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Original Research Article

Biosensor In Orthodontics: Biological feedback for precision therapy

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Abstract:

Background: Biosensor technology has become an innovative method for monitoring biological and mechanical parameters in healthcare. In orthodontics, integrating biosensors into diagnostic and treatment systems can offer real-time data on tissue responses, orthodontic forces, and patient compliance.

Objective: This scoping review aimed to map the existing evidence on biosensor technologies relevant to orthodontics and to identify their potential applications in clinical practice.

Methods: A structured literature search was performed across major scientific databases to identify studies investigating biosensors and sensor-based technologies related to orthodontic treatment monitoring. Studies focusing on biosensor applications such as biomarker detection, orthodontic force monitoring, compliance assessment, and oral habit detection were included. Relevant articles were screened according to predefined eligibility criteria, and key information regarding biosensor type, mechanism, and orthodontic relevance was extracted and synthesised.

Results: 17 studies met the inclusion criteria. The findings indicate that biosensors in orthodontics can be broadly categorised into biomarker-detection biosensors, orthodontic force-monitoring sensors, compliance-monitoring microsensors, and wearable intraoral sensors for monitoring oral habits. These technologies demonstrate potential for real-time monitoring of biological and mechanical parameters during orthodontic treatment.

Conclusion: Biosensors show promising potential to enhance orthodontic diagnosis, treatment monitoring, and patient management. However, most systems remain at an experimental stage, and further clinical research is required to establish their practical application in routine orthodontic care.

Keywords: Biosensors; Orthodontics; Wearable sensors; Salivary biomarkers; Orthodontic force monitoring; Patient compliance.

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Introduction

The oral cavity constitutes a critical interface between the human body's internal milieu and the external environment. As the primary entry point to both the respiratory and digestive systems, it facilitates the intake and initial processing of air, fluids, and nutrients, thereby playing a central role in the exchange of matter. Simultaneously, it functions as a dynamic protective barrier, equipped with anatomical structures and immunological mechanisms that help prevent microbial colonization and limit pathogenic invasion. This dual role underscores its significance in maintaining systemic homeostasis and overall health. (1)With recent advancements in biomedical technology, the introduction of innovative diagnostic aids and monitoring tools has enabled clinicians to assess biological processes in real-time. Among these innovations, biosensors have achieved significant attention in healthcare and dental research. A biosensor, if defined, is an analytical device that functions by combining a biological recognition element with a physicochemical transducer. This enables the detection of specific biological or chemical substances and converts them into measurable signals. This rapid, sensitive, and often non-invasive detection of biomolecules present in biological fluids such as saliva, blood, or gingival crevicular fluid makes them highly relevant for clinical monitoring and disease detection. (2)

At its core, a biosensor operates through a precise 'handshake' between a specific target molecule-the analyte-and a biological recognition element. This biological component, which can range from specialised enzymes and antibodies to nucleic acids or even whole cells, acts as the sensor's front line.

Once the analyte binds to this biological receptor, it triggers a localized biochemical reaction. The real magic happens next: a component called a transducer captures this reaction and translates it into a readable format. Depending on the sensor's architecture, this output might manifest as an electrical pulse, a change in light intensity, a shift in temperature, or a piezoelectric signal.(3) This conversion allows us to quantify complex biological data through clear, measurable metrics. The generated signal is further processed and amplified by a signal processing unit to provide quantitative or qualitative information about the analyte concentration. This mechanism enables biosensors to provide rapid and precise monitoring of biological changes associated with health and disease (4).

A typical biosensor consists of three fundamental components: the bioreceptor, the transducer, and the signal processing system. The bioreceptor is responsible for recognising the target analyte with high specificity. The transducer converts the biological interaction into a measurable physical signal, while the signal processor amplifies and interprets the signal to generate readable data for clinical interpretation. Together, these components allow biosensors to function as highly sensitive analytical tools for detecting biomarkers and monitoring physiological conditions. (5)

Types Of Biosensors

Biosensors can be broadly classified based on the type of transducer or the detection mechanism employed. The major categories include electrochemical biosensors, optical biosensors, piezoelectric biosensors, and thermal biosensors. Electrochemical biosensors are among the most widely used due to their high sensitivity, low cost, and compatibility with miniaturized devices. Optical biosensors detect changes in light properties such as fluorescence or absorbance, while piezoelectric biosensors measure changes in mass or mechanical vibrations during biomolecular interactions. Thermal biosensors, on the other hand, detect temperature changes resulting from biochemical reactions (4) (6).

In orthodontics, biosensors represent an emerging field with the potential to transform diagnosis, treatment monitoring, and patient compliance assessment. Biosensor-based technologies have been explored for monitoring orthodontic forces, detecting biomarkers associated with tissue response, evaluating patient compliance with removable appliances, and identifying biological markers linked to complications such as root resorption. The integration of biosensors with orthodontic appliances and wearable devices may allow clinicians to obtain continuous biological and mechanical data during treatment, thereby improving treatment efficiency and personalized patient care.

With the rapid development of biosensing technologies, orthodontics is gradually moving toward more precise and biologically driven treatment monitoring. Conventional orthodontic assessment methods rely primarily on clinical examination and radiographic evaluation, which often detect biological changes only after they have already occurred. Recent studies suggest that biosensor-based systems may allow orthodontists to monitor biological responses, appliance wear, and mechanical forces in real time during treatment (7).

From a clinical orthodontic perspective, the integration of biosensors into orthodontic appliances and wearable oral devices has the potential to improve treatment planning, patient compliance assessment, and early detection of treatment-related complications. For example, microelectronic sensors incorporated into removable appliances have demonstrated the ability to objectively record appliance wear time, enabling clinicians to evaluate patient compliance more accurately than self-reported data (8). Similarly, novel intraoral devices such as wireless mouthguard sensors have been developed to continuously monitor oral soft-tissue pressure and detect habits such as tongue thrusting that can influence orthodontic outcomes (9).

In addition to behavioural monitoring, biosensors have also been explored for measuring orthodontic forces directly within brackets or smart sensing devices embedded in orthodontic systems. These technologies allow real-time evaluation of force magnitude and direction, which could help clinicians optimise biomechanical control and reduce unwanted tooth movement or tissue damage (10). Furthermore, advances in biomarker detection using saliva and blood analysis have opened new possibilities for identifying biological markers associated with orthodontically induced inflammatory root resorption and other treatment-related tissue responses(11).

Therefore, the objective of this scoping review is to map and synthesise the current evidence on the application of biosensors in orthodontics. Specifically, this review aims to identify the types of biosensors investigated in orthodontic research, their mechanisms and clinical applications, and their potential role in improving diagnosis, monitoring, and personalised orthodontic treatment.

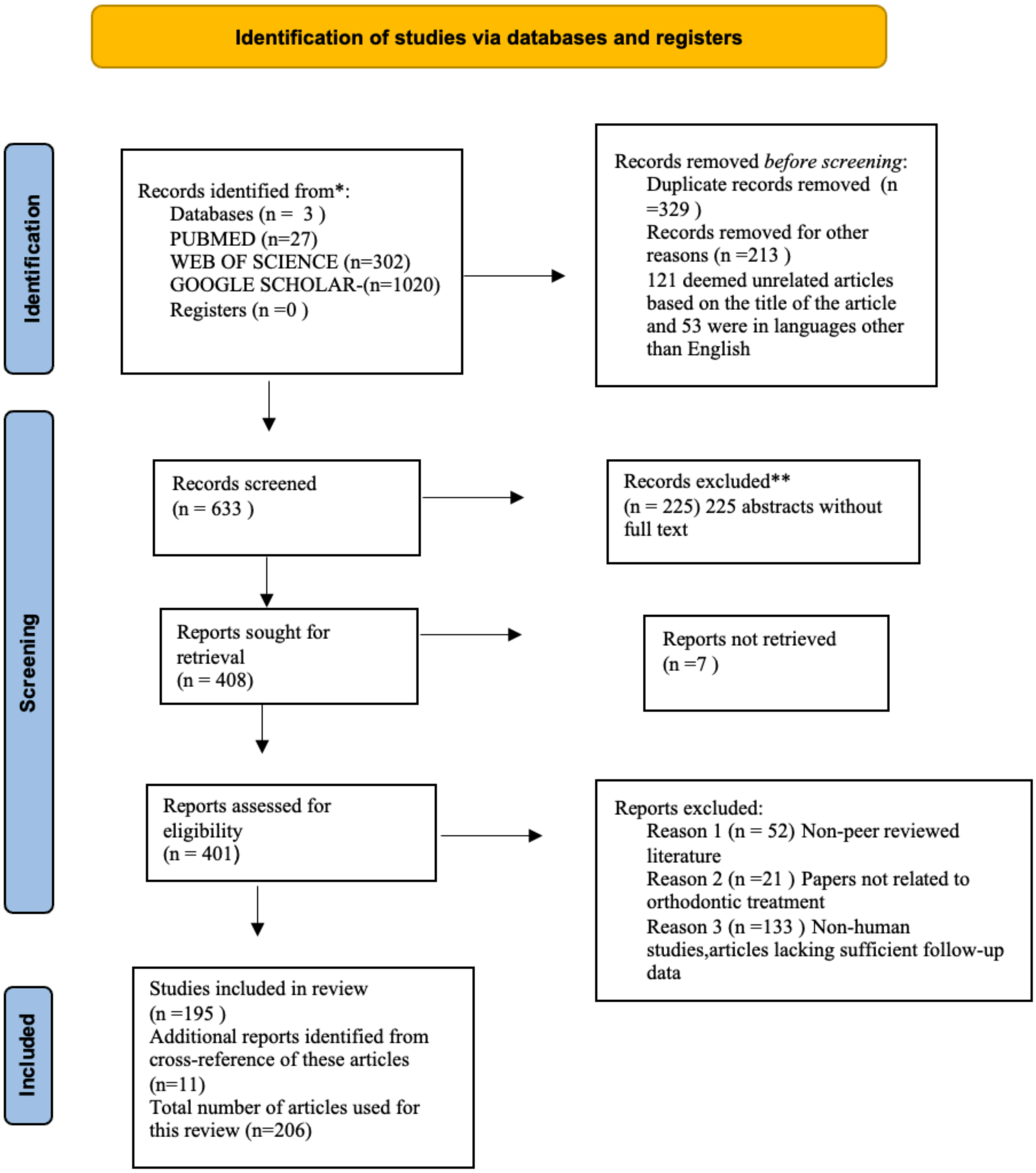
Methods

This scoping review was conducted to systematically map the existing evidence on the use of biosensors in orthodontics and to identify the current scope, applications, and research gaps in this emerging field. The methodology was designed following the general framework commonly used in scoping reviews, which involves systematic identification, selection, and synthesis of relevant literature.

Search Strategy

A structured literature search was carried out to identify studies related to biosensors and their applications. Relevant articles were identified from electronic scientific databases including PubMed, Web of Science, and Google Scholar. The search strategy combined keywords related to biosensing technology and orthodontics. The main search terms included combinations of **"biosensor," "wearable biosensor," "orthodontic biosensor," "smart orthodontic appliances," "force monitoring sensors," "salivary biomarkers,"** and **"orthodontics."** Boolean operators such as **AND/OR** were used to refine the search results and ensure that relevant studies were captured.

The search was limited to peer-reviewed articles published in English. The initial screening involved reviewing titles and abstracts to determine whether the articles were relevant to biosensor technology and orthodontic applications



(Fig 3- Depicts PRISMA flowchart)

Eligibility Criteria

For this scoping review, eligibility criteria were defined to ensure that the included studies were directly relevant to the application of biosensor technologies in orthodontics and related biological monitoring. The criteria were developed based on the scope of the articles selected for this review.

Inclusion Criteria

Studies were included in this review if they met one or more of the following criteria:

- Research articles describing the development, design, or application of biosensors or sensor-based technologies relevant to orthodontic practice.
- Studies investigating sensor-based monitoring of orthodontic forces, appliance performance, or biomechanical parameters during orthodontic treatment.
- Articles describing wearable or intraoral sensor systems used for monitoring oral habits, oral soft-tissue pressure, or patient compliance with orthodontic appliances.
- Studies exploring biological markers detected in saliva or blood that are associated with orthodontic treatment responses, such as orthodontically induced inflammatory root resorption.
- Articles evaluating biomarker identification, proteomic analysis, or biochemical monitoring techniques that could contribute to the development of biosensor-based diagnostic tools in orthodontics.

Exclusion Criteria

Studies were excluded if they met any of the following conditions:

- Articles unrelated to orthodontics or not relevant to biosensing, sensor technologies, or biomarker detection associated with orthodontic treatment.
- Studies focusing exclusively on general dental materials, restorative dentistry, or unrelated biomedical engineering topics without orthodontic relevance.
- Publications that did not provide primary scientific data or technological description, including editorials, commentaries, and non-research reports.
- Studies in which the technology described did not have potential application in orthodontic diagnosis, monitoring, or treatment evaluation.

These criteria ensured that the final set of included articles specifically addressed biosensor technologies and biological monitoring methods that may influence orthodontic diagnosis, treatment monitoring, or patient management.

Data Extraction and Analysis

Data from the selected studies were extracted and organized according to key variables relevant to orthodontic applications. These included the type of biosensor, sensing mechanism, biological or mechanical parameter measured, clinical application, and potential orthodontic significance.

The findings from the included studies were then categorized into thematic areas to better understand the range of biosensor technologies currently explored in orthodontics. Particular emphasis was placed on technologies that could support real-time monitoring of orthodontic forces, assessment of patient compliance, detection of oral habits, and identification of biological markers associated with orthodontic treatment outcomes.

Results

The search and screening process resulted in 22 articles that met the eligibility criteria for this scoping review. Analysis of these studies showed that biosensor technologies relevant to orthodontics can broadly be grouped into four major categories based on their sensing mechanism and clinical application: electrochemical biosensors for biomarker detection, mechanical force-sensing biosensors integrated into orthodontic systems, microelectronic temperature-based compliance sensors, and wearable intraoral pressure sensors. Across the reviewed literature, these technologies aim to improve real-time monitoring of biological responses, mechanical forces, and patient behaviour during orthodontic treatment.

Types of Biosensors in Orthodontic Applications

Biomarker-based biosensors

Several studies focused on biosensors designed to detect biochemical markers associated with orthodontic tissue responses. Electrochemical biosensors were the most commonly described mechanism in this category. These sensors operate by detecting biochemical reactions between the target analyte and a biological recognition element, producing an electrical signal proportional to the analyte concentration. Wearable electrochemical biosensors have demonstrated the ability to analyse biological fluids such as saliva and sweat for clinically relevant molecules.

Within orthodontic research, biomarker studies have investigated salivary proteins and inflammatory mediators associated with orthodontically induced inflammatory root resorption (OIIRR). Proteomic analyses have identified specific salivary proteins that may act as diagnostic markers for early detection of root resorption. Similarly, cytokines and other biochemical markers present in saliva and blood have been studied as indicators of inflammatory processes triggered by orthodontic tooth movement (12). The detection of such biomarkers through biosensor-based platforms may allow orthodontists to identify susceptible patients and monitor biological responses during treatment.

Orthodontic force-monitoring biosensors

Another important category identified in the reviewed studies involves mechanical biosensors designed to measure orthodontic forces directly within orthodontic appliances. These sensors are typically based on piezoresistive or flexible strain-sensing mechanisms, where deformation of the sensing material alters electrical resistance, enabling the measurement of applied mechanical forces.

Recent developments include smart flexible, three-dimensional sensors capable of measuring orthodontic forces in multiple directions. These devices consist of flexible sensing materials embedded within microelectronic circuits that convert mechanical deformation into electrical signals for real-time monitoring. Similarly, advanced bracket systems equipped with integrated sensing elements have been developed to measure force magnitude and direction directly at the bracket-wire interface(13). These technologies allow continuous evaluation of orthodontic biomechanics and may help clinicians apply optimal forces while minimizing adverse tissue responses.

Compliance monitoring biosensors

Patient compliance with removable orthodontic appliances remains a major challenge in orthodontic treatment. Several studies included in this review investigated microelectronic biosensors designed to objectively record appliance wear time. These devices commonly use temperature-based sensing mechanisms to determine whether the appliance is inside the oral cavity.

Temperature-sensitive microsensors embedded in removable appliances detect intraoral temperature levels and record wear time at regular intervals. The recorded data can then be downloaded and analyzed to determine daily appliance usage patterns (8). Similar technologies have also been used in Hawley retainers and functional appliances to quantify patient compliance during the retention phase 14 The mechanism is based on detecting the difference between intraoral temperature and ambient temperature, enabling accurate estimation of appliance wear duration.

Wearable intraoral pressure sensors

The literature also identified wearable intraoral biosensors designed to monitor oral functional habits and soft-tissue pressure. These devices are typically incorporated into mouthguards or intraoral appliances and use pressure-sensing mechanisms to detect forces exerted by the tongue, lips, or other oral structures.

Wireless mouthguard systems equipped with pressure sensors have been developed to continuously monitor oral soft-tissue pressure associated with habits such as tongue thrusting (8). These sensors convert mechanical pressure into electrical signals that can be transmitted wirelessly for real-time analysis. Such systems provide valuable information about functional habits that may influence orthodontic stability and treatment outcomes.

Telemetric smart bracket (TSB)

A telemetric smart bracket (TSB) represents an advanced orthodontic innovation in which a microelectronic chip embedded with piezoresistive stress sensors is incorporated into the bracket to facilitate real-time force assessment. The system detects mechanical stresses arising from the interaction of force and torque components transmitted through the archwire in six degrees of freedom, utilizing silicon-based piezoresistive sensing technology. The sensing unit consists of a complementary metal oxide semiconductor (CMOS) chip integrating 32 piezoelectric field-effect transistor elements, which are sequentially accessed via a 5-bit multiplexer for efficient signal acquisition. A planar spiral microcoil enables inductive coupling for wireless energy transfer and communication, while flip-chip bonding ensures compact integration of the chip–coil assembly within a small footprint. The acquired data are transmitted wirelessly to an external reader unit, where signals undergo demodulation, digitization, and decoding, allowing real-time visualization through a graphical interface. This system exhibits high measurement precision, achieving force resolution below 60 mN and moment resolution of approximately 0.14 N · mm (14).

Discussion

This scoping review synthesises evidence on biosensor technologies relevant to orthodontics and highlights their potential to reshape future orthodontic diagnosis, treatment monitoring, and patient management. Although innovations in medical technology are frequently adaptable to the oral environment, their translation into dental research has historically been delayed. This lag is exemplified by the emergence of publications on systemic biomarkers in dentistry during the 1970s over two decades after comparable advancements had already been reported in the broader field of medicine. Such a temporal gap underscores not only the slower integration of emerging diagnostic technologies into dental science but also reflects the unique biological, methodological, and clinical challenges inherent to the oral ecosystem, which necessitate additional validation before widespread application (15).

Orthodontic practice has traditionally relied on clinical examination, radiographic assessment, and patient-reported compliance to evaluate treatment progress. Although these methods remain essential, they often provide delayed or indirect information about biological and mechanical processes occurring during orthodontic tooth movement. Biosensor technologies offer the possibility of continuous, objective, and real-time monitoring of biological responses, orthodontic forces, appliance wear, and oral functional habits, which may significantly enhance the precision and predictability of orthodontic treatment

One of the most promising future applications of biosensors in orthodontics involves biomarker-based monitoring of biological tissue responses during orthodontic tooth movement. Orthodontic forces initiate a cascade of biological events within the periodontal ligament and alveolar bone, including inflammatory signalling, cytokine release, and bone remodelling. Several studies have shown that specific proteins and inflammatory mediators present in saliva and blood may reflect these biological processes. Proteomic investigations have identified potential salivary biomarkers associated with orthodontically induced inflammatory root resorption (OIIRR), suggesting that molecular diagnostics may enable early detection of treatment-related complications (11). Similarly, biochemical markers detected in saliva and blood samples have been correlated with susceptibility to root resorption during orthodontic treatment (12). In the future, biosensor-based diagnostic platforms capable of detecting these biomarkers chairside could allow orthodontists to monitor tissue responses continuously and personalize treatment mechanics accordingly.

Saliva has emerged as a particularly promising medium for biosensor-based diagnostics because it contains a wide range of proteins, enzymes, and metabolic compounds that reflect oral and systemic health conditions (15). Advances in wearable biosensor technologies have demonstrated the feasibility of detecting biochemical molecules directly in saliva using miniaturized sensing platforms (3),(4). For example, mouthguard-based biosensors have been developed for electrochemical detection of salivary metabolites such as uric acid, illustrating the potential of integrating biosensing systems directly into intraoral devices(16). Wearable chemical sensors capable of detecting biomarkers in body fluids such as saliva and sweat have demonstrated significant potential for non-invasive health monitoring and may be adapted in orthodontics to monitor biochemical changes associated with tooth movement and inflammation

These developments suggest that future orthodontic appliances could incorporate biosensors capable of continuously monitoring inflammatory mediators, metabolic markers, and other biological signals associated with orthodontic tooth movement.

In addition to biological monitoring, biosensor technologies may significantly improve the evaluation and control of **orthodontic forces and biomechanics**. The application of optimal orthodontic forces is essential for efficient tooth movement while minimizing complications such as root resorption or periodontal damage. Traditionally, orthodontists estimate force levels based on theoretical calculations and clinical experience. However, recent developments in sensor engineering have led to the design of flexible sensing devices capable of measuring orthodontic forces directly within orthodontic appliances. Flexible three-dimensional sensors have been developed that convert mechanical deformation into electrical signals, allowing real-time measurement of orthodontic forces in multiple directions (17). Similarly, smart orthodontic bracket systems equipped with integrated sensors have been proposed to measure force magnitude and direction during treatment (13). Such smart orthodontic systems may allow clinicians to continuously monitor biomechanical forces and optimize treatment mechanics in real time.

Recent advances in bioengineering and sensor design are enabling the development of miniaturized orthodontic monitoring systems that can be incorporated directly into appliances, allowing clinicians to obtain real-time information on biological and mechanical parameters during treatment.

Another important domain in which biosensor technology may influence orthodontic practice is **patient compliance monitoring**. The success of many orthodontic treatments—particularly those involving removable appliances and retention devices—depends heavily on patient cooperation. Historically, orthodontists have relied on patient self-reporting to estimate appliance wear time, which is often unreliable. Microelectronic temperature-sensitive sensors embedded within removable orthodontic appliances have demonstrated the ability to objectively record appliance wear time by detecting intraoral temperature changes (8)(18). These systems allow clinicians to accurately determine whether appliances are worn as prescribed and to differentiate between poor compliance and biological treatment limitations. Objective compliance monitoring may therefore improve treatment planning, patient motivation, and retention management.

Microelectronic systems capable of recording appliance wear behaviour have also demonstrated that objective monitoring of orthodontic appliance usage can provide valuable insights into patient compliance and help clinicians individualize treatment protocols.

Wearable biosensor technologies also provide new opportunities to monitor **functional habits and oral soft-tissue dynamics** that influence orthodontic outcomes. Functional disturbances such as tongue thrusting, abnormal swallowing patterns, and excessive muscular pressure can compromise orthodontic stability and contribute to relapse. Wireless mouthguard-based devices equipped with pressure sensors have been developed to continuously monitor oral soft-tissue pressure and tongue activity(9). These sensors convert mechanical pressure generated by oral musculature into electronic signals that can be transmitted and analyzed in real time. Continuous monitoring of oral functional patterns may help orthodontists identify detrimental habits early and integrate appropriate therapeutic interventions during treatment.

Beyond these specific applications, advances in nanotechnology, microelectronics, and wearable sensor systems are paving the way for **multifunctional biosensor platforms** capable of monitoring multiple physiological parameters simultaneously(4) (3,16,17). Such systems may eventually be incorporated directly into orthodontic appliances, allowing clinicians to monitor orthodontic forces, biochemical markers, temperature, and patient compliance within a single integrated device. Intraoral biosensors have already been investigated for systemic health monitoring using saliva-based diagnostic platforms, further demonstrating the versatility of oral biosensing technologies (15).

Another future direction for biosensor integration in orthodontics involves combining biosensor-generated data with digital orthodontics and remote monitoring technologies. As digital treatment planning, telemonitoring, and artificial intelligence become increasingly integrated into dental practice, biosensor data could be incorporated into digital platforms that allow orthodontists to monitor treatment progress remotely and adjust treatment protocols accordingly (18,19). Continuous monitoring of appliance wear patterns, force levels, and biological responses could provide valuable insights into treatment efficiency and patient-specific responses.

Although the potential benefits of biosensor technology in orthodontics are substantial, several challenges remain before these technologies can be widely implemented in clinical practice. Many of the biosensor systems described in the literature remain at experimental or prototype stages and require further validation through clinical trials. Additionally, issues related to sensor durability, miniaturization, biocompatibility, and long-term stability within the oral environment must be addressed. Ethical considerations related to patient data privacy and continuous health monitoring will also need careful consideration as biosensor-based monitoring becomes more prevalent.

Despite these challenges, the collective findings from the studies included in this review demonstrate that biosensors have the potential to significantly transform orthodontic care in the future. By enabling **real-time monitoring of biological responses, orthodontic forces, patient compliance, and oral functional habits**, biosensor technology may support a more predictive, preventive, and personalized approach to orthodontic treatment. Continued collaboration between orthodontists, biomedical engineers, materials scientists, and digital health specialists will be essential to translate these innovations from experimental research into clinically practical tools that enhance both treatment outcomes and patient care.

Limitations

1. **Limited orthodontic-focused research**

The number of studies specifically investigating biosensor applications in orthodontics is still limited, and much of the available literature consists of preliminary or laboratory-based research rather than large-scale clinical investigations.

2. **Heterogeneity of included studies**

Considerable variation existed among the reviewed studies in study design, biosensor type, target biomarkers or parameters, and outcome measures, which limited direct comparisons of findings and precluded quantitative synthesis.

3. **Early stage of technological development**

Many biosensor systems described in the literature remain in experimental or prototype phases, with limited in vivo validation in orthodontic patients.

4. **Small sample sizes**

Several studies were conducted using small sample populations or experimental models, which may limit the generalizability of the findings.

5. **Rapid technological evolution**

Due to the fast pace of advancements in biosensor technology, some recently developed platforms may not have been captured within the scope of this review.

6. **Limitations in the oral environment**

Despite these limitations, the present review emphasizes the expanding interest in biosensor-based technologies within orthodontics and highlights the necessity for multidisciplinary collaboration and high-quality clinical investigations to facilitate the translation of these emerging technologies into routine orthodontic care

Conclusion

This scoping review highlights the growing interest in biosensor technology and its potential role in advancing orthodontic diagnosis and treatment monitoring. The available literature indicates that biosensors can be used to detect biological markers, monitor orthodontic forces, assess patient compliance with removable appliances, and evaluate oral functional habits. These technologies offer the possibility of obtaining objective and real-time information about both biological responses and mechanical aspects of orthodontic treatment.

Although many of the currently reported biosensor systems are still in developmental or experimental stages, the findings suggest that they could play an important role in the future of orthodontic practice. The integration of biosensors into orthodontic appliances and wearable intraoral devices may allow clinicians to better understand tissue responses to orthodontic forces, identify potential complications at an earlier stage, and monitor patient behaviour more accurately. Such capabilities could support more individualized and biologically guided treatment approaches.

However, further research is needed before these technologies can be widely implemented in routine clinical practice. Future studies should focus on improving sensor design, ensuring long-term stability and biocompatibility within the oral environment, and validating these systems through well-designed clinical trials. Continued collaboration between orthodontists, biomedical engineers, and materials scientists will be essential for translating these innovations into practical clinical tools.

Overall, biosensor technology represents a promising direction for the evolution of orthodontics toward more precise, predictive, and personalized patient care

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