Journal of Medical Devices Technology
jmeditec.utm.my

Review Article

Wearable and Implantable Devices in Chronic Disease Management: Addressing Emerging Challenges

Abdur Razzak Khan[1*], Vinukumar Luckose[1], Md. Firoz Kobir[2], Noor Farhana Halil Binti Abdul Razak[1], Md. Ariful Islam[3], Md. Matiur Rahman[3]

[1]Centre for Advanced Electrical & Electronic System (CAEES), Faculty of Engineering, Built Environment, and Information Technology, SEGi University, 47610 Petaling Jaya, Selangor, Malaysia
[2]Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[3]Department of Medical Physics, Khwaja Yunus Ali University, Enayetpur, Chauhali Sirajganj-6751, Bangladesh

ARTICLE INFO

Article History:
Received 14 May 2025
Accepted 30 July 2025
Available online 1 August 2025

Keywords:
Wearable devices;
Implantable devices;
Chronic disease management;
Remote patient monitoring;
Drug delivery;
Artificial intelligence;
Block – chain;
Quantum mechanism;
Healthcare technology;

ABSTRACT

The management of chronic diseases has increasingly leveraged emerging technologies to meet the growing demand for proactive and personalized healthcare solutions. Among these, wearable and implantable medical devices have shown substantial promise by enabling continuous physiological monitoring, real-time data collection, and personalized therapeutic interventions. These devices play a critical role in managing conditions such as diabetes, cardiovascular diseases, and respiratory disorders, empowering patients through self-monitoring and active participation in their care. This review explores the current landscape of wearable and implantable technologies in chronic disease management, emphasizing their roles in monitoring, diagnosis, and therapy. Key challenges are discussed, including data privacy and security concerns, device interoperability, long-term reliability, and patient adherence. Furthermore, this paper highlights the integration of advanced methodologies such as artificial intelligence (AI) for predictive analytics and tailored feedback, block-chain for secure and transparent data sharing, and quantum mechanisms for enhanced bio-sensing and smart drug delivery. By critically examining current advancements and unmet clinical needs, the review outlines future directions for the effective implementation of these technologies to improve patient outcomes and reduce healthcare system burdens through innovative, secure, and intelligent care delivery.

INTRODUCTION

Wearable and implantable technology has seen significant growth in the healthcare sector over recent years, becoming a valuable tool for individuals managing chronic health conditions. Chronic diseases, such as cardiovascular diseases, diabetes, respiratory disorders, and neurological conditions, are the leading causes of morbidity and mortality worldwide. The long-term nature of these conditions necessitates continuous monitoring, lifestyle adjustments, medication adherence, and timely interventions to prevent exacerbations and improve patient quality of life. Conventional healthcare systems typically depend on scheduled clinic appointments, which may fail to reflect the ongoing changes in chronic conditions and can pose challenges for patient convenience (Baharuddin et al., 2024). The advent of sophisticated wearable and implantable medical devices has revolutionized chronic disease management by enabling continuous, real-time physiological data acquisition outside of traditional clinical settings. Implantable devices for signal identification from damaged tissues represent a cutting-

* Abdur Razzak Khan (abdurrazzakkhan346@gmail.com)

Centre for Advanced Electrical & Electronic System (CAEES), Faculty of Engineering, Built Environment, and Information Technology, SEGi University, 47610 Petaling Jaya, Selangor, Malaysia

edge advancement in biomedical system, aimed at enhancing the diagnosis and monitoring of tissue injury and associated disorders. (Guk et al., 2019) proposed devices that can be implanted within the human body. These devices enable real-time monitoring of physiological signals such as electrical impulses, biochemical changes, and mechanical stress in specific areas. By identifying abnormal patterns or disruptions in cellular signaling, implantable sensors can provide valuable insights into the extent and nature of tissue damage. For instance, in neural or muscular injuries, implantable electrodes can detect disrupted electrophysiological signals, facilitating early intervention and personalized treatment strategies. Moreover, integration with wireless data transmission allows continuous monitoring and remote assessment by healthcare providers.

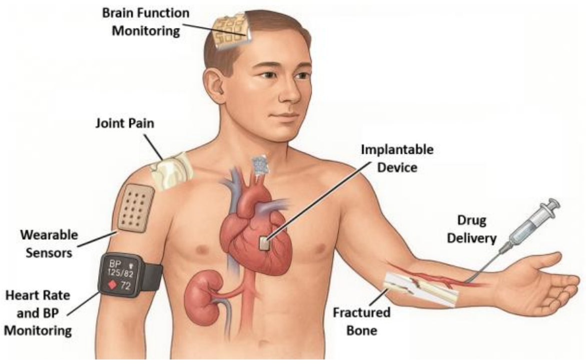

Figure 1 Schematic illustration of various wearable and implantable device for intelligent health monitoring system.

Technologies like fitness trackers, smartwatches, wearable biosensors, and biological antennas are developed to track various health parameters (Adeghe et al., 2024). These devices are intended to support continuous health monitoring and early detection of potential issues. Figure 1 shows the wearable and implantable devices for human health management. These intelligent device commonly tracked metrics include physical activity, heart rate, sleep patterns, calorie expenditure, damage organ, fractured bones and medication adherence. For individuals with chronic illnesses such as cancer, brain, diabetes, cardiovascular diseases, kidney disease, obesity, and asthma, these devices provide real-time feedback that can support lifestyle adjustments and treatment compliance. Wearable and implantable devices, for instance, can notify diabetic individuals of abnormal blood glucose levels, helping to prevent complications and enhance self-care (Ghazizadeh et al., 2024). As noted by (Yogev et al., 2023), implantable devices are surgically embedded in the body to enable continuous monitoring or deliver therapeutic functions, such as in the case of continuous glucose monitors, pacemakers, and neurostimulators. According to (Sim et al., 2022; Koydemir et al., 2018), implantable antennas and sensors are capable of detecting organ damage or bone fractures, aiding in the identification of abnormalities. A review on the use of wearable technology in managing respiratory conditions such as allergies and asthma revealed five important aspects. First, wearable devices are capable of monitoring symptoms in real time, which helps in receiving timely treatment. Second, this technology assists in identifying environmental and behavioural triggers responsible for the disease. Third, by tracking medication intake and adherence to treatment routines, wearable help improve patients' treatment compliance, ultimately increasing the chances of recovery. In their editorial (O'Keeffe et al., 2020), highlighted the significance of clearly differentiating between engaging in physical activity and spending extended periods in sedentary behavior. They stated that wearable technology is effective not only in increasing physical activity but also in reducing inactivity, which is associated with several health risks like obesity, diabetes, and heart disease. (Phillips et al., 2018), in a systematic review, showed that wearable technologies are highly effective in promoting physical activity among individuals managing chronic illnesses. In physical activity helps to improve the sleep quality. If someone faces trouble sleeping for any reason wearable device could also monitor sleep quality as well as calories burned, and other crucial health metrics. Another useful feature is medication reminders, which assist patients in staying consistent with their treatment plans by prompting them to take their medications on time. Wearable devices, as their name implies, are intended to be worn on the body, offering a non-invasive or minimally invasive approach to drug delivery.

A wide range of innovative wearable devices has been developed to support targeted and sustained drug delivery. These include microneedle-based skin patches (Yang et al., 2019), hydrogel-based drug reservoirs (Bagherifard et al., 2016), advanced wound dressings with functional properties (Mirani et al., 2017), intelligent bandages (Mostafalu et al., 2018), and drug-releasing contact lenses (Keum et al., 2020). Additional examples are polymer-based ocular inserts (Maulvi et al., 2016), personalized 3D-printed mouthguards (Liang et al., 2018), mucoadhesive patches for oral use (Colley et al., 2018), and contraceptive intravaginal rings, all highlighting the adaptability and effectiveness of wearable systems in modern drug delivery. Beyond disease prevention, wearable technologies contribute significantly to treatment by enhancing patient comfort and maintaining connectivity throughout the care process. Their capacity to deliver continuous health and vital sign data offers clinicians valuable insights for evidence-based medical decisions. For example, continuous glucose monitors have notably improved diabetes management in children by allowing around-the-clock blood sugar tracking without repeated finger-stick tests (Adepoju et al., 2024). (Greiwe et al., 2020) suggest that wearables have promising potential for routine integration into healthcare practices. Research by (Gresham et al., 2018) confirms the effectiveness of these technologies in remotely monitoring physical activity and digital health metrics across diverse environments. Nevertheless, despite their proven benefits and rising adoption, embedding wearables into standard clinical workflows remains a challenge (Phillips et al., 2018). Obstacles include concerns over measurement precision, sustained user engagement, complexities in interpreting data, absence of standardized formats, privacy and security issues, and high device costs-all of which can impact both short-term uptake and long-term utilization (John et al., 2012). Therefore, this study aims to provide a comprehensive overview of the current applications of wearable and implantable technology in chronic disease management, emphasizing opportunities for clinical integration and addressing the associated implementation challenges.

MATERIALS AND METHOD

Chronic Diseases Optimization Technique

Optimization in chronic disease management is becoming increasingly interdisciplinary, drawing on a broad range of fields including clinical expertise, advanced computational models, behavioral science, health informatics, and systems engineering. By integrating these diverse disciplines, healthcare providers can develop more effective strategies for early detection, continuous monitoring, and personalized treatment of chronic conditions. The ultimate goal is to transform chronic care into a more proactive, predictive, and patient-centered process that not only improves individual health outcomes but also enhances the efficiency and sustainability of healthcare systems.

Artificial Intelligence, Block Chain and Wearable Techniques

Emerging technologies such as artificial intelligence, block-chain, and wearable devices are increasingly being recognized for their transformative potential in managing chronic diseases. The integration of these tools into healthcare delivery has the ability to improve treatment effectiveness, personalize care plans, and reduce associated medical expenses. According to (Phillips et al., 2018), wearable technology allows for real-time monitoring of physical activity and other vital health parameters, aiding in the customization of treatment plans to suit individual requirements. Beyond basic monitoring, AI can be applied to analyze the continuous flow of data from wearable, offering deeper insights into disease trends and enabling early prediction of potential health events. Lu et al. highlighted the applications of AI in areas such as diagnosis, treatment design, and continuous patient monitoring using wearable devices. Additionally, block-chain technology plays a critical role in ensuring data privacy and security. With the increasing reliance on electronic health records, maintaining the integrity and confidentiality of patient information is essential. Block-chain provides a secure, tamper-proof system for storing medical data, fostering patient trust and compliance. Moreover, as (Xie et al., 2021) point out, block-chain can support reliable communication frameworks for telemedicine, which is becoming a key aspect of chronic disease care (Rowan et al., 2022). While wearable technology is already well-established in clinical settings, combining it with AI and block-chain offers innovative pathways to strengthen disease management and promote proactive healthcare delivery.

Quantum Sensing for Early and Accurate Diagnosis

Quantum mechanics holds significant promise for revolutionizing health monitoring through advancements in sensing, imaging, and computing. By applying the principles of quantum mechanics, researchers are developing tools and techniques that offer unmatched precision in detecting and treating disease. Using the principles of quantum mechanics, progressive quantum medicine technologies could overcome complex medical challenges with a new level of precision. The study show, use of quantum dots for bio-imaging, allowing them to trace specific proteins within cells and identify early signs of disease (Nabil et al., 2024). Early cancer screening, drug delivery as well as the remote health monitoring are the potential application of the quantum mechanism. Quantum sensors, for example, offer unprecedented sensitivity for detecting biomarkers and subtle changes in biological systems. Additionally, quantum computing can enable faster and more precise analysis of large datasets from wearable and medical devices, paving the way for personalized and proactive health management.

Chronic Disease Monitoring and Diagnosis

Cardiovascular Diseases: Wearable devices with photoplethysmography (PPG) sensors can track heart rate, variability, and detect arrhythmias like atrial fibrillation (AFib) (Sibomana et al., 2025). Advanced algorithms process PPG signals to estimate blood pressure trends, while continuous electrocardiogram (ECG) monitoring via wearable patches offers detailed cardiac data for early identification of arrhythmias and ischemic events (Chen et al., 2024). For example, smartwatches with built-in ECG features can accurately identify AFib, enabling prompt medical response.

Diabetes Management: Continuous glucose monitoring (CGM) systems, often considered a hybrid between wearable and implantable technologies, use minimally invasive sensors placed under the skin to deliver real-time glucose readings to a wearable receiver or smartphone (Chappon et al., 2019). This enables individuals with diabetes to monitor glucose levels continuously, identify trends, and make informed decisions regarding insulin management, diet, and physical activity. Wearable insulin pumps can be integrated with CGM systems to create automated closed-loop systems (artificial pancreas), adjusting insulin delivery based on glucose levels.

Chronic Kidney Disease: For chronic kidney disease (CKD), an integrated approach utilizing both wearable and implantable devices ensures continuous management (Han et al., 2024). Wearables such as smartwatches and activity trackers monitor key parameters like blood pressure, heart rate, activity levels, sleep, and weight fluctuations, helping to detect cardiovascular risks, fatigue, and fluid imbalances (Parker et al., 2023). These devices empower patients to self-monitor and adjust their lifestyle accordingly. Complementary implantable devices focus on advanced CKD complications, such as hemodynamic monitors in dialysis access sites to detect stenosis or thrombosis, ensuring the longevity of access points. Ongoing research explores implantable sensors in peritoneal dialysis catheters to enhance dialysis efficiency. Though fully implantable artificial kidneys are still under development, the combination of continuous non-invasive wearable monitoring and implantable devices targeting specific complications shows promise for improving the quality of life and outcomes for CKD patients (Kim et al., 2023).

Respiratory Disorders: Wearable sensors are used to monitor respiratory rate, oxygen saturation (SpO_2), and detect coughing patterns, which are critical for managing asthma and chronic obstructive pulmonary disease (COPD) (Sang et al., 2024). Smart inhalers with sensors track medication usage and provide reminders to improve adherence. Wearable chest patches also monitor lung sounds and breathing patterns continuously, potentially identifying early signs of exacerbations (Vitazkova et al., 2024).

Neurological Conditions: Wearable devices are being investigated to track symptoms associated with neurological disorders such as Parkinson's disease, epilepsy, and sleep disorders. Smartwatches and wristbands with accelerometers and gyroscopes monitor tremors, gait abnormalities, and motor fluctuations in Parkinson's disease (Moreau et al., 2023). EEG headbands detect brain activity to monitor seizures in epilepsy and assess sleep stages for sleep disorder management (Lehnen et al., 2025).

Fractured Bones Healing: The combined use of wearable and implantable devices provides a comprehensive approach to monitoring bone healing and rehabilitation (Pelham et al., 2017). Wearable devices like activity trackers and smart sensors monitor mobility, gait, and adherence to rehabilitation protocols, helping track recovery progress and prevent abnormal movements that could hinder healing (Liu et al., 2024). Implantable devices offer more detailed information directly at the fracture site, such as strain gauges and force sensors in internal fixation devices to measure the forces at the bone union site (Pelham et al., 2017). This data provides insights into the strength of healing and the safe timing for weight-bearing activities (Wang et al., 2024). Additionally, implantable biochemical sensors and miniaturized ultrasound devices are being researched for real-time monitoring of the healing process. Wearables give an overall view of the patient's activity, while implantable devices provide detailed biological and biomechanical data at the bone level.

Mental Health: Wearable devices indirectly monitor mental health by tracking physiological signals such as heart rate variability, sleep patterns, and activity levels, which can be influenced by stress, anxiety, and depression (Nasrin et al., 2025; Jolly et al., 2025). Some devices feature biosensors that measure electrodermal activity (EDA), which reflects the sympathetic nervous system's response (Chen et al., 2025). While these indicators are not direct measures of mental health, they provide valuable insights into an individual's well-being and can alert users to unusual patterns that may signal mental health concerns.

Chronic Disease Management Based on Telemedicine

According to a report by the World Health Organization (WHO), fewer than 50% of patients with chronic medical conditions in developed countries adhere to their prescribed medication regimens. Alarmingly, adherence rates are even lower in developing nations (Salim et al., 2024; Roos et al., 2023; Brown et al., 2011). Recent studies and surveys have shown that long-term adherence to prescribed medication among glaucoma patients ranges from only 30% to 37% over the course of a year (Feehan et al., 2016), with even lower rates approximately 25% observed in patients suffering from cardiovascular diseases (Brown et al., 2011). Moreover, poor medication adherence is not limited to the general patient population. Evidence suggests that even within the controlled environment of clinical trials, only 40% to 78% of participants follow their dosing schedules as prescribed (Osterberg et al., 2005). These statistics are deeply concerning, as continued non-adherence could lead to severe consequences for both healthcare systems and the broader economy if left unaddressed. Drug-delivering wearable devices (WDs), implantable devices (IDs), and hybrid wearable-implantable devices (WIDs) have recently emerged as patient-centric innovations for the management of complex soft-tissue-related medical conditions that require long-term and repetitive therapeutic intervention (Kar et al., 2022). Such conditions include diabetes, ocular disorders, cancer, wound healing, cardiovascular diseases (CVDs), and contraception (Pons-Faudoa et al., 2019; Wang et al., 2025). The development of safer and more effective drug delivery technologies is urgently needed to improve treatment outcomes for these chronic and recurrent condition. Telemedicine has become a fundamental component of contemporary healthcare, especially for managing chronic diseases. According to (Rowan et al., 2022) it offers improved accessibility to medical services, reduces healthcare expenditures, and contributes to better health outcomes. The role of wearable technology in supporting telemedicine is increasingly recognized. Wearable device enable continuous health monitoring by collecting real-time data on vital parameters such as blood pressure, heart rate, physical activity, and sleep patterns. This information helps clinicians track disease progression and identify early signs of complications, allowing timely intervention. Additionally, wearable empower patients to actively participate in their care by supporting treatment adherence and encouraging lifestyle modifications. The integration of wearable devices with telemedicine facilitates individualized care by aligning treatment plans with patient-specific health data. Introduced (Hirten et al., 2025), in managing inflammatory bowel disease (IBD), wearable device can record symptom patterns and transmit data directly to healthcare professionals, leading to timely adjustments in treatment and improved outcomes. Similarly, in chronic heart failure, monitoring heart rate and activity levels can alert physicians to early signs of deterioration, preventing hospital admissions. Telemedicine platforms further enhance this system by offering remote consultations and monitoring, ultimately supporting patient care while reducing costs. Furthermore, wearable technology has been effectively applied in managing conditions like asthma and allergies, as demonstrated by (Greiwe et al., 2020) who found that wearable can identify symptom triggers and monitor medication compliance. In stroke rehabilitation, studies by (Chae et al., 2020; Souza et al., 2022) introduced a smart watch-based rehabilitation system, which improved limb functions and daily living skills among stroke survivors. Wearable also show potential in increasing physical activity among older adults with chronic conditions through gamified health interventions. Noted (Hughes et al., 2023) that wearable devices combined with video games encouraged engagement and promoted better health among participants. Various wearable devices such as smart watches, rings, patches, and sensor-embedded garments can monitor physiological indicators like heart rate, blood pressure, blood oxygen levels, and VO_2 max (Hughes et al., 2023). These devices significantly enhance cardiovascular disease screening and management. Likewise, in diabetes care, integrating AI with modern sensors, pumps, and mobile applications has improved health outcomes by reducing hypoglycaemic episodes and increasing patient satisfaction. Despite challenges like data privacy, integration, and device cost, the combination of telemedicine, wearable devices, and AI represents a promising approach to the future of chronic disease management.

Advance Technology for Chronic Disease Management

In the context of chronic disease management, the integration of wearable and implantable devices with AI, block-chain, and quantum mechanics is revolutionizing patient care. Wearable sensors and implantable medical devices can continuously monitor vital parameters such as glucose levels, cardiac activity, blood pressure, and neural signals, offering real-time insights into disease progression. Artificial intelligence (AI) enables the interpretation of this massive data stream to detect anomalies, predict exacerbations, and guide personalized interventions with remarkable accuracy. Meanwhile, block-chain technology ensures secure, transparent, and decentralized data sharing across healthcare providers, safeguarding patient privacy while enabling seamless continuity of care. Quantum mechanics, though still emerging, promises enhanced precision in bio-sensing and ultra-fast processing of complex datasets from these devices, potentially accelerating diagnostics and therapeutic responses. Together, these technologies form an intelligent, secure, and responsive ecosystem that empowers proactive chronic disease management and improves patient outcomes.

Enhancing Patient Trust and Participation in Advanced Health Technologies

To ensure widespread adoption of wearable health technologies, establishing patient trust is crucial. A major barrier to trust involves concerns about data privacy, especially when artificial intelligence (AI) is integrated into healthcare systems. Healthcare providers must be knowledgeable about data security protocols, clearly communicate these measures to patients, and regularly update their systems to safeguard patient information. Empowering patients by granting them control over their personal health data can significantly strengthen trust. Moreover, enhancing digital literacy among both patients and healthcare professionals through structured education and training is essential (Ginsburg et al., 2024). To avoid exacerbating health inequities, efforts must be made to ensure that wearable technologies are affordable, internet connectivity is reliable, and collaboration between the public and private sectors is prioritized to close the digital divide. This divide often disproportionately impacts underserved and marginalized communities. Digital health technologies hold the potential to transform modern healthcare by enabling personalized and data-driven treatment plans. However, healthcare institutions must uphold patient autonomy and maintain strict adherence to privacy regulations to ensure ethical use of these technologies. Additionally, while the implementation of electronic health records (EHRs) has improved documentation and tracking, it has also introduced significant administrative burdens for physicians. Studies show that doctors now spend only 33% of their time on direct clinical care, while nearly half is consumed by administrative and EHR-related tasks often dedicating two hours to clerical work for every hour spent with patients (Reisman et al., 2017). This imbalance highlights the need for streamlined digital workflows that enhance productivity without compromising patient care.

RESULT AND DISCUSSION

While wearable and implantable devices have shown immense potential in chronic disease management, their integration with advanced technologies like artificial intelligence (AI), block-chain, and quantum mechanisms presents both opportunities and challenges that must be strategically addressed. One of the primary concerns is the accuracy and reliability of AI-driven health insights, which depend on robust data inputs and algorithmic transparency. Inadequate or biased training data can lead to misinterpretation, ultimately impacting patient outcomes and trust. User engagement also remains a critical factor, as the effectiveness of these devices depends on consistent usage and adherence. AI can offer personalized interventions to improve compliance, but these solutions must be ethically designed and accessible to all populations. Data privacy and security, particularly when using block-chain for health record management, demand standardized protocols and international interoperability to prevent data silos and unauthorized access. Though block-chain can enhance data integrity and patient ownership, scalability and high energy consumption remain limiting factors in real-time applications.

In the case of quantum-enhanced wearable, the technology is still in nascent stages but promises superior sensing capabilities and secure communication. However, the technical complexity, high cost, and need for infrastructure upgrades make immediate adoption challenging. Furthermore, inconsistencies in global regulatory frameworks, especially in data governance and AI use in healthcare, create disparities and legal uncertainties across borders.

Misconceptions and misinformation-such as exaggerated claims or health risks associated with wearable-continue to hinder public trust. Additionally, technical limitations, including short battery life, limited encryption, and unreliable connectivity, further complicate adoption. Without comprehensive regulatory oversight, transparent validation standards, and equitable access, these advanced technologies may exacerbate health inequalities rather than resolve them. Despite these concerns, the convergence of AI, block-chain, and quantum mechanisms offers a promising frontier for next-generation health monitoring. To achieve wider adoption, stakeholders must focus on building trustworthy systems that ensure data accuracy, protect privacy, promote patient engagement, and uphold ethical standards. Addressing these critical challenges will shape the future of smart health technologies for chronic disease management.

CONCLUSION

The integration of wearable and implantable devices marks a transformative shift in chronic disease management, moving from a reactive to a proactive and continuous care model. These technologies enable a personalized approach by providing real-time physiological data, which empowers both patients and healthcare providers to detect issues early, optimize treatments, and foster healthier lifestyles. Although challenges related to data security, interoperability, patient adherence, and regulatory pathways remain, advancements in encryption, standardization protocols, and user-centric design are actively addressing these issues. Furthermore, the application of artificial intelligence, block-chain technology, and emerging quantum mechanics in diagnostics and therapeutics opens up new frontiers for precision medicine. These converging innovations promise a future where chronic diseases are proactively predicted, precisely treated, and managed, ultimately improving the quality of life, reducing healthcare burdens, and contributing to a more sustainable and equitable healthcare ecosystem. The integration of these technologies has the potential to refine care models, boost patient outcomes, and cut healthcare costs, ultimately driving better healthcare outcomes.

ACKNOWLEDGEMENT

The authors express their sincere gratitude to the Centre for Advanced Electrical & Electronic System (CAEES), Faculty of Engineering, Built Environment, and Information Technology, SEGi University; the Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, Malaysia; and the Department of Medical Physics, Khwaja Yunus Ali University, Bangladesh, for their invaluable support in this study.

REFERENCES

Baharuddin, M. L. I., Mahmod, S. R., Azaman, A., & Sahalan, M. (2024). A prototype validation study of a digitized pressure biofeedback unit versus electromyography during transverse abdominis muscle activation. Journal of Medical Devices Technology, 3(2), 84–89.

Guk, K., Han, G., Lim, J., Jeong, K., Kang, T., Lim, E.K., Jung, J. 2019. Evolution of wearable devices with real-time disease monitoring for personalized healthcare. Nanomaterials, 9(6), 813.

Adeghe, E.P., Okolo, C.A., Ojeyinka, O.T. 2024. A review of wearable technology in healthcare: Monitoring patient health and enhancing outcomes. Open Access Research Journal of Multidisciplinary Studies, 7(1), 142–148.

Ghazizadeh, E., Naseri, Z., Deigner, H.P., Rahimi, H., Altintas, Z. 2024. Approaches of wearable and implantable biosensor towards developing in precision medicine. Frontiers in Medicine, 11, 1390634.

Yogev, D., Goldberg, T., Arami, A., Tejman-Yarden, S., Winkler, T.E., Maoz, B.M. 2023. Current state of the art and future directions for implantable sensors in medical technology: Clinical needs and engineering challenges. APL Bioengineering, 7(3), 031506.

Sim, D., Brothers, M.C., Slocik, J.M., Islam, A.E., Maruyama, B., Grigsby, C.C., Naik, R.R., Kim, S.S. 2022. Biomarkers and detection platforms for human health and performance monitoring: A review. Advanced Science, 9(7), 2104426.

Koydemir, H.C., Ozcan, A. 2018. Wearable and implantable sensors for biomedical applications. Annual Review of Analytical Chemistry, 11(1), 127–146.

O'Keeffe, N., Scheid, J.L., West, S.L. 2020. Sedentary behavior and the use of wearable technology: An editorial. International Journal of Environmental Research and Public Health, 17(12), 4181.

Phillips, S.M., Cadmus-Bertram, L., Rosenberg, D., Buman, M.P., Lynch, B.M. 2018. Wearable technology and physical activity in chronic disease: Opportunities and challenges. American Journal of Preventive Medicine, 54(1), 144–150.

Yang, J., Liu, X., Fu, Y., Song, Y. 2019. Recent advances of microneedles for biomedical applications: Drug delivery and beyond. Acta Pharmaceutica Sinica B, 9(3), 469–483.

Bagherifard, S., Tamayol, A., Mostafalu, P., Akbari, M., Comotto, M., Annabi, N., Ghaderi, M., Sonkusale, S., Dokmeci, M.R., Khademhosseini, A. 2016. Dermal patch with integrated flexible heater for on-demand drug delivery. Advanced Healthcare Materials, 5(2), 175–184.

Mirani, B., Pagan, E., Currie, B., Siddiqui, M.A., Hosseinzadeh, R., Mostafalu, P., Zhang, Y.S., Ghahary, A., Akbari, M. 2017. An advanced multifunctional hydrogel-based dressing for wound monitoring and drug delivery. Advanced Healthcare Materials, 6(19), 1700718.

Mostafalu, P., Tamayol, A., Rahimi, R., Ochoa, M., Khalilpour, A., Kiaee, G., Yazdi, I.K., Bagherifard, S., Dokmeci, M.R., Ziaie, B., Sonkusale, S.R., Khademhosseini, A. 2018. Smart bandage for monitoring and treatment of chronic wounds. Small, 14(33), 1703509.

Maulvi, F.A., Soni, T.G., Shah, D.O. 2016. A review on therapeutic contact lenses for ocular drug delivery. Drug Delivery, 23(8), 3017–3026.

Liang, K., Carmone, S., Brambilla, D., Leroux, J.-C. 2018. 3D printing of a wearable personalized oral delivery device: A first-in-human study. Science Advances, 4(5), eaat2544.

Colley, H.E., Said, Z., Santocildes-Romero, M.E., Baker, S.R., D'Apice, K., Hansen, J., Madsen, L.S., Thornhill, M.H., Hatton, P.V., Murdoch, C. 2018. Pre-clinical evaluation of novel mucoadhesive bilayer patches for local delivery of clobetasol-17-propionate to the oral mucosa. Biomaterials, 178, 134–146.

Adepoju, V.A., Jamil, S., Biswas, M.S., Chowdhury, A.A. 2024. Wearable technology in the management of chronic diseases: A growing concern. Chronic Diseases and Translational Medicine, 10(4), e156.

Greiwe, J., Nyenhuis, S.M. 2020. Wearable technology and how this can be implemented into clinical practice. Current Allergy and Asthma Reports, 20(8), 36.

Gresham, G., Hendifar, A.E., Spiegel, B., Neeman, E., Tuli, R., Rimel, B.J., Figlin, R.A., Meinert, C.L., Piantadosi, S., Shinde, A.M. 2018. Wearable activity monitors to assess performance status and predict clinical outcomes in advanced cancer patients. npj Digital Medicine, 1, 27.

John, D., Freedson, P. 2012. ActiGraph and Actical physical activity monitors: A peek under the hood. Medicine & Science in Sports & Exercise, 44(Suppl 1), S86–S89.

Xie, Y., Lu, L., Gao, F., He, S.J., Zhao, H.J., Fang, Y., Yang, J.M., An, Y., Ye, Z.W., Dong, Z. 2021. Integration of artificial intelligence, blockchain, and wearable technology for chronic disease management: A new paradigm in smart healthcare. Current Medical Science, 41(6), 1123–1133.

Rowan, C., Hirten, R. 2022. The future of telemedicine and wearable technology in IBD. Current Opinion in Gastroenterology, 38(4), 373–381.

Nabil, M., Megahed, F. 2024. Quantum dot nanomaterials: Preparation, characterization, advanced bio-imaging and therapeutic applications. Journal of Fluorescence, 34(6), 2467–2484.

Sibomana, O., Hakayuwa, C.M., Obianke, A., Gahire, H., Munyantore, J., Chilala, M.M. 2025. Diagnostic accuracy of

ECG smart chest patches versus PPG smartwatches for atrial fibrillation detection: A systematic review and meta-analysis. BMC Cardiovascular Disorders, 25, Article 45.

Chen, W.-C., Wu, Y.-L., Hsu, Y.-C., Hsu, J.-T., Tseng, H.-P., Chen, C.-C., Chiang, M.-H., Hsiao, J.-F., Chin, S.-K., Huang, Y.-L., Lei, M.-H. 2024. Comparison of continuous 24-hour and 14-day ECG monitoring for the detection of cardiac arrhythmias in patients with ischemic stroke or syncope. Clinical Cardiology, 47(3), 242–248.

Cappon, G., Vettoretti, M., Sparacino, G., Facchinetti, A. 2019. Continuous glucose monitoring sensors for diabetes management: A review of technologies and applications. Diabetes & Metabolism Journal, 43(4), 383–397.

Han, S., Yamamoto, S., Jung, C.-Y., Jin, D. Y., Lee, T., Kim, J.-S. 2024. Wearable sensors for monitoring chronic kidney disease. Communications Materials, 5(1), 153.

Parker, M. 2023. Implantable devices for kidney monitoring. Nature Electronics, 6, 719.

Kim, E.J., Chen, C., Gologorsky, R., Santandreu, A., Torres, A., Wright, N., Goodin, M.S., Moyer, J., Chui, B.W., Blaha, C., Brakeman, P., Vartanian, S., Tang, Q., Humes, H.D., Fissell, W.H., Roy, S. 2023. Feasibility of an implantable bioreactor for renal cell therapy using silicon nanopore membranes. Nature Communications, 14, 4890.

Sang, B., Wen, H., Junek, G., Neveu, W., Di Francesco, L., Ayazi, F. 2024. An accelerometer-based wearable patch for robust respiratory rate and wheeze detection using deep learning. IEEE Journal of Biomedical and Health Informatics, 28(3), 1234–1245.

Vitazkova, D., Foltan, E., Kosnacova, H., Micjan, M., Donoval, M., Kuzma, A., Kopani, M., & Vavrinsky, E. (2024). Advances in respiratory monitoring: A comprehensive review of wearable and remote technologies. Biosensors, 14(2), 90.

Moreau, C., Rouaud, T., Grabli, D., Benatru, I., Remy, P., Marques, A.-R., Drapier, S., Mariani, L.-L., Roze, E., Devos, D., Dupont, G., Bereau, M., & Fabbri, M. (2023). Overview on wearable sensors for the management of Parkinson's disease. npj Parkinson's Disease, 9, Article 153.

Lehnen, J., Venkatesh, P., Yao, Z., Aziz, A., Nguyen, P.V.P., Harvey, J.H., Alick-Lindstrom, S., Doyle, A., Podkorytova, I., Perven, G., Hays, R.S., Zepeda, R., Das, R., & Ding, K. (2025). Real-Time Seizure Detection Using Behind-the-Ear Wearable System. Journal of Clinical Neurophysiology, 42(2), 118–125.

Pelham, H., Benza, D., Millhouse, P.W., Carrington, N.A., Arifuzzaman, M., Behrend, C.J., Anker, J.N., & DesJardins, J.D. (2017). Implantable strain sensor to monitor fracture healing with standard radiography. Scientific Reports, 7, 1489.

Liu, H., Ding, S., Lin, X., Wang, S., Wang, Y., Feng, Z., & Song, J. (2024). Bone Fracture Healing under the Intervention of a Stretchable Ultrasound Array. ACS Nano, 18(30), 3001–3012.

Wang, J., Chu, J., Song, J., & Li, Z. (2024). The application of implantable sensors in the musculoskeletal system: a review. Frontiers in Bioengineering and Biotechnology, 12, 1270237.

Nasrin, I. A., & Divya, P. (2025). Smart Wearable Technologies for Real-Time Mental Health Monitoring: A Holistic Approach to Early Detection and Intervention. International Journal of Scientific Research in Engineering and Management, 9(4), 1–9.

Jolly, A., Pandey, V., Sahni, M., Leon-Castro, E., & Perez-Arellano, L.A. (2025). Modern Smart Gadgets and Wearables for Diagnosis and Management of Stress, Wellness, and Anxiety: A Comprehensive Review. Healthcare (Basel), 13(4), 411.

Chen, F., Zhao, L., Pang, L., Zhang, Y., Lu, L., Li, J., & Liu, C. (2025). Wearable physiological monitoring of physical exercise and mental health: A systematic review. Intelligent Sports and Health, 1(1), 1–12.

Salim, M. I. M., Al-Ashwal, R. H. A., Tan, T. S., & Abuzairi, T. (2024). A Review of Medical Device Procurement at National Level: Integrating Support Systems for Clinical Engineers Towards Efficient, Transparent and Standardized Procurement Processes. Journal of Medical Device Technology, 3(2), 75–83.

Roos, L. G., & Slavich, G. M. (2023). Wearable technologies for health research: Opportunities, limitations, and practical and conceptual considerations. Brain, Behavior, and Immunity, 113, 444–452.

Feehan, M., Munger, M. A., Cooper, D. K., Hess, K. T., Durante, R., Jones, G. J., Montuoro, J., Morrison, M. A., Clegg, D., Crandall, A. S., & DeAngelis, M. M. (2016). Adherence to glaucoma medications over 12 months in two US community pharmacy chains. Journal of Clinical Medicine, 5(9), 79.

Osterberg, L., & Blaschke, T. (2005). Adherence to medication. New England Journal of Medicine, 353(5), 487–497.

Kar, A., Ahamad, N., Dewani, M., Awasthi, L., Patil, R., & Banerjee, R. (2022). Wearable and implantable devices for drug delivery: Applications and challenges. Biomaterials, 283, 121435.

Pons-Faudoa, F. P., Ballerini, A., Sakamoto, J., & Grattoni, A. (2019). Advanced implantable drug delivery technologies: transforming the clinical landscape of therapeutics for chronic diseases. Biomedical Microdevices, 21(2), 47.

Wang, S., Yang, H., Zheng, J., Tong, A., Mu, S., Wang, D., Zhao, M., & Li, J. (2025). Recent advances and prospects of nanoparticle-based drug delivery for diabetic ocular complications. Theranostics, 15(8), 3551–3570.

Hirten, R. P., Danieletto, M., Sanchez-Mayor, M., Whang, J. K., Lee, K. W., Landell, K., Zweig, M., Helmus, D., Fuchs, T. J., Fayad, Z. A., Nadkarni, G. N., Keefer, L., Suarez-Farinas, M., & Sands, B. E. (2025). Physiological data collected from wearable devices identify and predict inflammatory bowel disease flares. Gastroenterology, 168(5), 939–951.e5.

Greiwe, J., & Nyenhuis, S. M. (2020). Wearable technology and how this can be implemented into clinical practice. Current Allergy and Asthma Reports, 20(36).

Chae, S., Kim, Y., Lee, K., & Park, H. (2020). Development and clinical evaluation of a web-based upper limb home rehabilitation system using a smartwatch and machine learning model for chronic stroke survivors: Prospective comparative study. JMIR mHealth and uHealth, 8(7), e17216.

Souza, J., Escadas, S., Baxevani, I., Rodrigues, D., & Freitas, A. (2022). Smart wearable systems for the remote monitoring of selected vascular disorders of the lower extremity: A systematic review. International Journal of Environmental Research and Public Health, 19(22), 15231.

Hughes, A., Shandhi, M. M. H., Master, H., Dunn, J., & Brittain, E. (2023). Wearable devices in cardiovascular medicine. Circulation Research, 132(5), 652–670.

Ginsburg, G.S., Picard, R.W., Friend, S.H. 2024. Key issues as wearable digital health technologies enter clinical care. New England Journal of Medicine, 390(12), 1118–1127.

Reisman, M. (2017). EHRs: The challenge of making electronic data usable and interoperable. P & T, 42(9), 572–575.