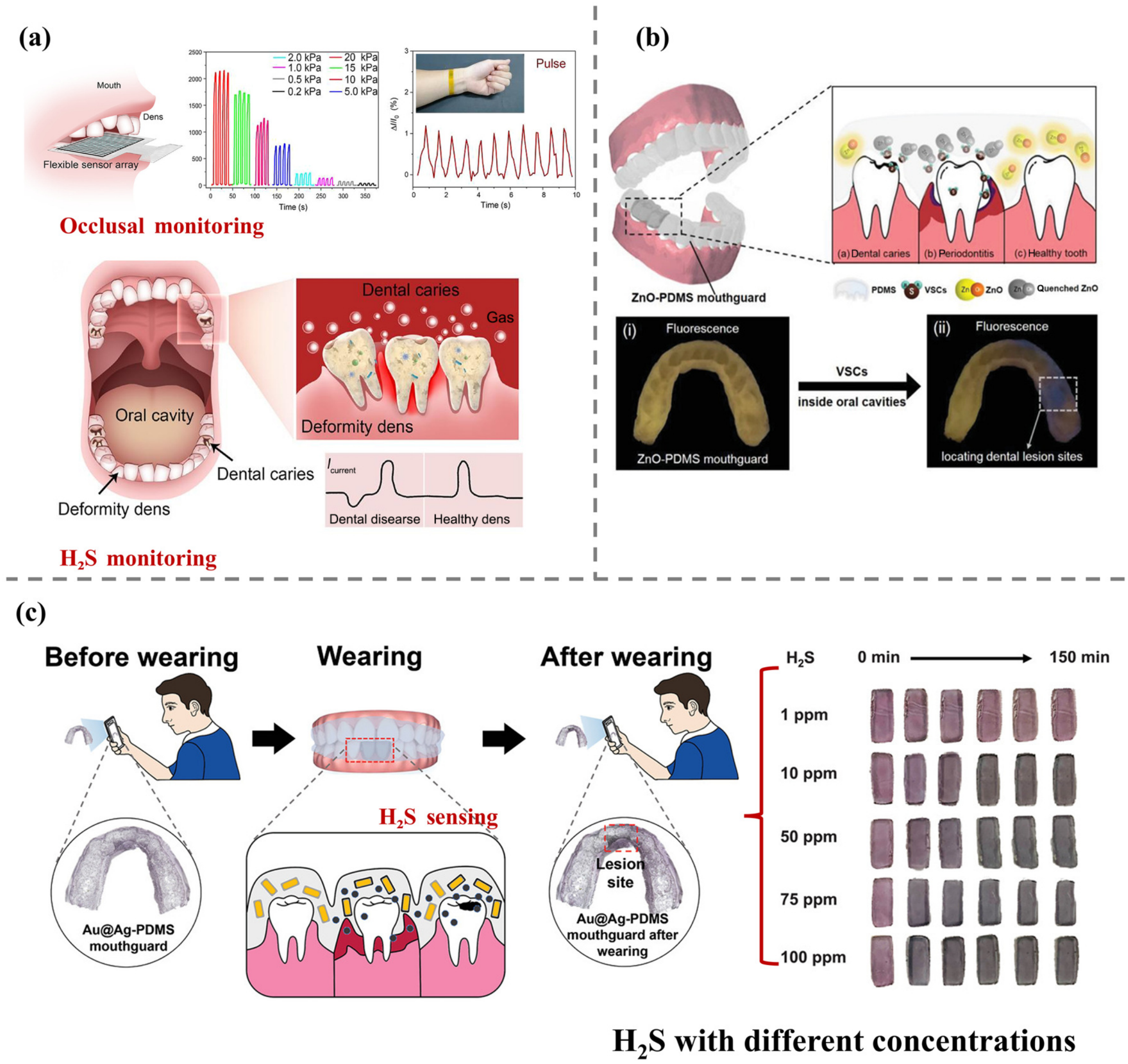

Figure 10 (a) Flexible sensor designed for site-specific monitoring of NH_3. Reproduced with permission from Ref. [255], © American Chemical Society 2021. (b) A fluorescent mouthguard platform for volatile sulfur compound sensing. Reproduced with permission from Ref. [260], © WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 2020. (c) Au@Ag NRs-PDMS mouthguard for visual H_2S sensing at lesion sites. Reproduced with permission from Ref. [261], © Wiley-VCH GmbH 2022.

appliance (EMSA) proposed by Wang et al. [264] represents a promising prototype platform. This design cleverly converts daily chewing pressure into a localized piezoelectric field, thus eliminating the need for power supply. Animal experiments have confirmed that the system can significantly enhance tooth movement efficiency, with the potential to perform execution functions. More importantly, the electric field generated by the platform provides an energy foundation for integrating various diagnostic sensors (such as pH, mechanical, and biofilm sensors). This may be a feasible technological pathway for integrated diagnosis and treatment, achieving true closed-loop management (Fig. 11(a)).

Further illustrating the concept of integrated diagnosis and therapy, Park et al. [265] developed a functional polysilsesquioxane (PSQ) coating (Fig. 11(b)). This coating essentially forms a "static" diagnostic-therapeutic system. The quaternary ammonium ions on the coating surface can effectively recognize negatively charged bacteria, adsorb, and kill them. The bactericidal mechanism, triggered by long alkyl chain-mediated membrane disruption, ultimately leads to bacterial lysis. Animal experiments showed that the appliance coated with this material significantly delayed plaque biofilm formation and maturation within two weeks.

Once dental caries progress into significant cavities, the process becomes irreversible and loses its self-limiting nature. Therefore, real-time monitoring and timely intervention are crucial for effective prevention. Shi et al. [266] designed a highly integrated, wearable, battery-free wireless diagnostic-therapeutic dental patch. (Fig. 11(c)). This device combines a pH monitoring system with an intelligently triggered drug delivery system, establishing a closed-loop diagnostic-therapeutic model. When a persistently acidic high caries risk oral environment is detected, fluoride is released in a controlled amount as needed, preventing the progression of orthodontic complications like caries.

Successful orthodontic treatment depends on the application of appropriate forces, which facilitate desired tooth movement through gradual remodeling of the periodontal tissues. In this process, orthodontic sensing primarily encompasses force sensing and biosensing: force sensing allows direct monitoring of orthodontic loads to prevent adverse effects from inappropriate force application, while biosensing assesses the health status of the teeth and periodontal tissues to provide objective parameters for

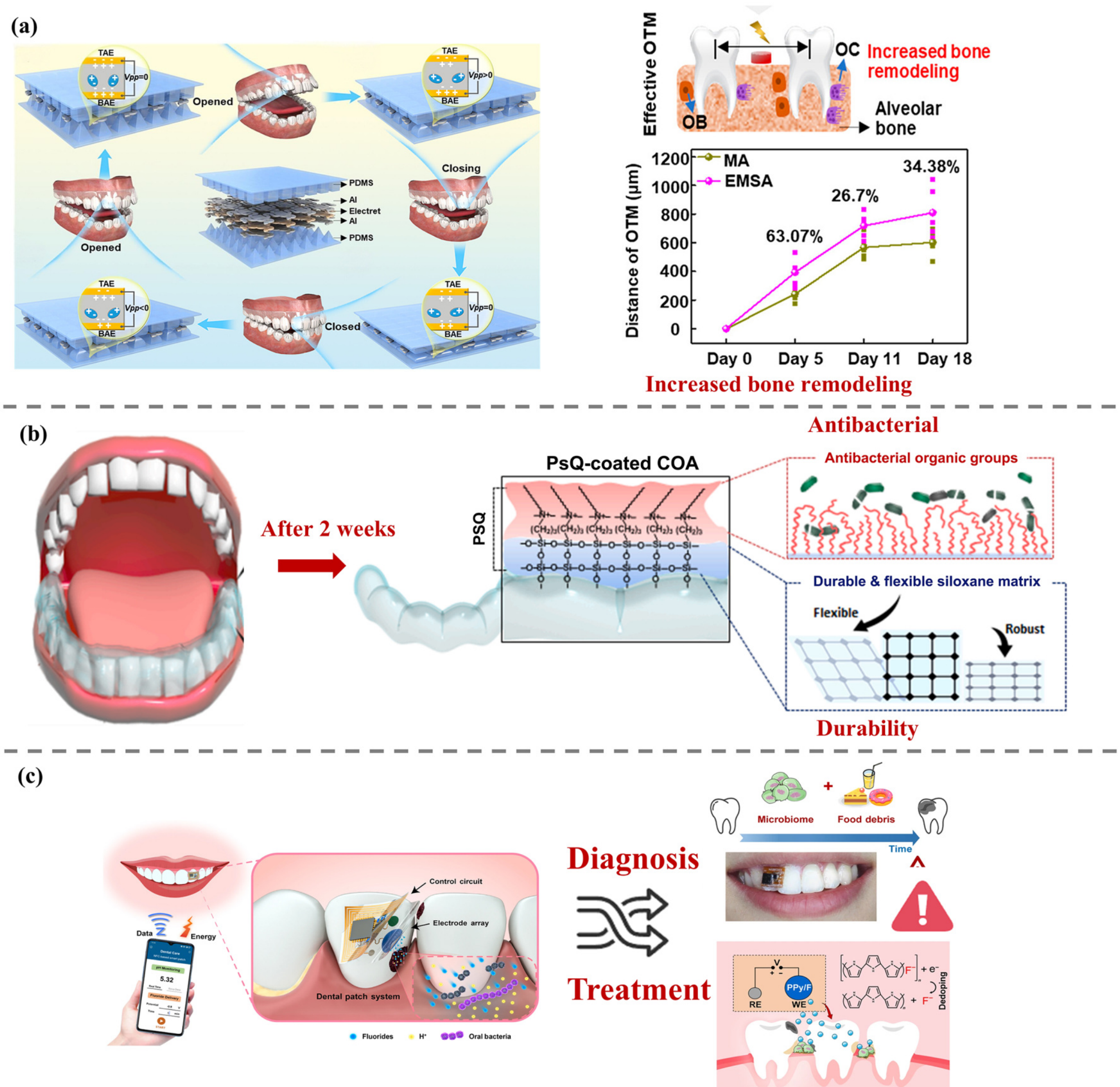

Figure 11 (a) Illustration showing the mechanism of an occlusion-activated piezoelectric synergistic aligner (EMSA) for enhanced tooth movement. Reproduced with permission from Ref. [264], © American Chemical Society 2023. (b) Antimicrobial and wear-resistant PSQ-coated clear aligner. Reproduced with permission from Ref. [265], © Elsevier B.V. 2021. (c) Wearable dental patch platform with combined diagnostic and therapeutic capabilities. Reproduced with permission from Ref. [266], © Shi, Z. H. et al. 2022.

safe orthodontic treatment. However, specific biomarkers capable of monitoring periodontal remodeling during orthodontic tooth movement have yet to be identified. Future developments will require breakthroughs in fundamental research to enable the design of highly specific biosensors capable of objectively evaluating the progression of orthodontic tooth movement. Ultimately, the integration of diagnosis and therapy represents the cornerstone of smart healthcare. Driven by big data and artificial intelligence, telemedicine, intelligent decision support, and real-time precision interventions will guide orthodontic practice toward a personalized and predictive era.

6 Typical applications

The design philosophy of orthodontic appliances is shifting from relying on clinical experience to relying on scientific data. This shift is reflected in the integration of real-time sensing and interactive features into the appliances. Nevertheless, mature products are still rare. A large body of academic research and patents outlines a possible path forward. Various integrated sensing methods for orthodontic appliances are presented here (see Table 2), with a focus on innovations in mechanical monitoring, biosensing, and compliance tracking. Most of these have not yet left the laboratory, but they provide direction for the development of next-generation precision orthodontic materials and devices.

As shown in Table 2, orthodontic appliances with integrated sensors have made significant progress over the past five years. Research has mainly focused on two directions: biosensing and force sensing. Furthermore, gas-sensing technologies are expected to become a significant focus in future research. The oral cavity is a naturally open ecosystem with a variety of bacteria, and volatile metabolites produced by microorganisms provide a basis for monitoring oral health. In the field of gas sensing, metal-organic frameworks (MOFs) possess great application potential owing to their large specific surface area and tunable pore size [267–269]. For example, detecting volatile organic compound (VOC) biomarkers in exhaled breath can enable the early diagnosis of lung cancer [270, 271]. Monitoring volatile organic compounds such as acetone,

Table 2 List of orthodontic braces with sensing function patents

Title	Publication number	Publication date	Medical function	Country
Orthodontic appliance performance monitor	US11612455B2	2020-02-13	Force sensing	USA
Customized aligner change indicator	US11779243B2	2020-07-09	Force sensing	USA
System for force measurement upon orthodontic appliances	US11992383B2	2022-12-28	Force sensing	USA
Orthodontic pressure real-time detection device integrated with MEMS sensor	CN119818222A	2025-04-15	Force sensing	China
An invisible aligner based on transparent piezoelectric film and its design method	CN119488373A	2025-02-21	Force sensing	China
Automated treatment staging for teeth	US11369456B2	2020-04-23	Force sensing	USA
Multilayer composite transparent dental floss based on pressure-sensitive deformation recognition and deformation recognition method thereof	CN115770116B	2024-01-23	Force sensing	China
Intraoral appliances with proximity and contact sensing	US10888396B2	2020-03-26	Compliance	USA
An invisible aligner device for monitoring wear time and treatment efficacy, and method thereof	CN112741699A	2021-05-04	Compliance	China
Orthodontic elastic monitoring methods and devices (duplicate family)	US20210128273A1	2021-05-06	Compliance	USA
A dental retainer for detecting periodontal hydrogen sulfide via MOF microporous adsorption and visual probes	CN120177447A	2025-06-20	Gas sensing	China
Tooth socket for monitoring human body physiological information and head movement data acquisition method	CN112773338A	2021-05-11	Biosensing	China
Wearable oral diagnostic and treatment device and manufacturing method thereof	CN120392029B	2025-09-16	Biosensing	China
Flexible intelligent sensing tooth socket	CN115211995A	2022-10-21	Biosensing	China
Biosensor performance indicator for intraoral appliances	US11576766B2	2020-07-09	Biosensing	USA
A smart retainer-based system for *in-situ* detection of periodontal status in individual teeth and dentition and its detection method	CN120531388A	2025-08-26	Biosensing	China
Embedded oral sensor platform	US12121368B2	2022-05-12	Multimodal sensing	USA

ethanol, ammonia, and other VOCs can facilitate the detection of systemic diseases, including diabetes [272]. MOF-based gas sensing technologies thus not only provide a novel approach for systemic disease screening but also offer promising directions for health monitoring in orthodontics. Additionally, patient compliance monitoring is another important research direction, which greatly determines the clinical outcomes of orthodontic treatment. Looking ahead, the development of orthodontic appliances lies in the integration of material properties with biosensing. The development of artificial intelligence technologies may accelerate this process, ultimately making orthodontic treatment more predictable, safer, and more effective.

7 Summary and outlook

The development of advanced orthodontic materials continues to confront substantial challenges. While metals, polymers, and ceramics have each contributed to transformative progress in orthodontic treatment, achieving fully intelligent therapeutics remains an unresolved goal. Metallic materials still pose issues of allergic potential and poor aesthetics. Among polymers, conventional resins lack the mechanical strength required for long-term use, and thermoplastics suffer from poorly defined 3D printing parameters. Meanwhile, high-performance ceramics face technical barriers such as sintering deformation and progressive friction increase over time.

The integration of sensor functions in orthodontic devices still faces many challenges. For instance, the long-term structural durability, biocompatibility, and power supply of such integrated systems must be rigorously validated. The lack of standardized production protocols, incomplete quality traceability systems, and stringent regulatory approvals (e.g., FDA certification) further hinder the translation from laboratory to clinical applications.

According to current trends, the development of future orthodontic devices will rely on the integration of multiple disciplines. For example, 4D printing can transform orthodontic devices from static to dynamic responses, allowing for self-adjustment based on the oral environment. Orthodontic devices are exposed to saliva and other oral fluids for extended periods, providing a unique platform for monitoring overall health, which is highly beneficial. It offers the potential for remote health management and early detection of conditions such as sleep apnea or diabetes. Especially when combined with artificial intelligence, it enables closed-loop treatment. For example, it can monitor and optimize orthodontic forces while collecting physiological data, achieving integrated diagnosis and treatment. In the future, these innovations may redefine orthodontic treatment, shifting from mere dental correction to proactive and comprehensive health management.

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

J. X. Z. and T. T. S.: Investigation, literature collection, formal analysis, writing manuscript. J. S. J.: Methodology, software, data validation, writing manuscript. H. P. R. and G. S. H.: Resource provision, data curation. Z. Z. and X. Y. L.: Conceptualization, supervision, project administration, funding acquisition. All authors have read and approved the final manuscript.

Use of AI statement

None.

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