Integration of Biosensor-Embedded Mouthguards for Oral Health Surveillance: Current Advances and Future Directions

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Abstract
The advent of smart mouthguard technology marks a transformative milestone in personalised oral health monitoring. These devices integrate biosensing materials, microelectronics, and wireless communication platforms to enable real-time detection of biochemical and biomechanical changes within the oral cavity. Owing to its biomarker-rich and physiologically dynamic environment, the oral cavity provides an optimal site for continuous, non-invasive monitoring of both oral and systemic health. This review comprehensively examines the current advancements in smart mouthguard technology, with emphasis on design architecture, sensing modalities, and clinical applications in oral hygiene surveillance. Additionally, the integration of artificial intelligence (AI), remote monitoring networks, and electronic health record (EHR) systems is explored in the context of enhancing diagnostic precision and longitudinal data management. The review also addresses critical challenges related to biocompatibility, data security, and regulatory standardisation, while proposing future directions for clinical implementation. Smart mouthguards hold significant potential to redefine preventive dentistry by facilitating early disease detection, promoting patient adherence, and advancing precision-driven oral healthcare.

Keywords: Artificial Intelligence; Digital Dentistry; Oral Hygiene Monitoring; Saliva Biosensing; Smart Mouthguard; Wearable Sensors

INTRODUCTION

Oral hygiene is a fundamental determinant of both oral and systemic health, playing a pivotal role in preventing local inflammatory conditions and systemic comorbidities. Poor oral hygiene is a well-established etiological factor in dental caries, gingivitis, and periodontal disease, and has been strongly correlated with systemic disorders such as diabetes mellitus, cardiovascular disease, rheumatoid arthritis, and adverse pregnancy outcomes through shared inflammatory pathways [1]. Conventional oral health surveillance predominantly relies on periodic clinical examinations and patient-reported symptoms, which are episodic in nature and often subjective, thereby limiting the early detection of disease progression and reducing opportunities for preventive intervention.

The rapid convergence of digital dentistry and biomedical engineering has facilitated the emergence of wearable biosensor technologies**,** enabling continuous, real-time, and non-invasive monitoring of health parameters with superior diagnostic accuracy [1]. These technologies support the transition from a reactive clinical model toward personalised and predictive healthcare**,** where patient-specific data can be continuously analysed to detect subtle pathological changes before clinical manifestation. Wearable devices such as sensor-integrated toothbrushes, retainers, and intraoral prostheses are transforming dental diagnostics by extending care beyond the dental operatory through remote monitoring and digital health platforms [2]. Among these technological advancements, smart mouthguards have emerged as a superior intraoral monitoring platform due to their stable anatomical positioning, direct interaction with saliva, and ability to accommodate multiple biosensing modalities [2]. The oral cavity provides a favourable environment for biosensing applications, as saliva contains a rich profile of biochemical markers reflective of both oral and systemic health [3]. Smart mouthguards fabricated using biocompatible polymers can be embedded with electrochemical, optical, piezoelectric, or microfluidic sensors capable of detecting salivary pH, glucose, lactate, inflammatory cytokines, electrolytes, and mechanical stress. These sensors are further integrated with microelectronics, Bluetooth or NFC (Near Field Communication) based wireless communication systems, and AI (Artificial Intelligence) enabled data analytics, allowing seamless transmission to smartphones, cloud databases, and Electronic Health Records (EHRs) for remote clinician access.

In addition to passive monitoring, modern smart mouthguards can incorporate biofeedback mechanisms to modify patient behaviour by providing real-time alerts on bruxism, enamel erosion risk, or inadequate salivary buffering capacity. This dual functionality diagnostic and preventive positions smart mouthguard technology at the forefront of precision oral healthcare, with significant implications for early disease detection, continuous oral hygiene assessment, systemic disease screening, and patient adherence monitoring. As research continues to evolve, smart mouthguards are expected to become central to the digital transformation of dentistry, bridging the gap between clinical assessment and continuous health surveillance.

DESIGN AND WORKING PRINCIPLES OF SMART MOUTHGUARDS

Smart mouthguards represent an innovative class of intraoral wearable devices designed for real-time monitoring of oral hygiene and systemic health parameters through the integration of advanced materials, biosensors, and wireless electronic systems. Engineered for both comfort and functionality, these devices are fabricated from soft, biocompatible polymers such as polydimethylsiloxane (PDMS) or ethylene-vinyl acetate (EVA), ensuring safety and adaptability for long-term intraoral use [4]. Their material composition emphasises biocompatibility to prevent adverse tissue reactions, flexibility to conform to dental arches, resistance to enzymatic degradation by saliva, and mechanical durability during continuous wear. Emerging materials like (poly lactic-co-glycolic acid) PLGA, hydrogels for moisture retention and enhanced sensor integration, and flexible printed circuit boards capable of functioning in humid, variable environments further expand their utility. Depending on the diagnostic objective, smart mouthguards employ electrochemical, optical, piezoresistive, or capacitive sensing mechanisms to detect physiological and biochemical changes in the oral cavity [5]. For instance, Li et al. developed mouthguard sensors utilising zinc oxide quantum dots and Au@Ag nanorods to detect volatile sulfur compounds (VSCs) associated with dental caries, where fluorescence quenching or colourimetric shifts indicate early demineralisation.

Similarly, microelectromechanical systems (MEMS) embedded in orthodontic appliances have been used to measure three-dimensional forces during tooth movement, improving treatment precision and safety [1].
Saliva serves as a non-invasive diagnostic medium, rich in biomarkers such as pH, glucose, lactate, uric acid, fluoride, calcium, and inflammatory cytokines, enabling the monitoring of both oral and systemic health. Embedded electrochemical and optical sensors track plaque formation, biofilm dynamics, temperature changes indicative of inflammation, and mechanical parameters such as occlusal force or bruxism activity. Wear-time and motion sensors further ensure compliance tracking in therapeutic or research contexts. Wireless communication technologies, including Bluetooth Low Energy (BLE), Near Field Communication (NFC), and inductive coupling, facilitate seamless, low-power data transmission to mobile devices or cloud-based platforms for real-time analysis and feedback. Power management relies on miniature medical-grade batteries, wireless charging systems, and emerging energy harvesting solutions like piezoelectric and thermoelectric generators, which enable sustained, maintenance-free operation [6]. Through the integration of these systems with mobile applications and cloud analytics, smart mouthguards offer continuous, user-centred monitoring, personalised alerts, and remote consultation capabilities, marking a significant advancement toward preventive, data-driven oral healthcare and broader systemic health surveillance [7].

APPLICATIONS IN ORAL HYGIENE MONITORING

Smart mouthguards are increasingly being applied in diverse and clinically meaningful ways to enhance oral hygiene monitoring through advanced detection, biochemical analysis, and behavioural tracking systems. These intraoral devices integrate fluorescence, impedance, and electrochemical sensing technologies to detect plaque, biofilm, and salivary biomarkers while simultaneously providing real-time feedback for improved oral care compliance. Fluorescence- and impedance-based systems, such as the BLISS (Biosensing Integrated Smart System) platform, utilise safe blue light or bacterial porphyrin excitation to visualise and quantify biofilm accumulation, enabling non-invasive mapping of plaque formation within days of onset. Impedance sensors further enhance diagnostic precision by detecting electrical changes associated with bacterial film development [8]. These technologies not only support early detection but also offer immediate hygiene feedback to guide brushing behaviour and preventive care. In parallel, electrochemical and colourimetric mouthguard sensors, often using ZnO-PDMS (Zinc Oxide-Polydimethylsiloxane) or Au@Ag-PDMS composites, enable dynamic monitoring of salivary pH, hydrogen sulfide (H_2S), and other disease-related molecules, providing actionable insights into caries risk, gingivitis, halitosis, and mucosal inflammation. Some devices have demonstrated potential for tracking hydration status and inflammatory responses, allowing early clinical intervention. Functional applications include pressure and capacitive-based monitoring of bruxism and bite force, using PDMS or PMMA layers to assess occlusal dynamics and correlate with stress or sleep patterns. Additionally, dietary habit monitoring systems can measure acid exposure from frequent consumption of acidic foods or beverages, assisting in preventive counselling. Smart mouthguards also enhance compliance tracking in orthodontic and night guard therapies through embedded wear-time and motion sensors [9].

Recent innovations, such as salivary turbidity sensors employing LEDs and phototransistors, allow continuous measurement of saliva clarity as an indicator of hygiene, while integrated pressure sensors quantify bite forces for bruxism assessment. Comprehensive oral hygiene systems now combine multiple functions, detecting brushing motions, regulating oral fluid output, and providing feedback on technique to maximise cleaning efficacy. Moreover, devices equipped with volatile sulfur compound (VSC) and pH sensors can identify early dental caries or periodontal changes by detecting biomarkers such as interleukin-6 (IL-6), C-reactive protein (CRP), and matrix metalloproteinases, enabling the monitoring of inflammatory processes and therapeutic responses [10]. Beyond oral health, smart mouthguards capable of analysing salivary glucose, cortisol, and electrolytes establish valuable links between oral and systemic conditions like diabetes or stress, reducing reliance on invasive blood tests. Further, mouthguard-based monitoring of chewing behaviour, hydration, and nutrient intake through motion and pressure sensing contributes to personalised dietary planning and may support broader health management strategies, including obesity and metabolic disorder prevention [11].

Category	**Function / Target**	**Technology / Sensor Type**	**Key Findings / Outcomes**
Plaque & Biofilm Detection	Detects plaque and bacterial biofilm accumulation	Fluorescence-based (blue light, porphyrin excitation); Impedance sensors	Enables early, non-invasive visualisation of biofilm within 3 days; guides hygiene compliance
Real-Time Hygiene Feedback	Provides instant feedback on brushing and cleaning effectiveness	Optical / Impedance sensors with Bluetooth transmission	Enhances patient engagement and preventive oral care
Salivary pH & Biochemical Monitoring	Monitors salivary pH, glucose, lactate, fluoride, and H_2S	Electrochemical, colourimetric (ZnO-PDMS, Au@Ag nanorods)	Detects early caries, gingivitis, and halitosis; maps localised risk zones
Inflammation & Hydration Tracking	Detects dehydration and mucosal inflammation	Ion-selective and colourimetric sensors	Supports early diagnosis and clinical action
Bruxism & Bite Force Measurement	Monitors occlusal pressure and grinding behaviour	Pressure and capacitive sensors (PDMS/PMMA layers)	Quantifies bite force; correlates with stress/sleep quality
Dietary Habit Monitoring	Tracks acid exposure from food/beverage intake	pH and motion sensors	Identifies risk from acidic diets; supports counselling
Orthodontic / Night Guard Compliance	Measures wear-time and patient adherence	Movement and contact sensors	Ensures accurate tracking of device usage
Salivary Turbidity Monitoring	Measures clarity/turbidity as an oral hygiene indicator	LED and phototransistor light transmittance sensors	Detects salivary clarity from 1–4000 FTU
Periodontal & Caries Detection	Monitors biomarkers for inflammation and demineralisation	VSC, pH, and cytokine sensors (IL-6, CRP, MMPs)	Enables early detection of periodontal and carious lesions
Systemic Health & Metabolic Monitoring	Tracks glucose, cortisol, and electrolytes in saliva	Electrochemical biosensors	Links oral data to systemic conditions like diabetes or stress
Comprehensive Oral Hygiene Systems	Integrates brushing motion detection and fluid regulation	Multi-sensor smart systems	Improves brushing efficiency and technique feedback

INTEGRATION OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN SMART MOUTHGUARD-BASED ORAL HEALTH SYSTEMS

Machine learning (ML) and artificial intelligence (AI) are revolutionising personalised oral healthcare by enabling intelligent data analytics, device interconnectivity, and predictive modelling that support prevention, early diagnosis, and tele-dentistry. Modern smart mouthguards and oral devices continuously capture detailed data on brushing habits, plaque accumulation, salivary biomarkers, dietary behaviour, and occlusal dynamics, which AI algorithms analyse to deliver personalised hygiene recommendations and preventive strategies tailored to each user's risk profile. These systems can automatically send reminders, progress summaries, and customised lifestyle tips, enhancing adherence, engagement, and overall oral health outcomes [12]. Integrated within Internet of Things (IoT) and mobile health (mHealth) ecosystems, smart mouthguards connect seamlessly to smartphones, digital apps, and cloud platforms, enabling real-time data transmission for both patient self-monitoring and professional oversight. By linking device-generated data to electronic health records (EHRs), these technologies promote longitudinal tracking, remote supervision, and integration of oral health information into comprehensive health profiles. Tele-dentistry platforms powered by AI and ML allow clinicians to assess oral health remotely, monitor disease progression, and offer timely interventions, which is particularly beneficial for underserved and rural populations [13]. Advanced predictive models utilise variables such as plaque indices, wear patterns, salivary composition, and microbiome data to forecast individual risk for caries or periodontal disease, frequently outperforming conventional diagnostic indices. These predictive capabilities facilitate early, personalised intervention and optimise recall scheduling and patient management. However, challenges persist regarding interoperability between devices and EHR systems due to proprietary data formats and communication protocols, necessitating the development of standardised, secure frameworks for data exchange. Ethical considerations such as ensuring transparency, minimising algorithmic bias, and safeguarding patient privacy are equally vital as AI becomes more embedded in clinical decision-making [14].

DISCUSSION

Smart mouthguard technology holds transformative potential for oral hygiene monitoring and preventive dentistry. Compared to traditional diagnostic methods, mouthguard-based biosensors offer advantages such as real-time data acquisition, non-invasive sampling, and integration with digital ecosystems [4]. However, several challenges must be addressed before widespread clinical adoption. Technical limitations include miniaturisation of sensors, long-term stability in the humid oral environment, and power management for continuous operation. Ensuring biocompatibility and comfort without compromising signal quality is critical. Advances in flexible electronics, wireless charging, and nanomaterials may overcome these barriers. Data management and privacy are major concerns. As mouthguards transmit sensitive health data, compliance with data protection regulations and secure encryption is necessary. Clear patient consent and transparent data governance must be established. From an ethical perspective, equitable access to such technologies is vital to prevent widening the digital divide. Vulnerable populations may face challenges related to affordability, connectivity, or digital literacy [9]. Ethical frameworks should ensure inclusivity, accountability, and patient autonomy. Despite these challenges, ongoing research demonstrates a clear trajectory toward practical clinical applications. Integration of smart mouthguards with AI-driven analytics and cloud-based platforms could redefine preventive dental care and support precision health approaches [15].

CONCLUSION

Smart mouthguards represent a promising frontier in digital dentistry, offering continuous, non-invasive monitoring of oral hygiene and related health indicators. Through the combination of advanced biosensing, wireless communication, and AI-assisted analysis, these devices have the potential to revolutionise disease prevention and personalised oral healthcare. Addressing current limitations related to sensor stability, data security, and clinical validation will be key to translating this technology into routine dental practice. As research and innovation continue, smart mouthguards could become indispensable tools for promoting oral and systemic health.

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