

“Oral Wearables- The Future of Smart Dentistry”

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ABSTRACT

Oral wearable devices represent a groundbreaking advancement in dental and systemic health monitoring, offering real-time, non-invasive tracking of oral conditions and overall well-being. These devices leverage flexible electronics and biosensors to monitor oral hygiene, detect disease biomarkers, assess treatment progress, and provide early warnings for systemic conditions such as diabetes, cardiovascular diseases, and stress. With the integration of artificial intelligence (AI) and the Internet of Things (IoT), these wearables enhance preventive care, improve patient compliance, and facilitate remote monitoring. Despite their potential, challenges such as durability, biocompatibility, data security, and regulatory compliance remain critical considerations. This paper explores the types, applications, technological advancements, and future directions of oral wearable devices, highlighting their role in transforming dentistry and personalized healthcare.

Overview of wearable technology in oral health care

Dental, oral, and craniofacial health plays a crucial role in both physical and social well-being. Common diseases in this domain include cavities, gum disease, oral tissue disorders, misaligned teeth, and tumors affecting the oral or craniofacial regions. Treating these conditions can be time-intensive, disrupt daily life, and create significant financial strain. However, since most diseases progress slowly, early diagnosis and treatment can prevent worsening conditions, improve outcomes and quality of life, and reduce time and financial burdens.¹

Current diagnostic methods in dentistry rely heavily on manual examinations and imaging technologies. These approaches lack the capability for real-time, on-the-go monitoring and diagnosis, limiting their effectiveness for primary prevention. Moreover, monitoring treatment progress and recovery is often inconvenient and costly, discouraging patients from attending follow-up hospital visits. The absence of point-of-care diagnostic tools hampers efforts to maintain long-term oral health.²

Flexible medical electronics offer a promising solution for healthcare. These devices are built on soft and stretchable substrates that conform to the skin and provide non-invasive, continuous health monitoring. Their portability and ease of wear enable long-term monitoring of biophysical and biochemical signals without interrupting daily life, thus reducing costs and enhancing convenience. Flexible electronics are already widely used in various medical fields and are gradually being integrated into dentistry.^{3,4}

In the context of dental and craniofacial health, these devices can be adapted to suit the unique environment and properties of the oral cavity. They can monitor factors such as oral hygiene, orthodontic forces, and cancer biomarkers, allowing for timely health assessments and predictions. This innovation holds significant potential to prevent disease progression and improve prognosis while minimizing the impact on patients’ daily lives.⁵

Advances in material science, manufacturing processes, and signal transmission technologies have enabled wearable sensors to be applied to various body parts, including the skin, eyes, and oral cavity, allowing non-invasive monitoring of numerous physiological parameters. Among these, oral wearable sensors are particularly noteworthy for their ability to continuously track physical and chemical conditions in the oral cavity, supporting effective health management. Unlike sensors used on the skin or eyes, oral wearable sensors offer distinct advantages, such as uninterrupted monitoring without hindering the user's movement. The oral cavity presents distinct advantages for wearable sensors, making it an ideal location for addressing various health and lifestyle needs.⁶

Firstly, the oral cavity is naturally accommodating to foreign objects, offering a high level of comfort for wearable sensors. Properly designed sensors have minimal impact on a user’s appearance or daily activities. In contrast, skin-mounted sensors can feel cumbersome and may restrict movement, while the sensitivity of the eyes makes them less suitable for such devices. Furthermore, the oral cavity’s stable, enclosed environment, especially during sleep, reduces external interference, enhancing the precision and reliability of the sensors.

Secondly, the oral cavity is vital for physiological functions, particularly the teeth, which are essential for eating and speaking. Dental diseases, such as cavities—the most prevalent global condition, according to the WHO's *Global Burden of Disease Study 2017*—can significantly impair these functions and lower quality of life. Untreated dental issues may lead to pain, bleeding, and even disfigurement. Oral wearable sensors in the oral cavity can monitor dental health, enabling early detection and prevention of disease while also supporting patients throughout treatment. Broad adoption of these sensors could reduce the global burden of dental diseases and ease pressure on healthcare systems and financial resources.⁷

Thirdly, saliva serves as a valuable medium for monitoring overall health, as it can reflect changes in both oral and systemic conditions. Substances from the bloodstream can enter saliva, offering insights into diseases beyond the oral cavity, such as stomach and lung conditions. For example, *Helicobacter pylori*, a marker for gastric ulcers and chronic gastritis, can be detected in saliva, and cortisol levels in saliva can indicate stress. Oral wearable sensors capable of analyzing saliva can provide comprehensive health assessments, addressing the growing demand for effective health monitoring.⁸

Lastly, as the starting point of the digestive system, the oral cavity plays a central role in food intake. Dietary habits and nutrient consumption have a significant impact on overall health. For instance, vitamins (A, B6, B12, C, D3, E) and minerals (zinc, iron) are crucial for a robust immune system. Oral wearable sensors can track food intake and help devise personalized dietary plans to prevent disease and support treatment. By facilitating healthier eating habits and lifestyles, these sensors make it easier for individuals to maintain their well-being.^{9,10}

On the other hand, wearable oral sensors face unique challenges compared to devices used on other parts of the body. These challenges arise from the specific conditions and demands of the craniofacial and oral environment:

1. **Frequent Movement and Friction:** The oral and craniofacial areas are subjected to constant motion due to activities such as speaking, chewing, and swallowing. These motions involve craniofacial muscles and the tongue, leading to frequent deformation and friction against surfaces such as the teeth and the tongue. Flexible electronics in these regions require exceptional durability and extensibility while maintaining strong adhesion to moist surfaces like the teeth, tongue, or craniofacial skin. Additionally, devices used inside the oral cavity must prevent accidental detachment, which could pose risks such as respiratory blockages. Comfort is also a priority, as these devices are worn for extended periods and must accommodate frequent facial movements.
2. **Material Biocompatibility:** The materials used in these devices must ensure high biocompatibility. Since they adhere to human tissues for prolonged durations, the substrates and adhesives should be gentle on the skin or mucosa, avoiding irritation or immune reactions. The oral cavity's connection to the digestive tract adds complexity, as these devices are exposed to acidic or alkaline substances from food, drinks, microbial activity, and enzymes in saliva. Materials must exhibit excellent chemical inertness, be encapsulated in inert biocompatible layers, or be non-toxic and edible, including their degradation products, to ensure safety if ingested.^{11,12}
3. **Environmental Stability and Functionality:** Flexible electronics must remain functional in the oral cavity's complex environment, which includes varying pH levels, enzyme-rich saliva, food and drink residues, and a high concentration of bacteria. This dynamic environment challenges the stability, selectivity, and sensitivity of these devices for accurate target detection and analysis. The presence of bioactive molecules and abundant bacteria further complicates the requirements for reliable and precise performance.

By addressing these specific needs, flexible electronics can effectively operate in dental, oral, and craniofacial applications, paving the way for advanced health monitoring and diagnostic solutions.¹³

Types and functions of intraoral wearable sensors

Physical sensors-

Physical sensors, like the accelerometer embedded in artificial teeth, can monitor oral activities such as chewing to track food intake, by analyzing tooth movements with the Fast Fourier Transform (FFT), they only monitor the frequency and timing of food intake, which is limited. Therefore, an ideal solution would be an integrated diet sensor system that utilizes chemical and physical sensing methods to monitor the time, frequency, food species, and nutrient contents of food intake in real time.¹⁴

Chemical sensors-

Chemical diet sensors are designed to monitor food ingredients and species by measuring changes in their levels in saliva during chewing. Sodium, a key element in controlling blood pressure and muscle function, has drawn particular attention due to its impact on health. Excessive sodium intake can lead to an increase in the risk of hypertension and cardiovascular diseases.¹⁴

For example, fiber-optic-based sensors can detect specific drinks like wine by analyzing changes in light absorption, while RF sensors monitor fluid intake by detecting changes in resonant frequency.¹⁴

Biosensors-

Oral wearable saliva sensors monitor metabolites like glucose, uric acid (UA), and lactic acid (LA) using enzyme-based electrochemical methods. These sensors correlate salivary and blood metabolite levels to provide non-invasive, real-time health monitoring.

Optical and electrochemical biosensors are used for salivary pH monitoring. A fully edible colorimetric sensor using fruit-based pH indicators allows safe, cost-effective, and visually observable pH detection.¹⁴

Motion sensors –

Recording of mandibular motion is being used to understand the normal jaw function and for the diagnosis and treatment of TMDs. Magnetometry-based approaches enable three-dimensional, occlusion-free measurements, providing reliable and reproducible data for tracking mandibular motion (TMM) in various settings. Modern systems employ miniature sensors, including optical, inertial, and magnetic technologies, as well as wireless jaw motion monitoring for enhanced accuracy and portability.¹⁵

Smart orthodontics –

Smart brackets allow dentists to learn the exact force applied to teeth rather than estimate by experience so that risks of orthodontic treatment caused by excessive force can be greatly reduced.¹⁴

Humidity sensors can be placed between teeth and brackets to detect bond breakage in orthodontics. Otherwise, bond failures can seriously delay the whole orthodontic treatment.¹⁴

Wearable devices could provide a level of unobtrusiveness not achievable with standard techniques and enable faster OSA screening with improved long-term characterization.¹⁴

Temperature sensors-

To diagnose peri-implant diseases and extend the lifespan of dental implants, a dental implantable temperature sensor can be utilized. Since temperature is a key indicator of inflammation, monitoring the local temperature near the implant serves as a crucial parameter for detecting and managing peri-implant diseases effectively.¹⁴

Applications in preventive dentistry and systemic health monitoring

3.1 Applications in Preventive Dentistry

Preventive dentistry emphasizes the importance of early detection, minimal intervention, and proactive oral hygiene practices for the maintenance of oral health.¹⁶ Digital wearable devices are one of the potential tools with various applications in preventive dentistry, as illustrated below:

i. Tracking Oral hygiene:

Wearable sensory devices such as smart toothbrushes and trackers monitor oral hygiene by gathering data on the determinants of oral hygiene, such as level of plaque and calculus,

brushing habits, brushing methods, pressure applied, etc.¹⁷ The data collected by these trackers provide insights into the actions required to improve dental hygiene, track oral hygiene progress, and thus empower people to engage in good oral hygiene practices.¹⁸

ii. Prevention of implant failures:

Common causes of implant failure, such as poor osseointegration and peri-implantitis, can be prevented using digital wearables. Sensors fitted to the implants monitor changes that impact the success of the implant, including the formation of new bone around the implant,¹⁸ detecting early signs of inflammation like temperature changes near the implant, identifying any microdisplacements between the implant components,¹⁷ and assessing the bite force.¹⁸ The identified information is transmitted to smartphones, alerting dentists to take prompt action to preserve the implant.

iii. Prevention of Muscular Disorders:

Wearable technology such as surface electromyography and mouthguard devices helps in recording the activity of masticatory muscles and gives real-time feedback on harmful oral parafunctional behaviours.¹⁹ The continuous real-time data and feedback provided by these devices encourage people to manage their parafunctional habits proactively,²⁰ aid in the early detection of muscle disorders such as bruxism¹⁹ and dysphagia²¹ and devise individualised rehabilitation approaches,²¹ thus preventing their progression to severe temporomandibular disorders.

iv. Early Detection of Dental Caries:

Wearable digital devices, such as dental patches, fluorescent mouth guards, etc., have been designed for the identification of early signs of caries, such as oral biofilm, PH of biofilm, PH of saliva, sugar intake, fluoride usage and volatile sulphur compounds released by pathogenic bacteria etc.²² These real-time data transmitted by the sensors can be tracked via smartphones, encouraging users to indulge in healthy eating habits and good oral hygiene practices. In addition, theranostic dental patches developed by researchers also have the drug-delivery feature of releasing fluoride, when necessary, thus providing effective dental caries detection as well as treatment.²³

v. Orthodontic applications:

Wearables such as smart brackets and digital aligners with wireless sensors incorporated into orthodontic appliances have various applications in orthodontics. These devices help in the real-time monitoring of orthodontic and bite forces²⁴ and three-dimensional force-movement systems²¹, thus enabling the gathering of real-time data for orthodontic research and improved clinical monitoring. This real-time monitoring helps in personalising the orthodontic forces to prevent adverse effects from uncontrolled tooth movements,¹⁴ improves compliance in patients with removable orthodontic appliances²⁵ and aids in accelerating orthodontic tooth movements.²⁶

3.2. Applications of Oral Wearables in Systemic Health Monitoring:

Salivary sensors have various applications in systemic health monitoring by analysing the saliva's pH, metabolites, and microorganisms.¹⁴ The salivary examination through wearable sensors serves as a non-invasive tool for the diagnosis of: Diabetes Mellitus in infants by monitoring the salivary glucose levels; hyperuricemia by monitoring salivary uric acid levels; stress by tracking levels of cortisol and other salivary stress markers; cancer by tracking levels of salivary TNF- α ; ^{27,28} fatigue by monitoring biomarkers such as creatine kinase and myoglobin; and neurodegenerative and demyelinating diseases by monitoring their biomarkers, such as acetylcholine; Gastroesophageal Reflux Disorders by tracking Salivary pH; and screening of drug abuse and toxic drugs etc.²⁹

Technological Integration of IoT and Artificial Intelligence in Dental Wearables

The Internet is a powerful tool used in all kinds of information systems. As we all know, the Internet has changed how we communicate, and as time has passed, many objects have come and connected to the Internet. Internet of Things (IoT) technologies can be defined as an amalgam of software and hardware products that can generate, gather, and compute data fundamentally in the form of binary digits. Artificial intelligence (AI) is the underlying automation mechanism behind these IoT technologies driving their applications and can be regarded as a distinguished field from IoT due to its intrinsic importance³⁰. The merging of AI and the IoT constitutes a rapidly advancing and transformative field known as AIoT (Artificial Intelligence of Things).³¹

Intelligent data analysis uses AI techniques to extract actionable insights from vast and complex datasets generated by IoT devices. Unlike traditional data analysis, it incorporates advanced algorithms such as machine learning and deep learning to make predictions by identifying patterns. AI-driven IoT is the use of AI technologies to enhance the capabilities of IoT systems. Traditional IoT primarily focuses on connectivity and basic data collection, on the other hand, AI-driven IoT leverages AI for real-time data processing, autonomous decision-making, and predictive analytics.³² Integration of AI and IoT is becoming increasingly important for success in today's fast-growing digital ecosystem.

The wearable Internet of Things (IoT) care system is an innovative and versatile application service system that can be worn on the body, and it helps to monitor and manage personal health. The system utilizes IoT technology and allows multiple sensors and devices to connect and communicate with each other, thereby enabling a variety of functions and applications.⁽³³⁻³⁸⁾

The development of the smart wearable physiological signal measurement and integration system is a promising solution for the healthcare industry. This system offers a comprehensive and real-time monitoring solution for patients or elderly individuals by integrating multiple physiological signal measurement technologies into a single wearable device and combining it with wireless transmission and location-based services. Additionally, the collected data can be stored in a database for further analysis and research purposes.

Through the integration of IoT and big data technologies, the system can provide valuable insights and enhance the overall efficiency and quality of healthcare services. The smart wearable physiological signal measurement and integration system serves as a practical and valuable tool for healthcare units and hospitals, thereby enabling them to enhance not only patient care but also patient safety. By connecting various smart devices through IoT technology and then integrating IoT with big data technologies, valuable data can be generated. This system can provide the most

complete, real-time service channels and demand information through the analysis of big data platforms. Therefore, the smart technology not only improves the efficiency of the original manual processes but also enables service management through an information platform. Furthermore, data analysis can enhance service quality and even lead to the development of innovative services.³⁹

In long-term care environments, the integration of artificial intelligence (AI) and wearable Internet of Things (IoT) systems holds significant potential by improving the quality of care and enhancing the well-being of individuals. One key advantage of integrating AI and wearable IoT systems is the ability to collect and analyze a wealth of physiological data including parameters such as heart rate, body temperature, blood oxygen level, and blood pressure, in real-time. Healthcare professionals can gain valuable insights into the health status of individuals by continuously monitoring these vital signs and detecting any abnormalities or changes that may require attention. This ultimately leads to better health outcomes by enabling early intervention and proactive care management.⁴⁰

The use of AI algorithms in analyzing the collected data enhances the capabilities of the wearable IoT system. AI algorithms can identify patterns, trends, and anomalies in the data, providing valuable diagnostic capabilities distinguishing between signal and noise. AI algorithms significantly enhance the quality of the signals by filtering out unwanted noise.⁴¹ Moreover, AI plays a vital role in improving the data normalization and transformation of wearable technology. AI algorithms can ensure that the data is easier to analyze and compare by converting data into a standard format. They can detect anomalies in data presented by the sensor, such as outliers or any missing data, and transform them to remove them, ensuring that the data is correct and reliable. Additionally, AI can personalize the data normalization and transformation processes of individual users by learning their behavior patterns.⁴²

IoT plays a crucial role in data collection and monitoring, while AI takes responsibility for analyzing the ever-growing volumes of data and making decisions based on the information extracted from this data. These applications offer many potential benefits for patients, healthcare providers, physicians, and healthcare facilities. However, the success of healthcare applications using technologies such as IoT and AI depends on the acceptance of these technologies by healthcare professionals and patients, the development of stronger and more uniform data security and privacy regulations, as well as the improvement of system efficiency and safety.³¹

Challenges and Considerations in Implementation

While the oral cavity holds great potential as a target for wearable sensors, their development remains far less prevalent compared to skin-based sensors.¹⁴ Temperature and stress significantly impact the stability of flexible sensors. The oral cavity, with its dynamic environment and frequent temperature fluctuations during functional activities, can further destabilize sensor materials. Additionally, the constantly moist or fluid environment can impair the functionality of biological receptors like enzymes, compromising the sensors' performance.⁴³ Reliability is another vital challenge for oral wearable sensors. The oral cavity's frequent physiological activities, such as talking, eating, and breathing, can compromise sensor performance. Additionally, saliva contains various contaminants, including charged ions, enzymes, and microorganisms, which can interfere with or damage the sensors. Despite significant advancements to enhance stability, anti-pollution, and anti-disturbance capabilities, current oral wearable sensors still fall short of user requirements.¹⁴

To address temperature effects, compensating elements like temperature sensors or temperature-insensitive materials can be utilized. Biofouling challenges can be mitigated with protective films to prevent biological contamination. Additionally, encapsulating key components, such as enzymes, within electrodes using 3D printing enhances packaging and prevents detachment.⁴⁴

Although considered "non-invasive," intraoral wearable devices pose potential risks of chemical exposure due to their proximity to the oral cavity. Electronic components like circuit boards and electrodes can be exposed to the oral environment, and even minor elements, such as solder, may risk accidental ingestion. Ensuring the biocompatibility of all materials is essential. Prolonged contact with the body also raises concerns about physical harm and allergic contact dermatitis reported with certain components.¹⁵

The advancement of flexible electronics requires integrating multiple technologies. A key challenge is limited durability because of the lack of long-term energy. Research shows that flexible electronics can harness energy from movements at the attachment site, providing continuous power for wearable devices.⁴⁵ The service life of sensors in the oral environment poses a significant challenge, impacting their cost, marketability, and widespread adoption. For oral wearable sensors integrated with dental implants, their lifespan must match that of the implants. However, no sensor with a sufficiently long service life to meet these requirements has been developed. The lifespan of oral sensors is influenced by factors such as detection methods, electronic components, usage frequency, and scenarios. A potential solution is a modular design, allowing components to be easily replaced when damaged, thereby extending the sensor's overall service life.⁴⁶

Another challenge is data transmission and power supply. Most oral wearable sensors rely on Bluetooth and RFID for data transfer. While Bluetooth enables real-time data transmission to smart devices, its size and power requirements pose challenges. RFID addresses size and power issues but only transmits data when the reader is active. Current power supply solutions, such as batteries or wireless transmission, struggle to meet safety and real-time monitoring needs. The selection of data transmission methods and power supply must align with the specific detection requirements of oral wearable sensors, based on human needs. Moreover, such devices should be capable of detecting multiple biomarkers simultaneously and monitoring physical, chemical, and biological signals. For monitoring biofluids like glucose or uric acid, enzyme-based electrochemical detection is recommended due to its high selectivity. However, the fragility and low stability of enzymes remain a significant drawback. Future research must identify or develop more suitable detection methods to advance the field of oral wearable sensors.^{14,15}

Wearable sensors enable real-time, multi-modal data collection but raise concerns about data security and privacy, hindering their widespread adoption. Developing hardware and software for wearable devices must prioritize security. Key issues include data compromise, unsecured communication, data theft, hidden components (like cameras or microphones), lack of encryption, and network vulnerabilities. Devices connecting to networks expose opportunities for data leaks, requiring strong security systems. Robust data security ensures reliable, secure operation with wireless transmission and connectivity. Reliable authentication, encryption, and early intrusion detection are crucial for protecting sensitive health data from both external and internal security breaches.¹⁵

Wearable technology remains largely unregulated, with most consumer devices not FDA-approved and classified as "wellness" products. Programs like the Digital Health Software

Precertification initiative are positive steps toward improved regulation.⁴⁷ Initiatives like the Digital Health Software Precertification Program aim to improve regulation. To foster medical innovation, the FDA has introduced a framework for utilizing real-world evidence in regulatory decisions. In the U.S., data protection for health information is governed by HIPAA, which mandates privacy guidelines for personal health data.¹⁴

Future Directions and Research Opportunities.

The integration of digital technology in oral healthcare is transforming the field, presenting exciting opportunities for innovation, research, and improved patient outcomes. Below is a detailed exploration of the potential future directions and areas for research.

Wearable Devices in Oral Care

Wearable devices are revolutionizing oral health monitoring by enabling real-time, personalized care.¹⁵ Orthodontic applications of wearables are particularly promising, with bio-integrated and implanted biosensors being explored for diagnosis, treatment, and oral health management.⁴⁸ Prior research has demonstrated the feasibility of attaching sensors to tooth surfaces, paving the way for future developments. However, for practical implementation, detailed validation studies focusing on biocompatibility, toxicity, sterilization, and operational stability are crucial. Innovations in device encapsulation and biocompatible materials are also needed to eliminate risks associated with salivary contact and chemical leaching.^{49,50,51}

Emerging materials like smart tattoos⁵² and soft epidermal electrodes offer the potential for enhanced biopotential acquisition.⁵³ Despite these advancements, further research is required to improve usability, durability, and overall user experience.¹⁷ Future wearable devices should enable continuous monitoring, operate on low power, provide real-time feedback, and integrate seamlessly into daily life without causing discomfort.⁵⁴

Technological Innovations in Oral Health

Technological advancements are reshaping oral healthcare. Systems like the Remote Oral Behaviors Assessment System (ROBAS)⁵⁵ have demonstrated high validity for monitoring brushing behaviors in real-world settings. Such systems can enable automated coaching and optimization of self-care practices on a population level.

Imaging technologies are also advancing, with Doppler ultrasonography being used to evaluate tissue perfusion at implant and donor sites.⁵⁶ Future imaging tools could provide precise 3D mapping of periodontal structures, allowing for non-invasive periodontal depth assessments. Additionally, flexible electronics are emerging as valuable tools for oral health monitoring and rehabilitation.⁵⁷ These devices, which combine materials science, physics, and clinical medicine, provide portable, non-invasive testing while minimizing interference with daily life.⁵⁸

Artificial Intelligence and Machine Learning in Dentistry

AI and machine learning can improve oral diagnostics, treatment planning, and public health interventions. AI can analyze large datasets and identify trends, predict disease outbreaks, and

suggest personalized treatment options. Machine learning algorithms can enhance diagnostic accuracy, predict treatment outcomes, and support evidence-based decision-making.⁵⁹

Despite these benefits, challenges such as ethical concerns, data security, and the lack of medical expertise among AI developers need to be addressed. Dental professionals have expressed reluctance to adopt AI due to its machine-based nature and its potential to replace traditional clinician-patient interactions. A hybrid model combining AI with human expertise could bridge this gap, preserving the human aspects of care while enhancing efficiency. Virtual dental assistants powered by AI can also streamline administrative tasks, maintain patient records, and assist with diagnosis and treatment planning.

Telehealth and Teledentistry

The COVID-19 pandemic outlined the importance of telehealth and teledentistry in providing accessible oral healthcare. Remote consultations allow dental professionals to diagnose, plan treatments, and monitor progress without the need for in-person visits. Digital imaging tools and teledentistry platforms enable patients to capture and share intraoral images, facilitating accurate diagnoses and follow-ups. This approach is particularly beneficial for underserved populations, as it reduces geographical and mobility barriers to care.⁶⁰

Big Data and Predictive Analytics

Big data analytics and predictive models are transforming public health dentistry by providing insights into oral health trends, risk factors, and disease patterns. These tools enable targeted interventions, resource allocation, and proactive public health strategies. Predictive analytics can also assist in forecasting disease prevalence and treatment outcomes, aiding in the efficient planning of healthcare resources.⁶⁰

Innovations in Smart Devices and AR/VR

The Internet of Things (IoT) and wearable devices are enhancing oral health monitoring and preventive care. Smart toothbrushes, oral health trackers, and sensor-based devices can collect real-time data on hygiene practices, dietary habits, and early signs of oral health issues. These devices offer personalized feedback, empowering users to improve their oral health while allowing dental professionals to deliver targeted interventions.

Virtual Reality (VR) and Augmented Reality (AR) technologies provide exciting possibilities for patient education, treatment planning, and professional training. VR can create immersive experiences to educate patients about oral hygiene and procedures, while AR can overlay digital information to improve precision in dental treatments and enhance clinical decision-making.⁶⁰

Ethical and Practical Considerations

As digital technologies become more prevalent in oral healthcare, ethical concerns such as data security, privacy, informed consent, and equitable access must be addressed. Ensuring transparency, safeguarding patient information, and bridging the digital divide are critical for the responsible adoption of these technologies. Moreover, maintaining the patient-provider relationship is essential to ensure trust and effective care delivery.⁶⁰

Collaboration and Future Outlook

The successful integration of digital technologies into oral healthcare requires collaboration among dental professionals, researchers, technology developers, and policymakers. Continued research and innovation are essential to tailor these advancements to the specific needs of oral health. By addressing the challenges and embracing digital solutions, the future of public health dentistry promises to be more efficient, accessible, and patient-centered.

In conclusion, the integration of wearable devices, AI, telehealth, and advanced technologies in dentistry has the potential to improve oral health outcomes, reduce disparities, and enhance overall well-being. With continued innovation and ethical implementation, the future of oral healthcare looks bright and promising.⁶⁰

Conclusion- Oral wearable devices play a remarkable role in monitoring and improving the overall health of patients as well as oral health. In dentistry, there are different oral wearable devices such as retainers, biosensors, and intraoral monitors which provide data to healthcare providers regarding patients' oral and systemic health and help in disease detection. These wireless devices, combined with artificial intelligence, enhance their accuracy and usability for patients and healthcare providers.

Despite their promising potential, there are a few challenges such as cost and biocompatibility. These challenges must be addressed to ensure greater patient compliance and widespread adoption.

In conclusion, oral wearable devices have the potential to transform personalized healthcare by allowing early disease detection, promoting preventive care, and enhancing treatment outcomes. With continued improvements, they can play a crucial role in linking oral and systemic health, leading to more proactive and efficient healthcare solutions.

References:

1. Peres MA, Macpherson LMD, Weyant RJ, Daly B, Venturelli R, Mathur MR, et al. Oral diseases: a global public health challenge. *Lancet*. 2019 Jul 20;394(10194):249-60. doi:10.1016/S0140-6736(19)31146-8. Erratum in: *Lancet*. 2019 Sep 21;394(10203):1010. doi:10.1016/S0140-6736(19)32079-3. PMID: 31327369.
2. Patil S, Khan SS, Hosmani J, Khan ZA, Muruganandhan J, Mushtaq S, et al. Identification of oral immune disorders - A review and a diagnostic algorithm. *Dis Mon*. 2023 Jan;69(1):101350. doi:10.1016/j.disamonth.2022.101350. PMID: 35337656.
3. Gao Y, Yu L, Yeo JC, Lim CT. Flexible hybrid sensors for health monitoring: Materials and mechanisms to render wearability. *Adv Mater*. 2020 Apr;32(15):e1902133. doi:10.1002/adma.201902133. PMID: 31339200.
4. Min J, Sempionatto JR, Teymourian H, Wang J, Gao W. Wearable electrochemical biosensors in North America. *Biosens Bioelectron*. 2021;172:112750. doi:10.1016/j.bios.2020.112750.

5. Yang Y, Gao W. Wearable and flexible electronics for continuous molecular monitoring. *Chem Soc Rev.* 2019;48(5):1465-91. doi:10.1039/C8CS00730A.
6. Gao W, Emaminejad S, Nyein HYY, Challa S, Chen K, Peck A, et al. Fully integrated wearable sensor arrays for multiplexed in situ perspiration analysis. *Nature.* 2016;529(7587):509-14. doi:10.1038/nature1652
7. Li , X., Lue, C., Fu, Q., Zhou, C., Rerelas, M., wang, Y., J., Wang, Y., Zhang, Y.S., Zhou, J., 2020.
8. Bhandodkar AJ, Wang J. Non-invasive wearable electrochemical sensors: a review. *Trends Biotechnol.* 2014;32(7):363-71. doi:10.1016/j.tibtech.2014.04.005.
9. Gleeson M, Nieman DC, Pedersen BK. Exercise, nutrition and immune function. *J Sports Sci.* 2004;22(1):115-25. doi:10.1080/0264041031000140590.
10. Sempionatto JR, Montiel VRV, Vargas C, Teymourian H, Wang J. Wearable and mobile sensors for personalized nutrition. *ACS Sensors.* 2021;6(5):1745-60. doi:10.1021/acssensors.1c00258.
11. Albrektsson T, Becker W, Coli P, Jemt T, Mölne J, Sennerby L. Bone loss around oral and orthopedic implants: an immunologically based condition. *Clin Implant Dent Relat Res.* 2019 Aug;21(4):786-95. doi:10.1111/cid.12793. PMID: 31134756.
12. Miron RJ, Bosshardt DD. OsteoMacs: key players around bone biomaterials. *Biomaterials.* 2016 Mar;82:1-19. doi:10.1016/j.biomaterials.2015.12.017. PMID: 26735169.
13. Fakhri E, Eslami H, Maroufi P, Pakdel F, Taghizadeh S, Ganbarov K, et al. Chitosan biomaterials application in dentistry. *Int J Biol Macromol.* 2020 Nov 1;162:956-74. doi:10.1016/j.ijbiomac.2020.06.211. PMID: 32599234.
14. Li Y, Tang H, Liu Y, Qiao Y, Xia H, Zhou J. Oral wearable sensors: health management based on the oral cavity. *Biosens Bioelectron X.* 2022;10:100135. doi:10.1016/j.biosx.2022.10013
15. Prasad S, Arunachalam S, Boillat T, Ghoneima A, Gandedkar N, Diar-Bakirly S. Wearable Orofacial Technology and Orthodontics. *Dent J (Basel).* 2023 Jan 10;11(1):24. doi: 10.3390/dj11010024. PMID: 36661561; PMCID: PMC9858298.
16. Balaji Ganesh S, Sugumar K. Internet of Things—A novel innovation in dentistry. *J Adv Oral Res.* 2021;12(1):42-48. doi:10.1177/2320206820980248.
17. Prasad S, Farella M. Wearables for personalized monitoring of masticatory muscle activity - opportunities, challenges, and the future. *Clin Oral Investig.* 2023 Aug;27(8):4861-4867. doi: 10.1007/s00784-023-05127-7. Epub 2023 Jul 6. PMID: 37410151.
18. Bornes R, Montero J, Correia A, Marques T, Rosa N. Peri-implant diseases diagnosis, prognosis and dental implant monitoring: a narrative review of novel strategies and clinical impact. *BMC Oral Health.* 2023 Mar 30;23(1):183. doi: 10.1186/s12903-023-02896-1. PMID: 36997949; PMCID: PMC10061972.

19. Dantas AMX, Lopes LW, Farias NDO, Silva HJD. Evaluating the use of wearables in the masseter and temporal muscles: a scoping review protocol. *Rev CEFAC*. 2023;25(1): e10522. doi:10.1590/1982-0216/2023251/10522.
20. Kantarcigil C, Kim MK, Chang T, Craig BA, Smith A, Lee CH, Malandraki GA. Validation of a novel wearable electromyography patch for monitoring submental muscle activity during swallowing: a randomized crossover trial. *J Speech Lang Hear Res*. 2020 Oct 16;63(10):3293-310. doi:10.1044/2020_JSLHR-20-00171. PMID: 32910735; PMCID: PMC8060014.
21. Flanagan D. Bite force and dental implant treatment: a short review. *Med Devices (Auckl)*. 2017 Jun 27;10:141-8. doi:10.2147/MDER.S130314. PMID: 28721107; PMCID: PMC5501108.
22. Dimitrova M, Kazakova R. Digital transformation in preventive dentistry: an overview of the role of technology in the evolution of preventive dentistry. In: *Leveraging Digital Technology for Preventive Dentistry*. 2024:25-54.
23. Salagare S, Prasad R. Internet of Dental Things (IoDT), intraoral wireless sensors, and teledentistry: a novel model for prevention of dental caries. *Wirel Pers Commun*. 2022;1-12.
24. Li P, Zhu L, Ding Y, Long Z, Yang Y, Pan J, et al. RF energy harvesting for intraoral orthodontic force monitoring. *Nano Energy*. 2024;121:109244. doi:10.1016/j.nanoen.2023.109244.
25. Wafaie K, Rizk MZ, Basyouni ME, Daniel B, Mohammed H. Tele-orthodontics and sensor-based technologies: a systematic review of interventions that monitor and improve compliance of orthodontic patients. *Eur J Orthod*. 2023 Jul 31;45(4):450-61. doi:10.1093/ejo/cjad004. PMID: 37132630.
26. Wang Q, Zhang J, Yao G, Lou W, Zhang T, Zhang Z, et al. Effective orthodontic tooth movement via an occlusion-activated electromechanical synergistic dental aligner. *ACS Nano*. 2023 Sep 12;17(17):16757-69. doi:10.1021/acsnano.3c03385. PMID: 37590490.
27. de Castro LF, de Freitas SV, Duarte LC, de Souza JAC, Paixão TRLC, Coltro WKT. Salivary diagnostics on paper microfluidic devices and their use as wearable sensors for glucose monitoring. *Anal Bioanal Chem*. 2019 Jul;411(19):4919-28. doi:10.1007/s00216-019-01788-0. PMID: 30941478.
28. Swetha P, Balijapalli U, Feng SP. Wireless accessing of salivary biomarkers-based wearable electrochemical sensors: a mini-review. *Electrochem Commun*. 2022;140:107314. doi:10.1016/j.elecom.2022.107314.
29. Pandit P, Crewther B, Cook C, Punyadeera C, Pandey AK. Sensing methods for stress biomarker detection in human saliva: a new frontier for wearable electronics and biosensing. *Mater Adv*. 2024.

30. Khan, J., Khan, J., Ali, F., Ullah, F., Bacha, J., & Lee, S. (2022). Artificial Intelligence and Internet of Things (AI-IoT) Technologies in Response to COVID-19 Pandemic: A Systematic Review. *IEEE Access, PP*, 1-1.
31. Gouiza N, Jebari H, Rekloui K. Integration of IoT-enabled technologies and artificial intelligence in diverse domains: recent advancements and future trends. *J Theor Appl Inf Technol.* 2024;102:1975-2029.
32. Marengo, A. (2024). Navigating the nexus of AI and IoT: A comprehensive review of data analytics and privacy paradigms. *Internet of Things (Amsterdam. Online)*, 27, 101318-. <https://doi.org/10.1016/j.iot.2024.101318>
33. Pace, P.; Aloï, G.; Gravina, R.; Caliciuri, G.; Fortino, G.; Liotta, A. An edge-based architecture to support efficient applications for healthcare industry 4.0. *IEEE Trans. Ind. Inform.* 2018, 15, 481–489.
34. Shukla, A.; Chaturvedi, S.; Simmhan, Y. RIoT Bench: An IoT benchmark for distributed stream processing systems. *Concurr.Comput.* 2017, 29, e4257.
35. Lu, Z.X.; Qian, P.; Bi, D.; Ye, Z.W.; He, X.; Zhao, Y.H.; Su, L.; Li, S.L.; Zhu, Z.L. Application of AI and IoT in Clinical Medicine: Summary and Challenges. *Curr. Med. Sci.* 2021, 41, 1134–1150.
36. Zajc, C.; Holweg, G.; Steger, C. System Architecture and Security Issues of Smartphone-based Point-of-Care Devices. In *Proceedings of the 2020 23rd Euromicro Conference on Digital System Design*, Kranj, Slovenia, 26–28 August 2020; pp. 320–324.
37. Sabban, A. New Compact Wearable Metamaterials Circular Patch Antennas for IoT, Medical and 5G Applications. *Appl. Syst. Innov.* 2020, 3, 42.
38. Shah, S.T.U.; Badshah, F.; Dad, F.; Amin, N.; Jan, M.A. Cloud-Assisted IoT-Based Smart Respiratory Monitoring System for Asthma Patients. In *Applications of Intelligent Technologies in Healthcare*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 77–86.
39. Wang WH, Hsu WS. Integrating Artificial Intelligence and Wearable IoT System in Long-Term Care Environments. *Sensors (Basel)*. 2023 Jun 26;23(13):5913. doi: 10.3390/s23135913. PMID: 37447763; PMCID: PMC10346723.
40. Li YH, Li YL, Wei MY, Li GY. Innovation and challenges of artificial intelligence technology in personalized healthcare. *Sci Rep.* 2024 Aug 16;14(1):18994. doi: 10.1038/s41598-024-70073-7. PMID: 39152194; PMCID: PMC11329630.
41. Shajari S, Kuruvinashetti K, Komeili A, Sundararaj U. The Emergence of AI-Based Wearable Sensors for Digital Health Technology: A Review. *Sensors (Basel)*. 2023 Nov 29;23(23):9498. doi: 10.3390/s23239498. PMID: 38067871; PMCID: PMC10708748.
42. Sree K.D., Bindu C.S. Data Analytics: Why Data Normalization. *Int. J. Eng. Technol.* 2018;7:209–213. doi: 10.14419/ijet.v7i4.6.20464.

43. Bandodkar AJ, Jeerapan I, Wang J. Wearable chemical sensors: present challenges and future prospects. *ACS Sens.* 2016;1(6):464-482. doi:10.1021/acssensors.6b00242.33) Luo, Y. et al. Technology roadmap for flexible sensors. *ACS Nano* 17, 5211–5295 (2023).
44. Luo Y, Abidian MR, Ahn JH, Akinwande D, Andrews AM, Antonietti M, Bao Z, Berggren M, Berkey CA, Bettinger CJ, Chen J, Chen P, Cheng W, Cheng X, Choi SJ, Chortos A, Dagdeviren C, Dauskardt RH, Di CA, Dickey MD, Duan X, Facchetti A, Fan Z, Fang Y, Feng J, Feng X, Gao H, Gao W, Gong X, Guo CF, Guo X, Hartel MC, He Z, Ho JS, Hu Y, Huang Q, Huang Y, Huo F, Hussain MM, Javey A, Jeong U, Jiang C, Jiang X, Kang J, Karnaushenko D, Khademhosseini A, Kim DH, Kim ID, Kireev D, Kong L, Lee C, Lee NE, Lee PS, Lee TW, Li F, Li J, Liang C, Lim CT, Lin Y, Lipomi DJ, Liu J, Liu K, Liu N, Liu R, Liu Y, Liu Y, Liu Z, Liu Z, Loh XJ, Lu N, Lv Z, Magdassi S, Malliaras GG, Matsuhisa N, Nathan A, Niu S, Pan J, Pang C, Pei Q, Peng H, Qi D, Ren H, Rogers JA, Rowe A, Schmidt OG, Sekitani T, Seo DG, Shen G, Sheng X, Shi Q, Someya T, Song Y, Stavriniidou E, Su M, Sun X, Takei K, Tao XM, Tee BCK, Thean AV, Trung TQ, Wan C, Wang H, Wang J, Wang M, Wang S, Wang T, Wang ZL, Weiss PS, Wen H, Xu S, Xu T, Yan H, Yan X, Yang H, Yang L, Yang S, Yin L, Yu C, Yu G, Yu J, Yu SH, Yu X, Zamburg E, Zhang H, Zhang X, Zhang X, Zhang X, Zhang Y, Zhang Y, Zhao S, Zhao X, Zheng Y, Zheng YQ, Zheng Z, Zhou T, Zhu B, Zhu M, Zhu R, Zhu Y, Zhu Y, Zou G, Chen X. Technology Roadmap for Flexible Sensors. *ACS Nano.* 2023 Mar 28;17(6):5211-5295. doi: 10.1021/acsnano.2c12606. Epub 2023 Mar 9. PMID: 36892156; PMCID: PMC11223676.
45. Mariello M, Quattieri A, Mele G, De Vittorio M. Metal-free multilayer hybrid PENG based on soft electrospun/-sprayed membranes with cardanol additive for harvesting energy from surgical face masks. *ACS Appl Mater Interfaces.* 2021;13(18):20606-20621. doi:10.1021/acsami.1c04795.
46. Yoon J, Joo Y, Oh E, Lee B, Kim D, Lee S, Kim T, Byun J, Hong Y. Soft Modular Electronic Blocks (SMEBs): A Strategy for Tailored Wearable Health-Monitoring Systems. *Adv Sci (Weinh).* 2018 Dec 20;6(5):1801682. doi: 10.1002/advs.201801682. PMID: 30886798; PMCID: PMC6402283.
47. Digital Health Software Precertification (Pre-Cert) Program. Available from:<https://www.fda.gov/medical-devices/digital-health-center-excellence/digital-health-software-precertification-pre-cert-program>.
48. Jacox LA, Mihas P, Cho C, Lin FC, Ko CC. Understanding technology adoption by orthodontists: A qualitative study. *Am J Orthod Dentofacial Orthop.* 2019 Mar;155(3):432-442. doi: 10.1016/j.ajodo.2018.08.018. PMID: 30826046.
49. Mannoor MS, Tao H, Clayton JD, Sengupta A, Kaplan DL, Naik RR, Verma N, Omenetto FG, McAlpine MC. Graphene-based wireless bacteria detection on tooth enamel. *Nat Commun.* 2012 Mar 27;3:763. doi: 10.1038/ncomms1767. Erratum in: *Nat Commun.* 2013;4:1900. PMID: 22453836.
50. Hashem M, Al Kheraif AA, Fouad H. Design and development of wireless wearable bio-tooth sensors for monitoring of tooth fracture and its bio metabolic components. *Comput Commun.* 2020;150:278-285. doi:10.1016/j.comcom.2020.03.005.

51. Li CY, Chen YC, Chen WJ, Huang P, Chu HH. Sensor-embedded teeth for oral activity recognition. In: Proceedings of the 2013 International Symposium on Wearable Computers; 2013 Sep 9-12; Zurich, Switzerland. p. 41-44.
52. Rodrigues D, Barbosa AI, Rebelo R, Kwon IK, Reis RL, Correlo VM. Skin-Integrated Wearable Systems and Implantable Biosensors: A Comprehensive Review. *Biosensors*. 2020; 10(7):79. <https://doi.org/10.3390/bios10070079>
53. Zhuang M, Yin L, Wang Y, Bai Y, Zhan J, Hou C, et al. Highly robust and wearable facial expression recognition via deep-learning-assisted, soft epidermal electronics. *Res*. 2021;2021:1-14. doi:10.34133/2021/7416825.
54. Nagele AN, Hough J, Dinnen Z. The subjectivities of wearable sleep-trackers: A discourse analysis. In: Proceedings of the CHI Conference on Human Factors in Computing Systems Extended Abstracts; 2022 Apr 30-May 5; New Orleans, LA, USA. p. 1-8.
55. Shetty V, Morrison D, Belin T, Hnat T, Kumar S. A Scalable System for Passively Monitoring Oral Health Behaviors Using Electronic Toothbrushes in the Home Setting: Development and Feasibility Study. *JMIR Mhealth Uhealth*. 2020 Jun 24;8(6):e17347. doi: 10.2196/17347. PMID: 32579118; PMCID: PMC7380983.
56. Tavelli L, Barootchi S, Majzoub J, Chan HL, Giannobile WV, Wang HL, Kripfgans OD. Ultrasonographic tissue perfusion analysis at implant and palatal donor sites following soft tissue augmentation: A clinical pilot study. *J Clin Periodontol*. 2021 Apr;48(4):602-614. doi: 10.1111/jcpe.13424. Epub 2021 Feb 3. PMID: 33465812; PMCID: PMC8058327.
57. Wang KN, Li ZZ, Cai ZM, et al. The applications of flexible electronics in dental, oral, and craniofacial medicine. *npj Flex Electron*. 2024;8:33. doi:10.1038/s41528-024-00095-3.
58. Devito KL, de Souza Barbosa F, Felipe Filho WN. An artificial multilayer perceptron neural network for diagnosis of proximal dental caries. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*. 2008 Dec;106(6):879-84. doi: 10.1016/j.tripleo.2008.03.002. Epub 2008 Aug 20. PMID: 18718785.
59. Tandon D, Rajawat J. Present and future of artificial intelligence in dentistry. *J Oral Biol Craniofac Res*. 2020 Oct-Dec;10(4):391-396. doi: 10.1016/j.jobcr.2020.07.015. Epub 2020 Jul 24. PMID: 32775180; PMCID: PMC7394756.
60. Srivastava R, Tangade P, Priyadarshi S. Transforming public health dentistry: Exploring the digital foothold for improved oral healthcare. *Int Dent J Student Res*. 2023;11(2):61-67.