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Application of Artificial Intelligence in Continuous Blood Glucose Monitoring Techniques and Management of Diabetes: A Review

Engr. Ifenze Ogochukwu Militus
Department of Biomedical Engineering Federal University of Allied Health Science, Enugu, Nigeria
Department of Biomedical Engineering Federal University of Technology, Owerri, Imo State, Nigeria

Prof. G. I. Ndubuka
Department of Biomedical Engineering Federal University of Technology, Owerri, Imo State, Nigeria

Engr. Dr. K. I. Nkuma-Udah
Department of Biomedical Engineering Federal University of Technology, Owerri, Imo State, Nigeria

Engr. Dr. E. Mbonu
Department of Mechatronics, Federal University of Technology, Owerri, Imo State, Nigeria.

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Abstract: *Emerging technologies and control systems revolutionized healthcare services which is very evident in self-management of diabetes mellitus by integrating continuous glucose monitors (CGMs), insulin pumps, and hybrid closed-loop systems, which significantly improve glycemic control and reduce hypoglycemia risk. In diabetes management, artificial intelligence (AI) technologies are used for three primary application which are closed-loop control algorithms, glucose prediction through continuous glucose monitoring (CGM) biosensors and AI algorithms, and the calibration of CGM biosensors with the assistance of AI algorithms. Integration of AI technologies into diabetes care supports better clinical outcomes, thereby reducing administrative burden and costs associated with diabetes management. Continuous Glucose Monitoring (CGM) systems, which plays vital role for immediate glucose data delivery, have shown effectiveness in improving diabetes management by reducing HbA1c levels and empowering self-care skills. This has nurtured an increased sense of confidence among patients in managing their medical condition. However, the successful adoption of these technologies requires substantial support from healthcare professionals and family members to ensure adherence and effective use, especially considering* *factors like family income, educational background, and technological proficiency. In spite of all the research advancements made continuous glucose monitoring (CGM) technologies are still evolving towards compactness, flexibility, sustained functionality, calibration-free operation, and closed-loop systems and free energy harvestability for prolong operation life.*

Keywords: diabetes mellitus, artificial intelligence, continuous glucose monitoring, biosensors, hypoglycemia.

INTRODUCTION

According to International Diabetes Federation projection, by 2045, 1 in 8 adults, approximately 783 million, will be living with diabetes, which is an increase of 46%, where 90% of people with diabetes have type 2 diabetes, which is driven by socio-economic, demographic, environmental, and genetic factors (Dutta et al. 2024; IDF 2021; Mbithi, Nguka, and Wanjau 2021). Similarly, Nigeria like other nations of the world is currently experiencing an increase in the prevalence of Type 2 Diabetes (T2D) and other non-communicable diseases (NCD). The International Diabetes Federation (IDF) projection is that the number of T2D cases in Nigeria, will rise from 3.6 million in 2021 to nearly 5 million by 2045 (Arueyingho et al. 2024). Diabetes Mellitus is a long-term chronic metabolic disease condition arises when pancreas fails to produce sufficient insulin or when the body struggles to utilize the insulin it creates. Insulin is a hormone whose function regulate sugar levels in the blood system. High blood glucose or elevated blood sugar also known as Hyperglycemia, is a common effect of unmanaged diabetes and eventually results in significant harm to various systems within the body, particularly the heart, blood vessels, eyes, kidneys, and nerves over time (Sahid, Babar, and Uddin 2024). According to International Diabetes Federation fact sheet, reports that 10.5% of the adult population (20-79 years) has diabetes, with almost half unaware that they are living with the condition (IDF 2021). The projected proliferation in the global diabetic population is expected to reach close to 439 million adults (Jin et al. 2023), with an overall global economic burden is projected to rise from U.S. $1.3 trillion (95% CI 1.3–1.4) in 2015 to $2.2 trillion (2.2–2.3) in the baseline, $2.5 trillion (2.4–2.6) in the historical trends, and $2.1 trillion (2.1–2.2) in the target scenarios by the year 2030. This increase in costs as a percentage of global GDP is anticipated to go from 1.8% (1.7–1.9) in 2015 to a peak of 2.2% (2.1–2.2) (Bommer et al. 2018). It is anticipated that surge in prevalence of Diabetes Mellitus (DM) points to an estimated 578 million individuals being impacted by the year 2030, with a projected escalation to 700 million by 2045, thus, the regulation of glucose levels in individuals with diabetes is crucial (Di Filippo et al. 2023). Traditional blood glucose monitoring entails the utilization of standard capillary blood glucose testing through a finger puncture (ElSayed et al. 2024; Jin et al. 2023; Mohanram and Shirly Edward 2021). Despite this, the method fails to promptly acknowledge the importance of glycemic functions. The advancement towards continuous glucose monitoring (CGM) has turned into a field of active exploration, heavily dependent on technical advancements that have been refined over numerous years (ElSayed et al. 2024; Jin et al. 2023).

Continuous glucose monitoring (CGM) devices, operating based on this principle, utilize a glucose-oxidase-doped platinum electrode inserted into the subcutaneous tissue to initiate and promote glucose oxidation. Consequently, the production of gluconolactone, hydrogen peroxide, and an electric current signal occurs as a result of this process, ultimately being transformed into a glucose concentration after a calibration process that includes a small number of self-monitoring of blood glucose (SMBG) samples gathered by the individual (Cappon et al. 2019). Continuous glucose monitoring (CGM) devices, operating based on this principle, utilize a glucose-oxidase-doped platinum electrode inserted into the subcutaneous tissue to initiate and promote glucose oxidation. Consequently, the production of gluconolactone, hydrogen peroxide, and an electric current signal occurs as a result of this process, ultimately being transformed into a glucose concentration after a calibration process that includes a small number of self-monitoring of blood glucose (SMBG) samples gathered by the individual (Ahmed et al. 2022; Avari et al. 2023; Lei et al. 2023).

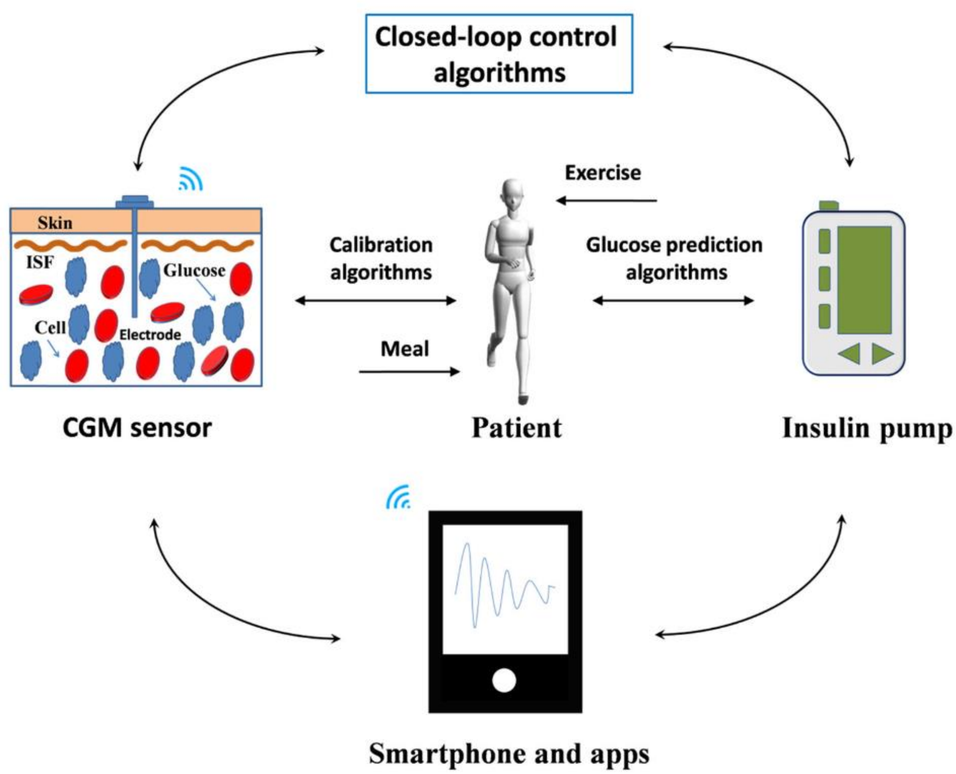

Figure 1.0: Artificial Intelligence Algorithm Application in the field of diabetes management. Continuous glucose monitoring (CGM) and interstitial fluid (ISF) are among the key technologies utilized in this area (Jin et al. 2023).

The Historical Development of Continuous Glucose Monitoring (CGM) Sensors.

A typical Continuous Glucose Monitoring (CGM) system, comprises of glucose recognition biosensor, a physical or chemical transducing circuitry, a wireless transmission and receiver elements. The glucose recognition element displays remarkable specificity for glucose and plays a key role in the efficiency of CGM. The primary purpose of transducer component is to convert glucose levels into a measurable analytical signal. Ideally, this signal is transmitted wirelessly to a receiver, and may appear as a mobile application or a designated handheld device that includes specific algorithms for monitoring glucose levels or an insulin delivery tool. Depending on the nature of the transducer component, CGM systems can be classified into electrochemical sensors and optical sensors (Abubeker et al. 2024; Jin et al. 2023).

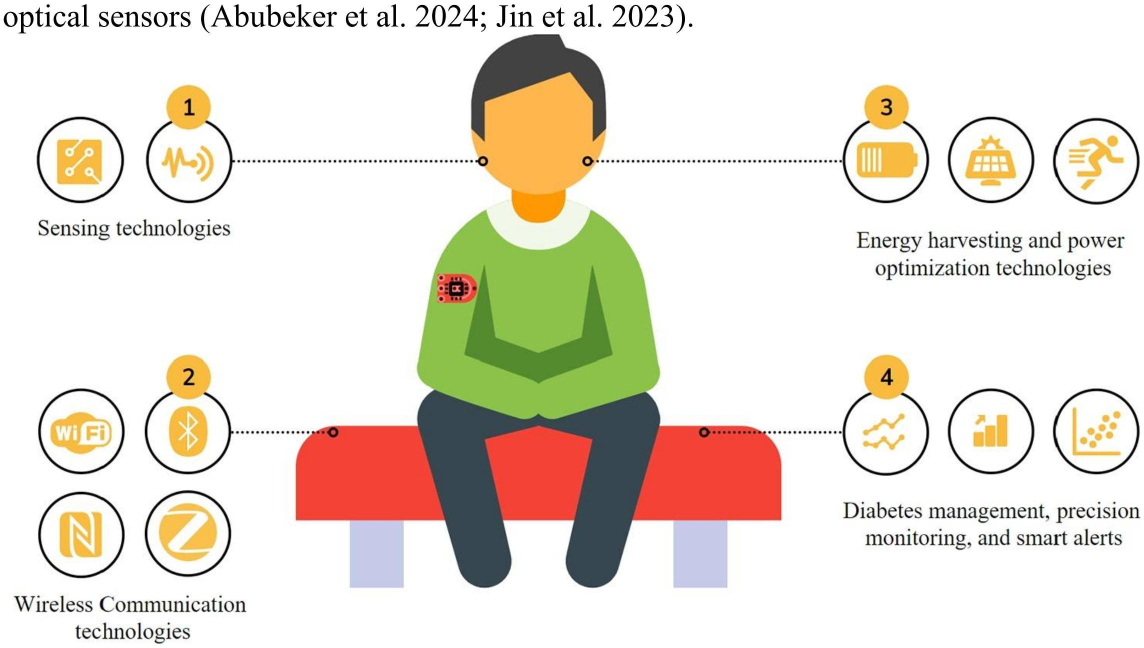

Figure 1.1: A conceptual diagram illustrating various research areas in wearable devices, including sensing technology, energy management, communications, and data analysis (Mansour, Saeed Darweesh, and Soltan 2024).

The initial CGM prototypes were developed in 1999, with the first professional CGM system approved by the FDA for retrospective data analysis. Despite its limitations, the system lacked accuracy and was compared to precise BG concentration values collected in hospitals using advanced medical instruments. Over the past decade, manufacturers of CGM devices have made significant efforts to address accuracy issues in their initial models (Cappon et al. 2019; Yoo and Kim 2023). The Medtronic Enlite Continuous Glucose Monitoring (CGM) system was the

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pioneering next-generation product with a Mean Absolute Relative Difference (MARD) of 13.6% and a wear time of up to 6 days. This device also improved sensor comfort through size and weight reduction, was waterproof, and had the capability to store BG data for up to 10 hours in case of connection loss between receiver and transmitter(Almurashi, Rodriguez, and Garg 2023; Yoo and Kim 2023).

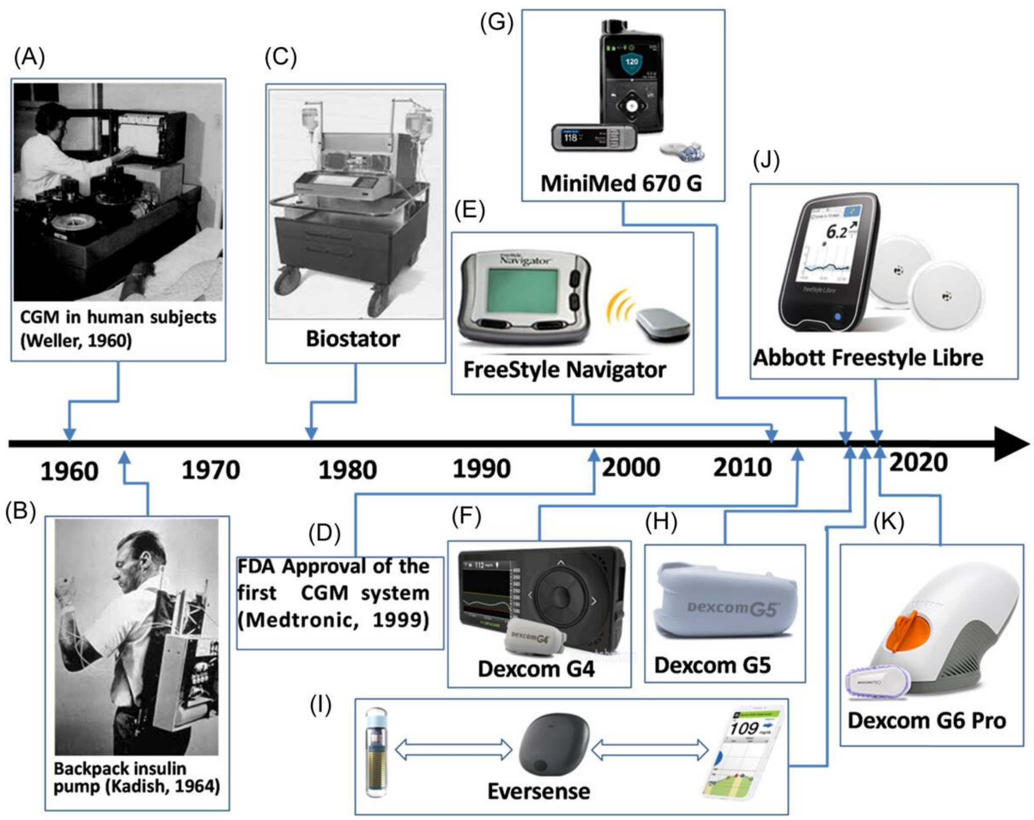

Figure 1.2: A visual depiction of the Continuous Glucose Monitoring (CGM) system over different time periods (Jin et al. 2023).

Blood Glucose Monitoring Techniques

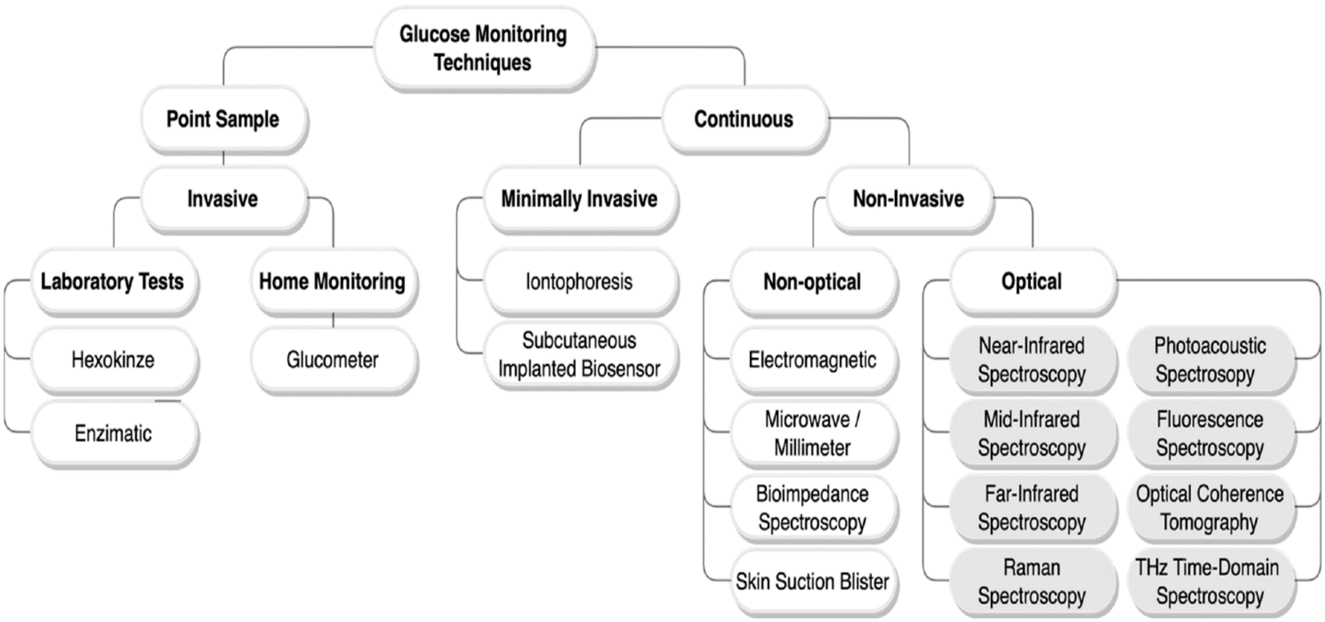

Figure 2.0: An Overview of different Techniques for measuring Blood Glucose levels (Alsunaidi et al. 2021).

Various techniques have been proposed for blood glucose detection, encompassing invasive, minimally invasive, and non-invasive approaches:

Invasive Blood Glucose Monitoring Technique:

The invasive techniques represent the benchmark and widely utilized for blood glucose monitor (Alsunaidi et al. 2021; Gonzales, Mobashsher, and Abbosh 2019). Home Inversive Glucose Monitoring devices involve collecting a sample of capillary blood by breaking the skin barrier at the subject's finger with a sharp lancing device (Shang et al. 2022). Whilst these methods deliver precise measurements, they are constrained by a range of limitations such as discomfort, increased risk of infection, reliance on expensive blood glucose testing materials, and diminished accuracy with prolonged use (Karon et al. 2008; Tang et al. 2020; Wu et al. 2023). Current conventional devices, like self-monitoring blood glucose (SMBG) devices, commonly referred to as glucometers, continuous-glucose-monitoring (CGM) devices, adhere to invasive and minimally invasive techniques, respectively (Ahmed et al. 2022; Ajjan et al. 2018; Tang et al. 2020; Wu et al. 2023). This technique of finger pricking is considered inadequate when juxtaposed with Continuous Glucose Monitoring (CGM) since it mandates frequent checks by the individual throughout the day, as opposed to at regular intervals (Jin et al. 2023; Porumb et al. 2020; Xue et al. 2022).

Minimal Invasive Blood Glucose Monitoring Technique:

Glucose sensing through minimally invasive methods involves the use of microneedles that are inserted into the skin at sites where the interstitial fluid is present (Xue et al. 2022). The attention towards microneedles (MNs) has significantly increased in recent years owing to their micron-scale dimensions and low invasiveness. Microneedles (MNs) have found extensive applications in extraction of biofluids, detection of bacteria, transdermal sensing, and drug delivery through the skin for a range of medical conditions such as diabetes. Specifically, Microneedles are widely utilized in the sampling of interstitial fluid (ISF) and the measurement of distinct biomarkers for the purposes of diagnosing, predicting outcomes, and treating diseases, primarily due to the painless nature of the procedure and the favorable level of patient adherence (Y. Wang, Wu, and Lei 2023). The technology has ability to remain stationary over extended periods, ranging from days to months, during the process of repeatedly measuring glucose levels. During the last twenty years, minimal inversive glucose monitoring devices have been introduced to various global markets and act as the cornerstone for advanced wearable continuous glucose monitoring (CGM) platforms (Samant et al. 2020; Shang et al. 2022; Zeng et al. 2023).

Non-Invasive (NI) Blood Glucose Monitoring Technique:

Non-invasive blood glucose monitoring aims to guarantee a pain-free and comfortable experience during the process of glucose measurement. This approach can be classified based on the specific glucose sensing technique utilized. In non-invasive glucose monitoring method, the key sensing techniques involve electrochemical and electromagnetic-based approaches. For the electrochemical non-invasive glucose sensors, analysis is carried out on specimens such as saliva, tear drops, or exhaled breath. While, electromagnetic techniques are based on the interaction between electromagnetic waves and the human body. The wavelengths employed in these methodologies range from the meter-range (utilizing impedance spectroscopy) to the millimeter-range (employing microwaves) up to the nanometer-range (utilizing optical frequencies) (Kang et al. 2024; Nooshnab et al. 2024; Di Filippo et al. 2023; Wu et al. 2023; Xue et al. 2022; Gonzales et al. 2019). The noninvasive assessment of blood glucose is essential for enabling continuous glucose monitoring within smart healthcare systems. Achieving accurate glucose predictions poses a significant challenge in the realm of non-invasive measurements (Agrawal et al. 2023).

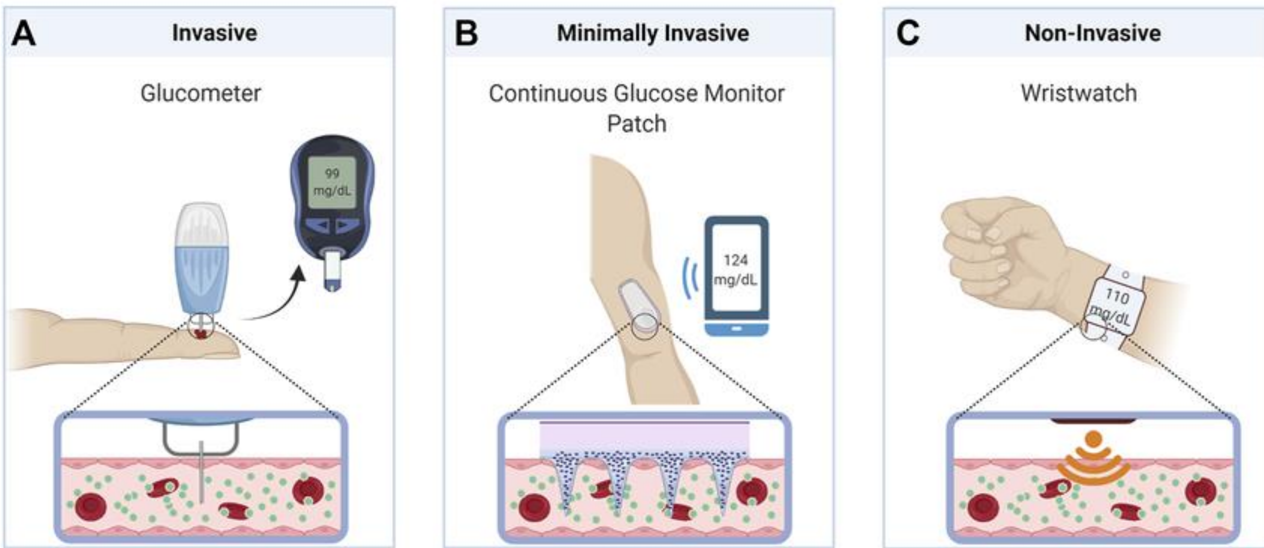

Figure 2.1: Blood Glucose Levels Monitoring systems (A) Invasive Glucometer, (B) Minimally Invasive Continuous Glucose Monitoring Patch, and (C) Non-Invasive Wristwatch (Todaro et al. 2022).

Several studies in the past have focused on glucose measurement, exploring invasive, noninvasive, and minimally invasive techniques. Numerous trials have been conducted for continuous glucose monitoring through non-invasive methods, principally optical or non-optical. Optical techniques like Raman Spectroscopy, NIR spectroscopy, and PPG are the most frequent (Agrawal et al. 2023; Laha et al. 2022). The measured glucose levels are strongly influenced by numerous factors, among the most serious problems are clinical 'outliers', where the Point-Of-Care glucose measurement is misleading, leading to clinical errors and patient harm (Hellman 2015). Studies on continuous glucose monitoring sensors revealed a potential influence of decreased blood circulation during sleep and pressure from sensor readings. (Elian et al. 2023). Amidst different Body Mass Index (BMI) categories, the dimensions of subcutaneous adipose tissue may influence the precision of Continuous Glucose Monitoring (CGM) readings, while the compatibility of sensors with the body can be a critical factor in discerning variations among different abdominal locations (Agrawal et al. 2023; Elian et al. 2023). Traditional methods for monitoring level of blood glucose are more invasive and requires whole blood, plasma, or serum for analysis. Recently, there are significant focus on research concerning minimally invasive and non-invasive devices for blood glucose monitoring. These cutting-edge devices have the capability to assess blood glucose levels with minimal discomfort, pain, or invasiveness typically associated with standard blood glucose measurement techniques. Minimally invasive devices, like Continuous Glucose Monitors (CGMs), extract interstitial fluid to determine blood glucose levels, while non-invasive devices utilize technologies such as spectroscopy to measure blood glucose on the body's surface without the requirement of a needle prick (Mittal et al. 2024).

Comparison of Current and Future Continuous Glucose Monitoring Systems

During the process of regulating the concentration of blood glucose within a stable range, the employment of a screening tool to track glucose levels in the bloodstream is recognized as an essential instrument for overseeing blood glucose levels and keeping them within a moderately normal range (Zheng et al. 2018; Xue et al. 2022). The Ames Reflectance Meter, developed by Tom Clemens in 1969, is considered the first blood glucose meter. This meter enable diabetic individuals to independently monitor their blood glucose levels, this device measures the intensity of blue light using a needle. The light is reflected off a Dextrostix paper strip and is converted into numerical values that signify glucose levels, depending on the varying exposure levels of the Dextrostix (Kokila et al. 2020; Rajendran and Rayman 2014; Salam et al. 2016; Tonyushkina and Nichols 2009). In 1974, Boehringer Mannheim released the first portable blood glucose meter in the world called Reflomat which was designed for healthcare professionals office and requires only a small amount of blood (Hirsch 2018; Roche 2023; Yamada 2011). Advancements have been made in the development of an enzymatic electrode strip at Cranford University and Oxford University in the United Kingdom. In 1990, a fourth glucose meter was created with a sample size range of 30µl to 0.3µl and a reduced test time of 2 minutes (Moodley et al. 2015). However, all the aforementioned equipment necessitates the extraction of a blood sample, and the processing of this extraction involves actions such as fingertip pricking, ear pricking, exsanguinating, and so on. Monitoring blood glucose levels continuously requires frequent measurements, usually more than four times a day (Zheng et al. 2018). Hence, frequent extraction of blood and the documentation of glucose levels are the most reliable approaches for assessing glucose levels in individuals with diabetes or pre-diabetes, but nevertheless, frequent skin pricking is not only unpleasant but also inconvenient and can lead to skin infection (Mathew, Zubair, and Tadi 2024; Todd et al. 2017). Indeed, skin puncture can cause irritation and may yield inaccurate results in the presence of changes in the body's condition or the ambient temperature (Xue et al. 2022; Zheng et al. 2018) The extraction of blood samples through skin pricking poses risks like inaccuracy, infection, inconvenience, and discomfort for individuals. Thus, precise, secure, convenient, and comfortable techniques for assessing blood glucose levels are imperative (Krleza et al. 2015; WHO 2010; Xue et al. 2022).

Artificial Intelligence (AI) Technologies Applied in Continuous Glucose Monitoring (CGM) Biosensors

Healthcare industry is presently undergoing a significant shift towards digital health technology, propelled by a growing demand for immediate and continuous health monitoring as well as disease diagnosis (Amjad, Kordel, and Fernandes 2023; Junaid et al. 2022; Kulkov et al. 2023; Paul et al. 2023; Stoumpos, Kitsios, and Talias 2023). The rising prevalence of chronic diseases such as

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diabetes and its complications like cardiovascular conditions, renal dysfunction, stroke etc, alongside an aging population, has heightened the need for remote and continuous health monitoring (Harris et al. 2021; Ravender et al. 2024; Sun and Li 2023). Accordingly, a surge has been observed in the development of wearable sensors that leverage artificial intelligence (AI) technology, enabling the retrieval, assessment, and real-time delivery of health data to medical professionals, thereby expediting decision-making based on patient information (Junaid et al. 2022; Yelne et al. 2023; Trinanda Putra et al. 2024). Thus, wearable sensors have become more and more popular because of their capacity to provide a non-intrusive and user-friendly approach to monitoring patient well-being (Kazanskiy, Khonina, and Butt 2024; Nguyen et al. 2024; Shajari et al. 2023; X. Wang et al. 2023).

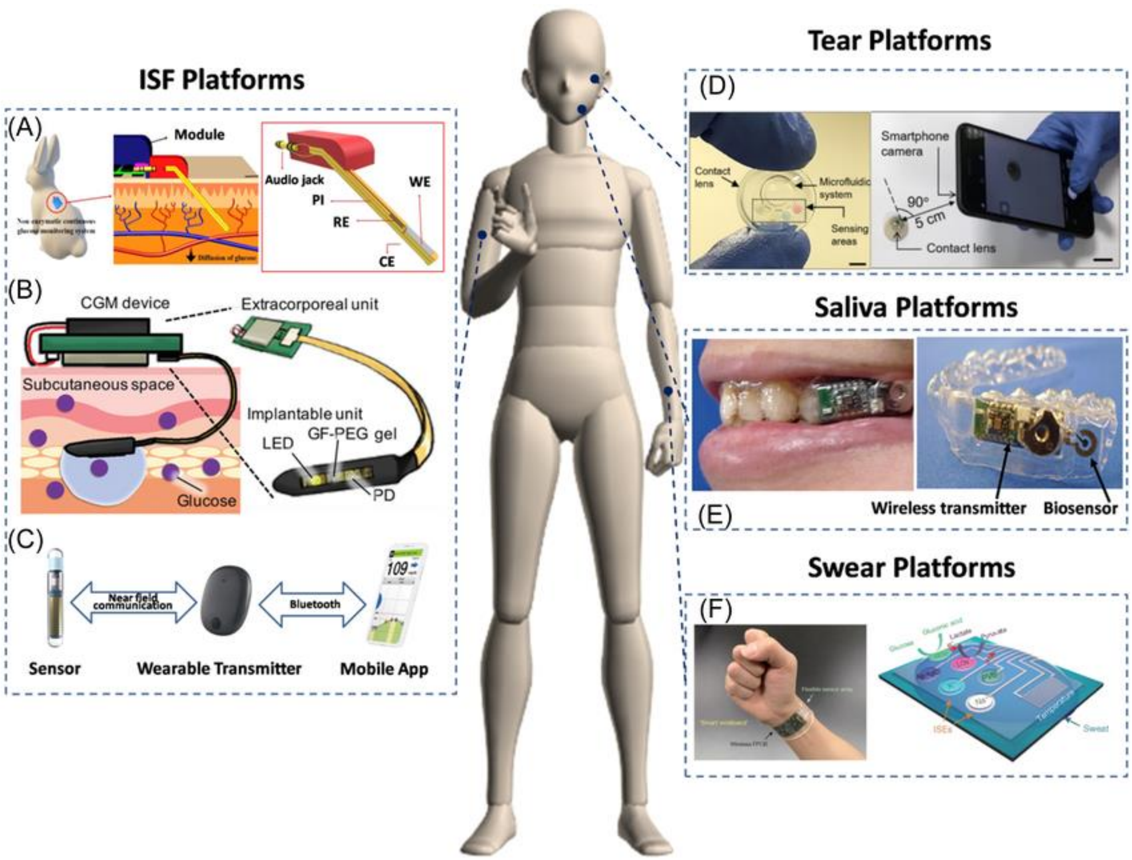


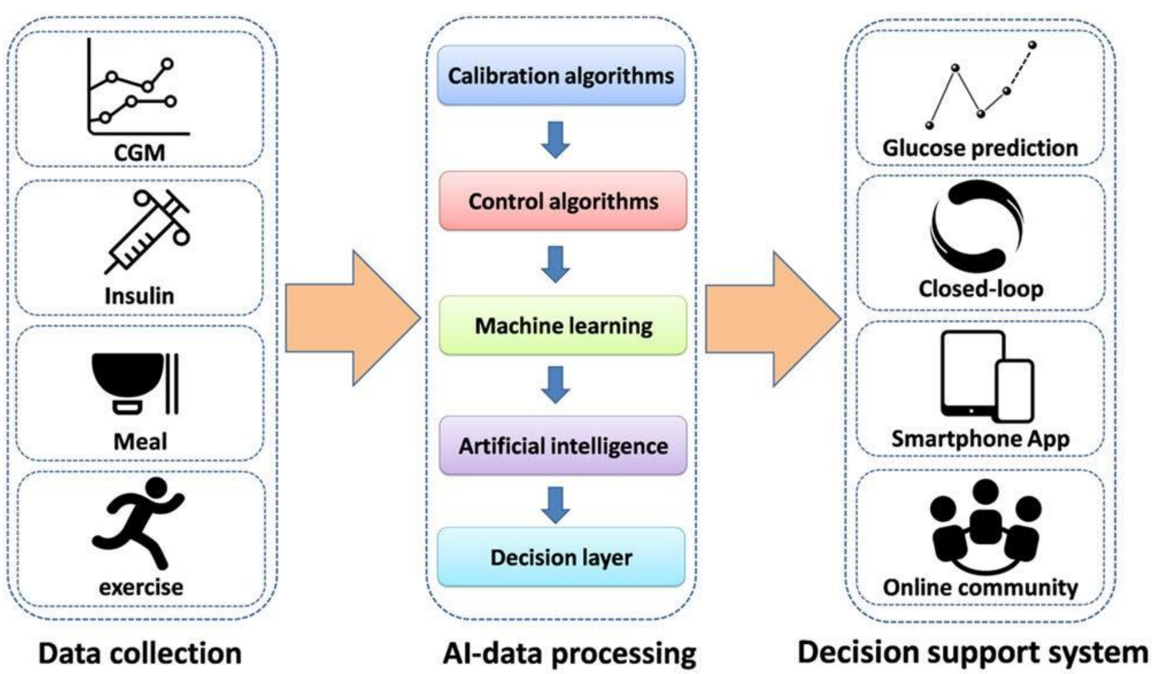
Figure 3.0:

Illustrative instances of wearable Continuous Glucose Monitoring (CGM) biosensors. (A) An electrochemical nonenzymatic CGM system. (B) A fluorescence-based CGM biosensor. (C) Commercialized Senseonics CGM sensor. (D) A contact lens biosensor for real-time glucose monitoring. (E) A wearable mouthguard CGM biosensor. (F) A smart wristband for monitoring glucose in sweat (Jin et al. 2023).

There has been an increasing presence of Artificial Intelligence with the aim of enhancing the efficiency of Continuous Glucose Monitoring biosensors in the last decade (Jin et al. 2023; C.

Wang et al. 2023; Mansour et al. 2024). The recommendation by American Diabetes Association is to employ AI not only as a replacement for traditional screening methods, but also for the detection of mild diabetic retinopathy and diabetic macular edema (Rajesh et al. 2023; Lam et al. 2024). Among the AI algorithms commonly used in diabetes care are the support vector machine, artificial neural networks (ANNs), supervised machine learning (SML), and principal component analysis algorithms (Li et al. 2020; Arora et al. 2023; Guan et al. 2023). The incorporation of machine learning within continuous glucose monitoring (CGM) has showcased its potential in various diabetes management scenarios such as calibration, decision support systems, closed-loop control, patient self-management tools, and automated retinal screening (Anjum, Saher, and Saeed 2024; Contreras and Vehi 2018; Marik and Darbari 2022; Medanki et al. 2024; Tyler and Jacobs 2020). Our primary focus remains on closed-loop control, decision support systems, and calibration utilizing artificial intelligence techniques.

Figure 3.1: A Schematic representation of continuous glucose level monitoring system incorporating artificial intelligence in diabetes management (Jin et al. 2023).



Prediction of Glucose Levels Using Continuous Glucose Monitoring (CGM) Biosensors and Artificial Intelligence (AI) Algorithms.

Artificial Intelligence deployed in Continuous Glucose Monitoring (CGM) is a decision support system typically for analytical tool that employs data gathered through CGM biosensors to give personalized recommendations to patients (Ahmed et al. 2023; Jin et al. 2023; Vettoretti et al. 2020). The prediction of glucose levels plays a vital role in decision support systems for diabetes management. Balancing the risks associated with hyperglycemia and the immediate perils of hypoglycemia is crucial in the management of glycemic control (Duckworth et al. 2024; Sugandh et al. 2023). Application of CGM is instrumental in preserving glycemic control and supporting the prediction of glucose levels, which in turn helps to prevent hypoglycemic and hyperglycemic episodes. The combination of AI algorithms with CGM biosensors serves to bridge the gap between data collection and analysis, resulting in enhanced precision in therapeutic interventions (Gandhi et al. 2011; Jin et al. 2023; Porumb et al. 2020; Zhu et al. 2022). For example, a machine learning algorithm rooted in statistical machine learning (SML) principles, was introduced by Marcus et al to leverage continuous glucose monitoring (CGM) biosensor data for purpose of scrutinizing the glucose concentrations among a cohort of eleven patients diagnosed with Type 1 Diabetes (T1D) falling within the age range of 18 to 39 years. The team successfully reached a hypoglycemia prediction rate of 64% through the application of the SML algorithm, demonstrating its ability to optimize blood sugar level control (Marcus et al. 2020). Georga et al. introduced a support vector regression (SVR) algorithm aimed at conducting multivariate predictive assessment of subcutaneous glucose levels in patients with Type 1 Diabetes (T1D). The SVR model demonstrates proficiency in addressing nonlinear regression challenges and enhancing the precision of short-term and long-term glucose forecasting (Georga et al. 2013). A real-time prediction Artificial Neural Network (ANN) algorithm was introduced by exclusively training the data originating from the Continuous Glucose Monitoring (CGM) biosensor. The root-mean-square error outcome of the proposed model indicates that the ANN algorithm exhibited superior accuracy compared to the autoregressive model (Bequette 2010; Hamdi et al. 2017; Pérez-Gandía et al. 2010).

Continuous Glucose Monitoring (CGM) Biosensors Calibration Utilizing Artificial Intelligence (AI) Algorithms.

Commercially readily accessible continuous glucose monitoring (CGM) biosensors shows sensitivity towards glucose compound concentration and converts this concentration into electrical signals for purpose of detection of glucose level in the blood system (Ahmed et al. 2022; Chen et al. 2017; Peng et al. 2022; Yoo and Lee 2010). Sequel to this, through a calibration process utilizing data from previous self-monitoring of blood glucose (SMBG), converts the electrical signal into an estimated glucose concentration. During the initial phase, CGM biosensors in the first generation utilized a linear regression function as the calibration model; however, these fundamental techniques proved inadequate in addressing the complex time-dependent relationship between glucose levels and electrical signals crucial for diabetes management. As a result, consistent calibration using SMBG data is crucial to uphold the accuracy of the CGM biosensor (Acciaroli et al. 2018; Rossetti et al. 2010; Vettoretti et al. 2020; Yadav, Singh, and Dubey 2022). Calibration algorithms have potential to worsen the inaccuracies of Continuous Glucose Monitoring (CGM) biosensors, thereby increasing risk of dangerous hyper-/hypoglycemia forecasts. In response to these challenges, a plethora of machine-learning algorithms have been developed in the past decade (Gadaleta et al. 2019; Signal et al. 2012; Zahedani et al. 2023). Acciaroli and colleagues for instance, proposed a calibration algorithm that is founded on a Bayesian multiple-day model for subcutaneous glucose sensors. The effectiveness of this algorithm is evidenced by decreased calibration frequency from 2 to 0.25 day−1, as well as enhanced accuracy achieved through reduction of the mean absolute relative difference (MARD) from 12.83% to 11.62% (Acciaroli et al. 2018). In the work of Vettoretti et al., they introduced a retrospective fitting algorithm which relies on constrained deconvolution for calculating outcome metrics in clinical settings. Additionally, this recommended retrofitting algorithm has capability of enhancing precision of CGM biosensor estimations (Vettoretti et al. 2020). Lee et al. (2017) introduced a methodology that requires the use of historical data to personalize calibration parameters of continuous glucose monitoring (CGM) biosensors, by adjusting the slope and intercept of the curve, and modifying the mean reference error and sensitivity drift curve, to improve precision. The initial week marked a substantial enhancement in the CGM biosensor's performance by 25%, while also achieving a 27% reduction in the Mean Absolute Relative Difference (MARD). The application of machine learning methods not only improves the effectiveness of electrochemical CGM biosensors but also suggests potential utility in noninvasive optical CGM biosensors (Jin et al. 2023; Li et al. 2020; Xue et al. 2022). Trained domain knowledge clustering technique and the AdaBoost algorithm was deployed for the purpose of executing personalized calibration for the glucose monitoring system, leading to the achievement of a final MARD of less than 7.3%. The progression in calibration algorithms is driving the focus of next generation of CGM biosensors towards either factory-calibrated systems or calibration-free solutions. One such case is the FreeStyle Libre, a factory-calibrated CGM biosensor that is capable of operating without the need for finger sticks for a maximum of 14 days. Likewise, the upcoming Dexcom CGM biosensor has the ability to adopt a calibration-free methodology through the utilization of an online Bayesian calibration algorithm (Chan et al. 2022; Klyve et al. 2023; Tomani et al. 2023).

Artificial Intelligence (AI) Algorithms for closed-loop control

Closed-loop control systems, commonly known as artificial pancreas systems, have revolutionized the management of Type 1 Diabetes (T1D) by automating insulin delivery and reducing the need for constant dosing decisions. These systems comprise three essential components: a Continuous Glucose Monitor (CGM) for real-time glucose monitoring, a control algorithm for supervising insulin delivery, and an insulin pump for constant infusion (Almurashi et al. 2023; Fuchs and Hovorka 2020; Lakshman, Boughton, and Hovorka 2023; Templer 2022). The concept of closed-loop glucose regulation dates back to the 1960s, but it was not until 2016 that the first fully integrated commercial system, the MiniMed 670G, was approved for T1D management (Fuchs and Hovorka 2020; Lakshman et al. 2023; Templer 2022). The importance of control algorithm is evident in its responsibility of analyzing continuous glucose monitoring (CGM) data for purpose of making essential adjustments to insulin administration, with the objective of maintaining blood sugar levels within a designated range. Multiple hybrid closed-loop systems, such as the MiniMed 780G, Tandem's T slim x2 Control IQ, and Insulet's Omnipod5, have demonstrated significant improvements in glycemic control and overall quality of life for their users (Parise et al. 2023; Pozhar et al. 2023; Reddy, Verma, and Dungan 2000). Multiple clinical trials have shown these systems to improve duration, during which glucose levels are maintained within desired range, lower HbA1c levels, and reduce occurrence of hypoglycemia with no notable safety issues. The integration of sophisticated algorithms, including artificial neural networks and robust control theories, further strengthens the system's capability to adapt to variations among and within patients, thus fostering more consistent glucose management (Lakshman et al. 2023). In spite of these advancements, the challenges persist in ensuring equitable access and the importance of user participation for meal notifications in hybrid systems. Looking ahead, the priority is on building fully closed-loop systems that eliminate necessity for user-triggered insulin boluses and integrating dual-hormone systems with glucagon to mitigate the risks of hypoglycemia. Overall, closed-loop systems indicate a noteworthy improvement in diabetes management, providing physiological and psychosocial benefits to individuals with Type 1 diabetes (Grunberger et al. 2021; Shalit et al. 2023; Wilson et al. 2022). The core framework of a closed-loop control system for insulin therapy comprises three primary elements: a CGM biosensor for glucose measurement, a controller utilizing an algorithm to regulate insulin pump delivery, and an insulin infusion pump for continuous insulin administration (Fuchs and Hovorka 2020; Olçomendy et al. 2022). The control algorithm plays an essential role in closed-loop systems. It can be located in a smartphone as well as incorporated into the insulin pump. Three main traditional types of control algorithms are proportional-integral-derivative (PID), fuzzy logic, and model predictive control (MPC) (Bequette 2012, 2013; Dermawan and Kenichi Purbayanto 2022; Zavitsanou et al. 2016). The PID controller is commonly used as a computational tool in the field of biomedical engineering to control blood glucose levels. Attainment of this is done through the assessment of the variance between the desired setpoint and the current measurement, considering both the current time and past error terms, and integrating the error to optimize insulin delivery (Andrikov and Kurbanov 2023; Arafat and Weiwei 2023; Dubey and Al 2021). However, the performance of the PID controller may face limitations due to the nonlinearities existing in the system. This is the juncture at which fuzzy logic controllers (FLC) can be employed. FLCs integrate expert knowledge to mimic the decision-making process of diabetes specialists, ensuring robust control by managing nonlinearities and uncertainties within the system (Benzian, Ameur, and Rebai 2021; García 2020). For instance, fuzzy Proportional-Integral-Derivative (PID) controllers have exhibited improved effectiveness in various scenarios, such as temperature regulation and motor drive mechanism control. This is achieved through automated fine-tuning of parameters, leading to improved stability and precision. Furthermore, advanced methodologies such as the fuzzy self-tuning PID (f-SmartPID) enhance control at a more sophisticated level by continuously adjusting controller gains to prevent oscillations and maintain stability in demanding operational conditions. (Sandeep Rao et al. 2021). Model Predictive Control (MPC) algorithms, conversely, employ dynamic predictive models for the purpose of predicting blood glucose levels and accurately modifying insulin administration, thereby providing a proactive strategy for glucose regulation (Aiello, Jaloli, and Cescon 2023; Esna-Ashari et al. 2017; Hajizadeh, Rashid, and Cinar 2019). The integration of fuzzy logic with neural networks and other meta-heuristic algorithms, such as Invasive Weed Optimization (IWO) and Particle Swarm Optimization (PSO), has also been explored to enhance the control of blood glucose levels, demonstrating promising results in terms of settling time, overshoot, and control inputs (Benzian et al. 2021; Dirik 2022; Ghabousian et al. 2024; Melin et al. 2022; Shi and Li 2010). The integration of these sophisticated control strategies holds potential to significantly improve the management of diabetes by furnishing precise, consistent, and adaptable insulin delivery mechanisms. Despite the ongoing progress in the area of closed-loop control algorithms, a number of crucial barriers persist, including the precision of dosing, patient participation, unforeseen variations in glucose levels due to dietary intake and physical activity, patient-specific prediction, and additional elements that need to be resolved in order to improve the efficiency of the closed-loop artificial pancreas system (Berget, Messer, and Forlenza 2019; Mennella et al. 2024). Although the closed-loop system is now commercial accessibility for regulating blood glucose levels automatically, the use of an artificial pancreas may still present unreliability and potential challenges for certain individuals (Jin et al. 2023; Mackenzie, Sainsbury, and Wake 2024; Mehmood et al. 2020).

CONCLUSION

Emerging technologies and control systems are revolutionizing healthcare services which is very evident in self-management of diabetes mellitus by integrating continuous glucose monitors (CGMs), insulin pumps, and hybrid closed-loop systems, which significantly improve glycemic control and reduce hypoglycemia risk (Elian et al. 2023; Huang et al. 2023; Klonoff et al. 2021; Svetlova and Gurieva 2023). These advancements, such as sensor-augmented insulin pump therapy, are particularly beneficial for both children and adults with Type 1 diabetes, enhancing their quality of life and glycemic outcomes (Racey et al. 2023). The integration of these technologies into diabetes care not only supports better clinical outcomes but also reduces the administrative burden and costs associated with diabetes management (Jacobsen et al. 2023). Continuous Glucose Monitoring (CGM) systems, acknowledged for their immediate glucose data delivery, have shown effectiveness in improving diabetes management by reducing HbA1c levels and empowering self-care skills. Thus, this nurtures an increased sense of confidence among patients in managing their medical condition (Chaithanya and Sharath 2023). However, the successful adoption of these technologies requires substantial support from healthcare professionals and family members to ensure adherence and effective use, especially considering factors like family income, educational background, and technological proficiency (Nwokolo and Hovorka 2023; Teo et al. 2023). Despite the promising benefits, there are still barriers to widespread adoption, including the high cost and limited accessibility in low- and middle-income countries, which necessitate equitable access to these technologies (Young, Wong, and Vanderwyk 2023). Additionally, the psychosocial impact of diabetes management technologies, such as reducing diabetes distress and improving mental health, underscores the need for integrated care that includes mental health support (Biswas, Behera, and Madhu 2023). While the current technologies offer significant improvements, they are not without limitations, such as the need for user-initiated actions in hybrid systems and the potential burden on those not technologically fluent (D'Agostin et al. 2022). Therefore, ongoing research and development are essential to optimize these technologies and explore alternative strategies to ensure they meet the diverse needs of all individuals living with diabetes mellitus, ultimately enhancing their self-confidence, motivation, and adherence to treatment regimens. In diabetes management, three primary application of artificial intelligence (AI) technologies are closed-loop control algorithms, glucose prediction through continuous glucose monitoring (CGM) biosensors and AI algorithms, and the calibration of CGM biosensors with the assistance of AI algorithms (Jin et al. 2023; Sadagopan 2023). Primarily, CGM biosensors have the capability to transform provision of healthcare to patients with diabetes through diabetes management and various therapeutic interventions. The primary hinderance to integration of CGM biosensors include the expenses associated with materials (35.3%), lack of accuracy (30.1%), and resistance towards wearing devices on the body (29.7%) (Jin et al. 2023). Despite this, advancements in CGM technologies are evolving towards compactness, flexibility, sustained functionality, calibration-free operation, and closed-loop systems.

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