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Article

Advancements in wearable sensor technology for enhanced diagnosis and management of Parkinson’s disease

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Abstract: Parkinson’s disease (PD) is a progressive neurological disorder that gradually impairs bodily movements, making early diagnosis critical for slowing symptom progression and improving patients’ quality of life. As initial symptoms can be subtle, modern wearable sensor technologies play a vital role in monitoring patient movement and behavior. This review explores the applications of wearable sensors in diagnosing and managing Parkinson’s disease, drawing from 35 relevant studies published between 2015 and 2024. Findings indicate that 60%–80% of early-stage PD patients exhibit both motor and non-motor symptoms that can be effectively detected using motion sensors and electrophysiological methods, achieving approximately 90% accuracy in monitoring movement patterns. The incorporation of the Internet of Things (IoT) and machine learning has significantly enhanced the performance of these devices. Overall, wearable sensors are recognized as effective tools for early diagnosis and ongoing management of Parkinson’s disease, with the potential to improve patients’ quality of life and facilitate treatment processes. Future advancements should focus on developing smarter sensors and utilizing advanced algorithms for data analysis to maximize their clinical utility.

Keywords: wearable sensor; Parkinson’s disease (PD); motion sensors; biofeedback sensors; magnetic sensors; electrophysiological sensors

1. Introduction

Parkinson’s disease (PD) is a neurodegenerative disorder that primarily affects the brain, leading to the degeneration of dopaminergic neurons. This degeneration results in various motor disturbances that significantly impair mobility and diminish the quality of life for those affected [1,2]. Among the most critical issues are motor symptoms and gait disorders, which severely impact the daily lives of PD patients. Typically, individuals with PD exhibit a slower gait, characterized by shorter stride and step lengths compared to healthy individuals. One of the most concerning symptoms for PD patients is the gradual loss of motor independence. Therefore, having effective and reliable tools for gait analysis is essential [2].

Wearable sensor systems have emerged as a promising approach for assessing spatiotemporal parameters related to gait issues in PD patients, allowing for monitoring outside of specialized motion analysis facilities. A variety of methods and tools have been developed to aid in the management and oversight of the disease [3].

The developing area of vibration machine diagnostics employs sophisticated sensors to assess equipment health by capturing vibration and acoustic signals. Analyzing these signals allows for the early detection of potential malfunctions and the implementation of preventive strategies, which can significantly decrease repair times and costs. This method has proven effective in evaluating the health of knee joints. Additionally, machine learning (ML) plays a vital role in enhancing signal analysis, improving the diagnostic accuracy for patients suffering from osteoarthritis [4,5].

Wearable sensors are integrated devices that utilize non-invasive techniques to detect subtle physiological changes in individuals. Modern wearables offer measurement quality comparable to that of regulated medical devices. The initial generation of wearables typically included watches, shoes, and headsets, focusing mainly on biophysical monitoring such as tracking physical activity, heart rate, and body temperature. The next generation of wearable sensors has advanced to include skin-applied patches, tattoos, dental films, contact lenses, textiles, and even invasive microneedles or injection devices, enhancing their functionality [6,7].

Studies have shown that combining Recurrence Quantification Analysis (RQA) with Machine Learning Perceptron (MLP) produces notable outcomes, achieving a specificity of 0.896 and a sensitivity of 0.933. These results align with earlier research where Vibration Analysis for Gait (VAG) demonstrated exceptional performance, exceeding 90% in sensitivity, specificity, and accuracy [4].

Furthermore, vibroacoustic diagnostic techniques offer a promising alternative to traditional methods for assessing damage to articular cartilage. By analyzing the sounds and vibrations produced during the movement of knee joints, this diagnostic strategy can effectively detect early signs of damage. Specialized sensors are utilized to gather and analyze these signals, which hold potential for applications in musculoskeletal diagnostics, especially concerning knee joints. The vibroacoustic evaluation of knee joints leverages advanced signal analysis methods to assess the signals generated by moving joint surfaces, thus unveiling new opportunities in this domain. By capturing and analyzing the vibroacoustic signals emitted by the joint during motion, alongside machine learning-based classification techniques, this approach enables a non-invasive evaluation of the condition of articular cartilage [5,8].

2. Basic concepts

This study will explore the applications of first-generation sensors in managing the progression of Parkinson’s disease. Additionally, it will detail the components of wearable sensors and analyze data obtained from various types of sensors, including those based on inertial measurement units (IMUs), motion detection, electrophysiology, magnetism, and biofeedback. In **Figure 1**, the block diagram of the survey method is shown. For these innovations to be trusted, they must be backed by reliable scientific research, especially in areas where they are being widely adopted. The most useful studies are those that explore the tangible, everyday benefits of wearable sensors for people living with Parkinson’s, highlighting real patient stories and outcomes. Moreover, these studies should be grounded in rigorous clinical data, including results from randomized controlled trials and long-term observational studies, to offer a thorough assessment of the technology’s impact and efficacy [8].

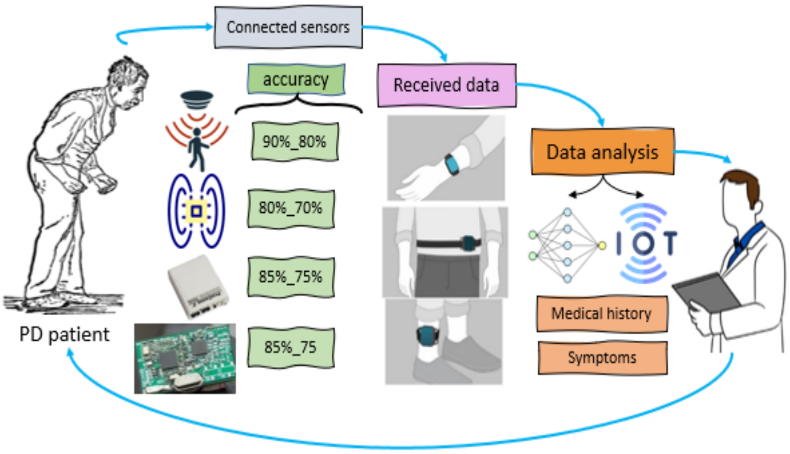

Figure 1. The block diagram of the survey method.

2.1. Components of wearable sensors

The use of wearable sensors has been increasing in the management of Parkinson’s disease, particularly for symptom tracking and monitoring disease progression towards personalized care. These sensors are capable of collecting a diverse range of data essential for grading symptoms of Parkinson’s disease, providing insights into both the nature of the symptoms and the progression of the disease. Each type of sensor consists of various components that enhance its functionality. Among the most significant and commonly utilized sensors are motion sensors, which include an accelerometer, gyroscope, magnetometer, transducer, processing unit, memory unit, communication unit, and power supply. Each component measures different parameters [9].

Accelerometer: This device quantifies steps taken, distance traveled and calories burned, and detects sudden movements such as falls.

Gyroscope: It assesses body rotation, such as turning while walking or running.

Magnetometer: This sensor indicates the direction of body positioning, including location, heading, and altitude.

Transducer: It converts physical information related to temperature, light, pressure, and movement into electrical signals, making the data interpretable by digital systems.

Processing unit: This unit collects input from all sensors and processes the data to provide practical information, including step count, distance covered, and calories burned [10].

Memory unit: This component stores the collected data for further analysis.

Communication unit: Responsible for transmitting the data for display and analysis on devices such as smartphones or computers.

Power source: This may refer to a battery or a solar cell.

While the architecture of other wearable sensors generally includes motion sensors, there are slight variations in specific areas. Magnetic sensors incorporate a magnetometer to measure the direction and intensity of the Earth’s magnetic field. Biofeedback sensors utilize biological sensors to measure physiological signals. Biochemical sensors are designed to detect biochemical molecules [11]. Together, these components enable comprehensive monitoring and analysis, which are crucial for the effective management and treatment of Parkinson's disease.

Recent investigations have shown that accelerometers and gyroscopes can achieve an accuracy rate between 85% and 90% when it comes to detecting vibrations and irregular movements related to Parkinson's disease. For example, a particular study found that motion sensors were able to accurately identify freezing of gait (FOG) in patients at a rate of 89.77%, highlighting their effectiveness as trustworthy diagnostic tools [5].

In addition, sophisticated multi-mode sensors that combine different types of data inputs, including acceleration, angular measurements, and electromagnetic signals, have demonstrated notable enhancements in their detection capabilities, with accuracy rates reaching as high as 92%. This information reinforces the credibility of wearable technologies in the effective monitoring and management of Parkinson's disease symptoms [5].

Analysis of wearable sensor data

The Internet of Things (IoT) encompasses a network of physical objects that incorporate sensors, software, and internet connectivity. This advancing technology holds significant promise for enhancing the management of patients with Parkinson's disease (PD). Sensors are capable of gathering diverse data regarding a patient's symptoms and overall health, including sleep patterns, movement, and psychological state. The data collected by IoT sensors can be transmitted wirelessly to healthcare providers and caregivers, enabling them to monitor the patient's condition remotely and make necessary adjustments. Additionally, this data can be analyzed using artificial intelligence, specifically machine learning, to predict complications or identify disease patterns, which can assist in delivering personalized care to patients [12].

In the context of Parkinson's disease, IoT has the potential to facilitate this process. It specifically involves connecting wearable sensors to cloud systems or devices, transforming sensor data into time-stamped and remotely accessible information. Such connectivity can enhance multiple aspects of care and offer significant benefits for managing Parkinson's disease. Overall, IoT improves the monitoring, diagnosis, and treatment of Parkinson's by linking wearable sensors with medical and health information systems [13,14].

In the current medical landscape, assessing postural instability and tremor levels often requires patients to visit clinical facilities, incurring costs related to transportation, consultations, and hospital infrastructure. A systematic and self-contained approach to measuring these symptoms could significantly reduce these expenses. Moreover, traditional assessments are often subjective and rely heavily on the physician's judgment, introducing potential biases. To address this, there is a need for automated, objective tests or the use of sensor-based information regarding gait instability. The integration of multiple wearable sensors with online platforms will provide various options for remote patient monitoring. Interoperability-based IoT platforms can facilitate lateral labor division rather than a centralized, top-down approach, decentralizing resources within a distributed healthcare system [15,16]. In the realm of IoT-enabled wearable devices, collecting data about a person's lifestyle is crucial. However, analyzing this lifestyle data presents computational challenges. The volume of data stored in databases can be substantial, and frequent analysis requires significant resources, often conflicting with the limited capabilities of IoT devices [17,18]. For this reason, various recent devices with limited computational power initially perform preliminary analysis at the edge, after which finally data is processed in databases. Analyzed patient data is then reviewed by intelligent clinical decision support systems. Reports can be escalated to medical personnel when needed, who may contact the patient directly for needed actions [19]. IoT also plays a vital role in integrating medical devices associated with video oculography to analyze brain structures and functional activities. Changes in eye movements have been documented in relation to the progression of Parkinson’s disease [16]. All these can provide superior outcomes if integrated with intelligent machines. First, the machine has to be trained with a substantial dataset, and for that periodical recording of a person’s eye movement is necessary. Since real-time data can be obtained, development for knowledge acquisition needs to be pursued. This remote healthcare mechanism (**Figure 2**) removes the traveling and consultation expenses of elderly individuals along with removing the need for a series of tests and detailed examinations to obtain even small medical reports. By using facilities such as mobile phone apps on the Internet. This cost reduction increases frequent medical checkups and treatment methodologies, thereby increasing medical facilities [13].

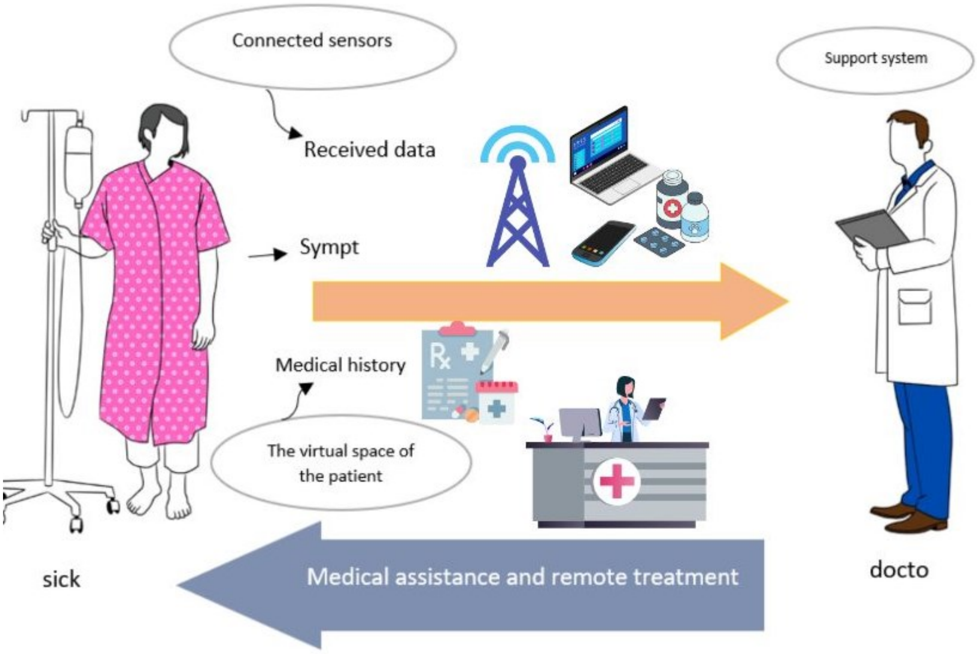

Figure 2. Remote treatment model based on the Internet of Things.

Various convolutional neural network (CNN) algorithms can be employed for analyzing wearable sensor data in Parkinson’s disease (PD). These algorithms are essential for tasks such as detecting body tremors, predicting attacks, and analyzing movement patterns, including changes in disease severity [20].

CNNs effectively utilize data from wearable sensors like accelerometers and gyroscopes to monitor patient status. By integrating temporal data from wearables, CNNs can develop models for attack prediction and patient monitoring. Typically, a CNN extracts key features from sensor data, and after applying continuous wavelet transforms (CWT) to raw data, it trains a six-channel deep learning architecture. Performance comparisons across models are made using waist sensor data, focusing on each channel's contribution to model effectiveness [18].

By leveraging cutting-edge sensors that function in multiple modes, healthcare professionals can gain a more comprehensive insight into a patient's health status by gathering data from a range of sources, including accelerometers, gyroscopes, and biochemical sensors. This multifaceted approach creates a nuanced understanding of the patient's vibrational and movement patterns, providing a detailed snapshot of their overall well-being. Through the utilization of edge computing, data analysis is conducted in real-time at the point of collection, thereby eliminating the need for server transfers and significantly reducing latency. This streamlined process enables faster response times and more efficient decision-making. The seamless integration of artificial intelligence, particularly deep learning algorithms, empowers the predictive analysis of disease progression, allowing healthcare providers to develop personalized treatment plans that cater to the unique needs and requirements of each patient, ultimately leading to more effective and targeted care.

The integration of artificial intelligence into interfaces has given rise to groundbreaking interaction methods, particularly through the utilization of intelligent digital companions like chatbots and virtual assistants. This technology empowers patients to seek answers to frequently asked questions or obtain medical information with ease. Furthermore, by analyzing data from wearable sensors using AI, healthcare professionals can access detailed reports that track patients' progress and highlight any notable fluctuations in their health status [21].

The IMU (BWT901CL Wit-Motion) with a 3-axis accelerometer and a 3-axis gyroscope was used to collect motion data, which could be simultaneously transmitted via Bluetooth to a personal computer. Five IMUs attached to the wrist, ankle and lower back using comfortable Velcro straps formed a body sensor network, as shown in **Figure 3a**. The selection of these five positions allows for comprehensive movement recording during the test while minimizing physiological strain [22]. This fixed setup ensures consistent sensor positioning and orientation throughout the recording. From the sensors' perspective, the x, y, and z axes were defined as lateral (positive left), anterior-posterior (positive posterior) and vertical (positive up) directions, respectively.

Participants with the body sensor network were instructed by a neurologist to perform a 10-meter straight walking test at their preferred pace, repeating the test three times as illustrated in **Figure 3b**. All sensors collected walking data at a sampling frequency of 50 Hz, and the calibration of the internal accelerometer eliminated human error due to varying angles of sensor placement [18].

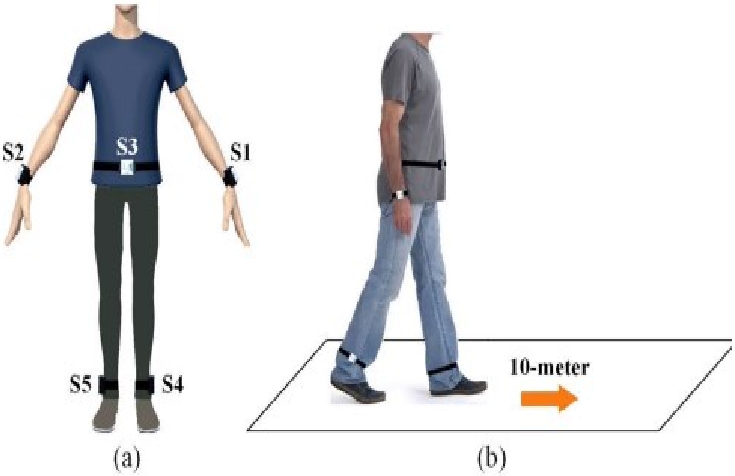

Figure 3. Data collection, (**a**) placement of sensors; (**b**) 10-meter straight walking test [18].

Research indicates that a minimum sampling rate of 30 Hz for accelerometer and gyroscope data is necessary to detect tremors or bradykinesia. More complex features, such as entropy, are required for tremor detection, while simpler features suffice for bradykinesia [23]. Studies have compared smartwatch data, which typically uses only an accelerometer, to data from wearables with both accelerometers and gyroscopes. While bradykinesia is detectable with accelerometer data alone, tremors require gyroscope data. Moreover, combining sensors with machine learning can support automatic decision-making. Although research on wearable sensor approaches for PD is extensive, studies integrating both sensors and machine learning are still emerging. For instance, researchers developed an AI model that tracks PD using nighttime breathing data, allowing for non-touch assessments at home, which could assist in pre-clinical risk evaluation [20].

Wearable sensors, when combined with machine learning, can detect and predict PD symptoms, helping mitigate adverse effects through appropriate stimuli. Beyond accelerometers and gyroscopes, various technologies are being employed for PD detection. Machine learning plays a role in both the early diagnosis of PD and preventing misdiagnosis of similar neurological conditions, utilizing diverse data types [19].

3. Types of wearable sensors in Parkinson's disease

Wearable sensors are portable devices that can be worn or embedded in clothing, including smart glasses, smartwatches, and pressure-sensitive shoes. They are equipped with specialized hardware and software for collecting kinematic parameters, processing data, and transmission. Most wearable devices used in PD rely on gyroscopes, accelerometers, and magnetometers, processing real-time movement signals to generate data models for detailed patient analysis. These sensors can connect directly to motion capture systems, enabling real-time data transmission for comprehensive body movement information [24]. The analysis of gait and measurement of the various forces applied while walking is normally completed with the use of a motion capture system. They usually require cameras positioned at strategic locations to capture motions from all sides for recording, hence providing motion data from multi-directions for software analysis. One drawback to these motion capture systems is they must be in some type of controlled environment to realize optimal results. On the other hand, it has a certain value in the investigation and treatment of movement disorders [24]. Wearable sensors use similar technology to motion capture sensors. They record the involuntary activities of a patient through parameters like acceleration, angular velocity, and inertia. Generally, hardware and software are used in the analysis of motion data. The components of hardware that are used include accelerometers, gyroscopes, and magnetometers, which can provide three-dimensional motion measures comprehensively. They can be used for many purposes, such as physiotherapy and home rehabilitation, especially those that could be applied in uncontrolled environments. [9]. Different types of sensors will be discussed in detail in the following sections. For instance, individuals can utilize intelligent wristwear to track nighttime tremors, providing valuable data on their symptoms in a home environment. Meanwhile, in medical settings, these sensors are employed to assess the efficacy of pharmaceutical interventions, allowing healthcare providers to make informed decisions based on real-time monitoring.

3.1. IMU-based sensors

Inertial Measurement Units (IMUs) represent a significant advancement in diagnosing and monitoring PD. Most IMUs feature a three-axis accelerometer and gyroscope, measuring acceleration and inertia in response to external forces. These devices use Micro-Electro-Mechanical Systems (MEMS) to convert mechanical signals into electrical signals, allowing for the calculation of acceleration, speed, and displacement [25]. Accelerometers can measure the acceleration of an object by determining its inertia when subjected to external forces and acceleration. These devices consist of a transducer called a Micro-Electro-Mechanical System (MEMS), which detects movement and converts mechanical signals into electrical signals. Accelerometers can be used to determine acceleration through signal integration, as well as speed and displacement. In addition to dynamic accelerations, accelerometers also measure the static gravitational acceleration (g) [26]. Over time, sensors have become more sophisticated and can be worn unobtrusively and attached to nearly any part of the body to measure movement. These wearable devices can record not only the direction, magnitude and frequency of movements but also the velocity of the body part to which they are attached. This data allows physicians to assess the presence and severity of key PD features such as tremors, bradykinesia and dyskinesia and to continuously analyze PD symptoms over time in a patient. Movement analysis can be performed with one or more devices. Information about gait oscillation rhythm, step length and even walking cycle speed can be obtained using a signal processing algorithm. These devices operate based on general principles: (a) Preprocessing the signal generated by the IMU using a determining or specific method; (b) extracting important features from the motion signal; and (c) generating a summary variable of the movement pattern [3].

Typically, in IMUs, three single-axis accelerometers are integrated into a three-dimensional accelerometer to simultaneously measure three orthogonal axes. Often, accelerometers in Inertial Measurement Units (IMUs) are combined with gyroscopes. IMUs consist of three orthogonal accelerometers that can independently measure acceleration along the X, Y, and Z axes.

IMUs can unobtrusively measure movement and provide data on tremors, bradykinesia, and dyskinesia over time. They analyze gait rhythm, step length, and walking speed using signal processing algorithms. Typically, three single-axis accelerometers are integrated into a three-dimensional accelerometer to measure acceleration across three axes. Gyroscopes are often combined with accelerometers to enhance measurement accuracy [27,28].

IMUs are cost-effective tools for motion analysis, revolutionizing functional assessments for patients with neurological disorders in both clinical and home settings. They accurately estimate kinematic parameters, position, acceleration, and velocity generated by movement. **Figure 4** shows an example of the electronic board of a wearable sensor containing an IMU. This node includes a microcontroller, an IMU with a combination of accelerometer, gyroscope and magnetometer flash memory for local data storage, and a micro USB port for battery recharging. The output signals from the accelerometers and gyroscopes are processed at very high speeds in the signal processing section. The measurements are then aggregated to obtain the total acceleration and rotation for the IMU's sample period. For instance, in a 200 Hz IMU, the sample period represents the total movement of the IMU within a 5-millisecond interval [1].

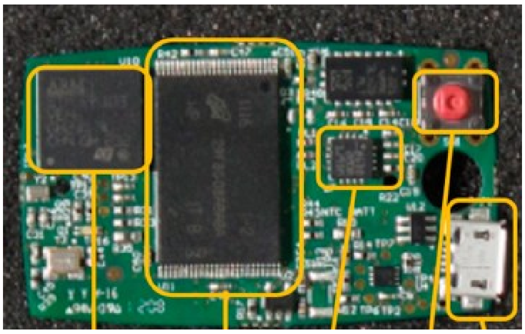

Figure 4. Electronic board of a wearable sensor with inertial measurement unit (IMU) [1].

IMU sensors are also used for detecting motor symptoms in Parkinson's disease. In some clinical studies, six kinematic sensors have been utilized. These sensors are placed on the wrist, ankle, chest, and lower back. Each sensor provides tri-axial accelerometer, gyroscope and magnetometer data at a sampling frequency of 128 Hz. The output signals from the IMUs are processed at very high speeds in the signal processing section [29].

3.2. Motion sensors

In this respect, the IMU can be considered one of the most important steps forward in supporting the diagnosis and monitoring of PD patients. Most of the commercially available IMUs these days are supported by a three-axis accelerometer and a three-axis gyroscope. For instance, accelerometers enable the measurement of object acceleration by determining its inertia in case of external forces and acceleration. These devices consist of a transducer called a Micro-Electro-Mechanical System-MEMS-transducer that detects movement and converts mechanical signals into electrical signals. Accelerometers can be used to measure acceleration by integrating the signal, as well as velocity and displacement. Other than dynamic accelerations, static gravitational acceleration is measured using an accelerometer [27]. The motion sensor units have five independent sensors, which have a size of 45.01 mm × 36.30 mm × 15.09 mm and a weight of 27.8 g. **Figure 5** shows the hardware structure. **Figure 6** illustrates the hardware structure. The utilized microcontroller is the CC3220 MCU chip CC3220, Texas Instruments, Dallas, TX, USA). A rechargeable lithium-ion battery with 600 mAh has so far powered the system. The MCU and docking station control the power control unit of the system, which, in turn, controls the charging of the battery and monitors its voltage. There are two timing systems contained in the sensor: One is the RTC, which is a low-accuracy, low-power clock; another one is a high-precision timer synchronized by a signal emitted from a docking station. It contains two timing systems so that various sensors can record the data with minimum time discrepancy. Besides, all the data sampled by the sensor can be stored on an SD card. The function of wireless, transmission-free data recording is possible. It allows long-term continuous activity recording; up to 22 h of recording is possible with a motion sensor. However, if the wireless transfer of data faces some environmental interference, there can be significant data loss. The data on the SD card can protect the test results [27].

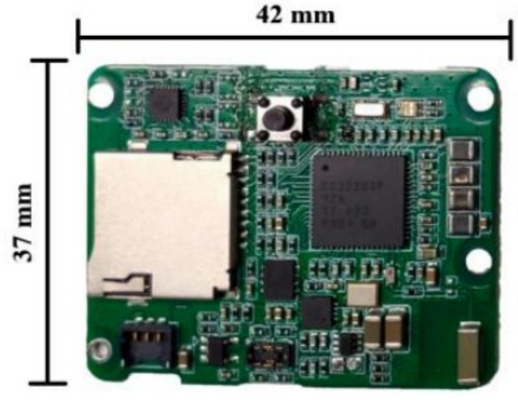

Figure 5. Motion sensor [27].

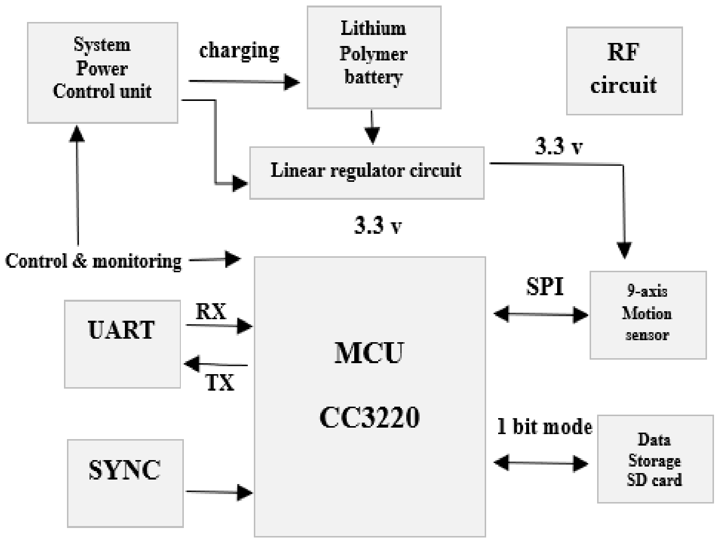

Figure 6. Motion sensor hardware diagram.

3.3. Electrophysiological sensors

Electrophysiological sensors diagnose conditions such as cardiac arrhythmias, epilepsy, muscular disorders, and neurological diseases. They are not intrusive and thus do not pose any danger to a patient. Their portability is another merit of their application in homes, hospitals, and other environments. However, electrophysiological sensors may be quite expensive for every person to purchase. Secondly, gathering and storing electrophysiological data may raise several privacy issues. Electrophysiological sensors can support the diagnosis and monitoring of diseases by observation of physiological signs and give information on treatment tailoring for Parkinson’s disease. The sensor unit includes the following three different sensors: The dimensions of the sensor are 51.08 mm × 44.79 mm × 15.09 mm, and the weight is 41.2 g. **Figure 7** shows the hardware structure and **Figure 8** shows the block diagram structure and the location of sensitive components. The core chip in the circuit is the Analog-to-Digital Converter, or ADC, with an extremely low input noise of 1 µVPP, a high resolution of 24 bits, and a low-power chip from Texas Instruments, Dallas, TX, USA. This chip helps the sensor in minimizing the front-end circuitry to reduce the size of the sensor. Each sensor supports eight bipolar or unipolar input channels with programmable input amplifiers. This can input common-mode signals from sampled signals and feed back to the body with a negative feedback amplifier circuit to suppress common-mode noise. The sensor also involves a single-pole low-pass filter that removes signals not in focus. It can adjust the sampling rate from 250 to 2000 Hz, and the system is able to transmit 24 channels of raw data simultaneously in real time via Wi-Fi. The RF hardware design and MCU-related circuitry in the two motion sensors are quite similar to each other. This power management unit provides a 3.3-volt supply for the digital circuitry and a high-precision ± 2.5-volt LDO regulator for the ADC analog reference. The electrophysiological sensors could record up to 25 h in continuous long-term recording mode [27].

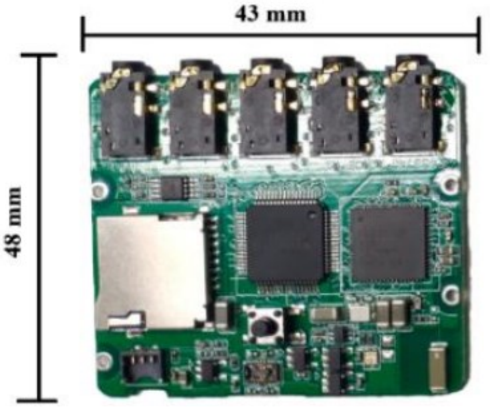

Figure 7. Electrophysiology sensor [27].

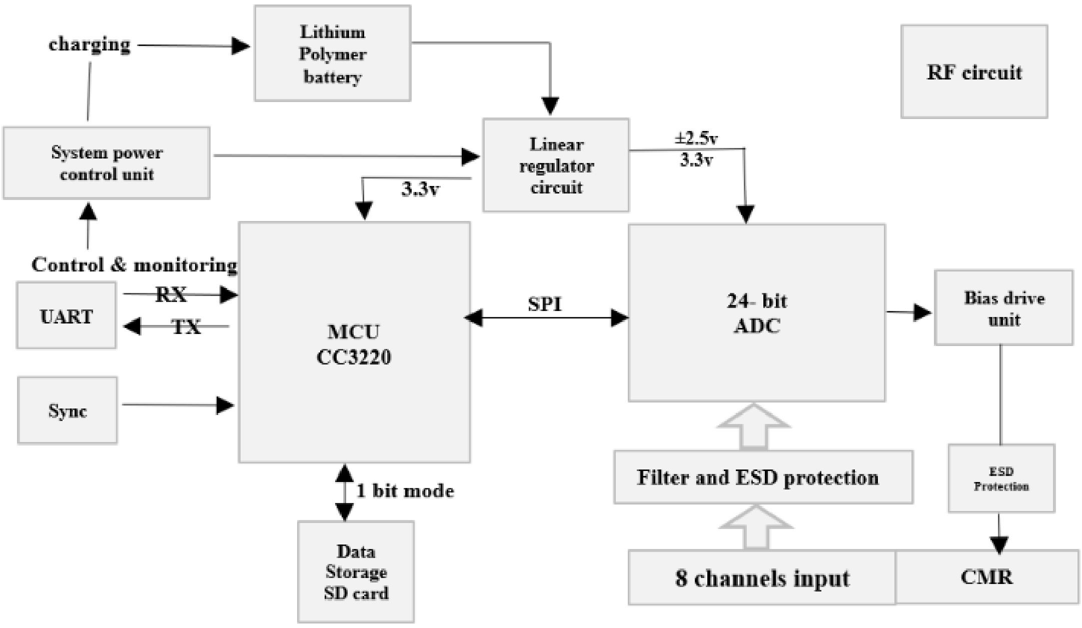

Figure 8. Electrophysiology sensor hardware diagram.

3.4. Magnetic sensors

Magnetic sensors are integral to the treatment of Parkinson’s disease (PD), utilized for tracking symptoms, providing real-time feedback, and enabling automatic medication adjustments [17]. Such sensors might be highly useful in the early detection of Parkinson’s disease even before a clear manifestation of the symptom sets in. They help in collecting vital data on the symptoms of Parkinson’s during a clinical study by measuring the magnetic field produced by the body, which in turn is produced by the electrical activity in the brain and muscles. This magnetic field, if altered, can provide effective symptoms of Parkinson’s, like tremors, muscle rigidity, and abnormal gait. Such sensors, with the use of advanced computer algorithms, perform rigorous analyses of the data they record and give comprehensive feedback to the patient about his or her symptoms. With this, the patient will gain full awareness of his symptoms and be able to adopt positive measures to overcome them. The algorithms are also good at monitoring tremors and gait abnormalities [30]. Other varieties include induction magnetometers that, in addition to those mentioned, measure the Earth's magnetic field and may track, quite effectively, both tremors and gait abnormalities. These sensors are also very good at monitoring both tremors and muscular rigidity using weak magnetic fields. There are also SQUID magnetometers, which represent the most sensitive type of magnetic sensor, and less expensive magnetometers that have lower sensitivity compared to SQUID magnetometers but do have great utility. Last but not least, light acts as a means of measurement for magnetic fields in optical magnetometers [31].

3.5. Biofeedback sensors

Biofeedback therapy involves attaching sensors to the body to measure key physiological functions. This approach helps individuals understand their bodily responses, enabling better control over functions and alleviating physical issues. Biofeedback techniques, such as regulating breathing and heart rate, are particularly effective for stress-related disorders. Electrical sensors connected to monitors measure indicators of stress, like heart rate and muscle tension. A biofeedback therapist guides patient in techniques to lower heart rates through relaxation and mental exercises [32]. The results of these exercises and techniques are viewed on a monitor to further encourage positive responses and achieve relaxation. A typical session of biofeedback can run for a period of 30 to 60 min, with the number of sessions dependent on variables such as the speed at which an individual learns to control bodily responses. There are also biofeedback devices that are commercially available for home use. It is also reported that biofeedback is safe and has no known adverse effects so far. However, biofeedback is not for everyone, and this modality should not be initiated without prior consultation with a physician, as with any complementary therapy [33]. In the case of the treatment of Parkinson's disease, biofeedback is an already known method to alleviate symptoms. Such techniques that aim to affect cognition and behavior to reduce symptoms, teaching the patients to control some bodily functions, include biofeedback. It helps a person improve his capabilities by using the power of the mind to control physical and psychological responses to various conditions and symptoms. That is helpful in the case of Parkinson's disease, as it keeps the patient in a state of continuous stress and psychological anxiety. Biofeedback relaxes the muscles, decreases the frequency of breathing, and maintains a low heart rate, hence offering better comfort to the patients and reducing their pain. These features also enable this non-invasive, non-pharmacological treatment to contribute to accelerated recovery from the disease [1,32]. In general, wearable sensors in the diagnosis and management of Parkinson's disease present some advantages and disadvantages. Wearable sensors are non-invasive, portable, and comfortable for everyday use, with considerable variation in their effectiveness across patients. Advantages include early detection of patient status changes and appropriate treatments, while challenges such as privacy management and sensor accuracy may impede disease management. Other sensors, such as electroencephalograms (EEG) and electromyograms, measure electrical activity in the brain and muscles, respectively [33].

3.6. Biochemical sensors

Biochemical sensors measure biomolecules, including enzymes, DNA, RNA, proteins, and metabolites, with applications in medical research, disease diagnosis, food quality control, and environmental monitoring. In PD, biochemical sensors can detect dopamine levels, which are typically low in patients. They can also measure alpha-synuclein, a protein that aggregates in the brain, and inflammatory biomarkers associated with disease progression. Such sensors facilitate early detection, monitor disease progression, and assess treatment efficacy, aiding in personalized treatment decisions based on individual biochemical profiles [7,34]. The placement of sensors depends on various factors, including the type of information to be collected. For instance, EEG sensors must be placed on the head. They should be positioned to avoid discomfort to the patient and not interfere with daily activities. Sensors need to be calibrated regularly and the collected data should be analyzed by medical professionals. Studies validated by the Parkinson's Disease Foundation and the Global Parkinson's Disease Association have summarized research on wearable sensors for Parkinson's disease diagnosis and management from 2014 to 2022 as outlined in **Table 1**, providing an overview of the types of wearable sensors involved in Parkinson's disease diagnosis [35].

Table 1. Types of wearable sensors.

Sensor type	Measured parameters	types	accuracy	Feature	The sensor connection point
Motion Sensors [27,35]	Movement parameters: Walking speed/stride length/body rotation Hand movements/hand tremors/muscle stiffness Body changes/sleep disorders Measurement of balance and body stability Body rotation/arm and leg movements Changes and body condition	Accelerometer/Gyroscope/Barometric/Cameras	80%–89%	1) Early detection 2) Tracing disease progress 3) Evaluation of treatment effectiveness 4) Differential diagnosis 5) Increasing objectification 6) reducing the care burden 7) Increasing patient independence	Wrist/ankle/chest/waist/head
Magnetic Sensors [17]	Brain activity/heart activity/muscle activity/body rotation/hand and leg movements Body changes and posture	SQUID magnetometers/magnetic magnetometers/Optical magnetometers	70%–80%	1) Early diagnosis 2) Being less aggressive 3) Portable 4) Tracing disease progress 5) Differential diagnosis 6) Increasing objectification	Head/chest/hands
Biofeedback Sensors [25,32]	Brain activity/heart activity/muscle activity/body rotation/hand and leg movements Body changes and posture	EEG/EMG/accelerometer/gyroscope	75%–85%	1) Early diagnosis 2) Being less aggressive 3) Portable 4) Tracing disease progress 5) Differential diagnosis 6) Increasing objectification	Head/Muscles and Nerve
Biochemical Sensors [7,34]	Measurement of enzymes, metabolites, and DNA in the body	Enzyme sensors/metabolite sensors/DNA sensors	75%–85%	1) Rehabilitation 2) Increasing patient awareness 3) Early diagnosis 4) Tracing the progress of the disease	Cerebrospinal fluid/head/blood

3.7. Sensors BAN & LAN

The rapid advancement of physiological sensors, low-power integrated circuits, and wireless communication has led to the emergence of wireless sensor networks for monitoring traffic, crops, infrastructure, and health. Body area networks (BANs) represent an interdisciplinary field that facilitates inexpensive and continuous health monitoring, enabling real-time updates of medical records via the Internet. Smart physiological sensors can be integrated into wearable wireless networks for computer-assisted rehabilitation or early diagnosis of medical conditions. These networks rely on small, comfortable biosensors implanted in the human body that monitor various physiological changes and transmit data wirelessly to external processing units. This information is relayed in real-time to healthcare providers globally, allowing for immediate alerts in emergencies. However, current limitations include the amount of information provided and the energy sources available for these sensors. Despite being in the early stages of development, extensive research is underway, and successful implementation is anticipated to revolutionize healthcare, facilitating concepts such as telemedicine and mHealth.

BAN sensors are used to monitor various physiological and medical indicators. By placing sensors on or near the body, data related to health and physical condition is collected and sent to a central device. These sensors track vital signs like body temperature, blood pressure, heart rate, and oxygen levels, as well as physical activity metrics such as steps taken and calories burned [36,37]. **Figure 9** generally shows the performance of the body sensor network.

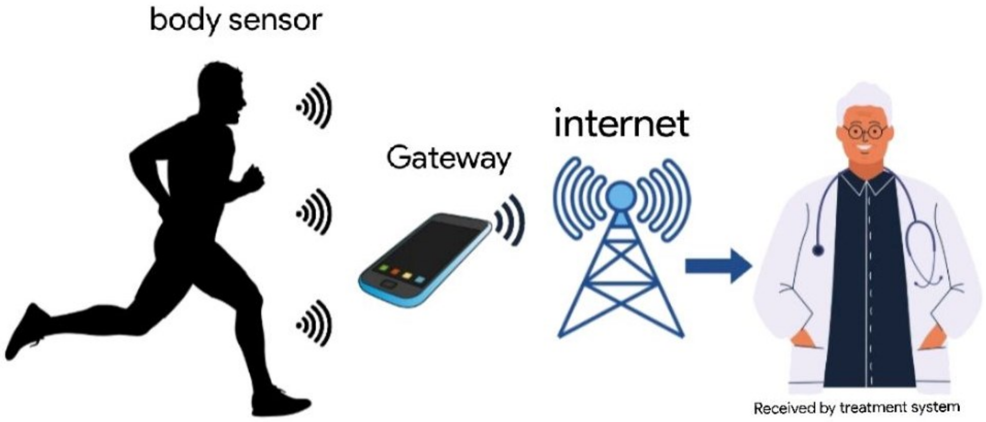

Figure 9. Body sensor network model.

In the medical field, MAN sensors (urban area network sensors) refer to sensor systems that facilitate health monitoring and data transmission in urban networks. These sensors are integrated into telemedicine, remote patient monitoring, and other healthcare applications, enabling real-time patient data collection and analysis. Here is a detailed description of MAN sensors in the medical field:

MAN, sensors are devices used to monitor various health parameters of patients, including vital signs, glucose levels, and other physiological measures. They transmit data through a metropolitan area network (MAN) to healthcare providers for monitoring, analysis, and timely intervention [37,38].

Several types of sensors are commonly used in healthcare settings, including:

Vital signs monitor: Measure parameters such as heart rate, blood pressure, body temperature, and oxygen saturation, transmitting data wirelessly for continuous monitoring.

Glucose monitoring sensors: Used by diabetic patients to continuously track blood sugar levels, enabling real-time data sharing with healthcare professionals.

(ECG) and (EEG) sensors: Monitor electrical activity in the heart and brain, respectively, providing vital data for diagnosing and managing conditions.

MAN, networks act as the communication backbone to transmit the data collected from these sensors. The advantages of using MAN in healthcare are:

Real-time monitoring: Facilitating continuous health tracking and timely interventions. Data from various sensors can be centralized, creating comprehensive patient profiles that support data-driven decision-making by healthcare providers. This enables at-home monitoring, reducing hospital visits and improving chronic disease management [37].

The application of MAN sensors in the medical field includes the following [35]:

Telemedicine: Facilitates remote consultation and monitoring and improves access to patient care in urban and rural settings. In an emergency, rapid data transmission from wearable sensors can alert medical personnel to critical conditions and improve response time. Continuous monitoring helps manage chronic conditions such as diabetes, high blood pressure, and heart disease, leading to better health outcomes. Data from MAN sensors can be used in clinical research, providing insights into patient responses to treatments and medications. While MAN sensors offer several advantages, there are challenges associated with their implementation:

Protecting sensitive patient data transmitted over networks is critical to maintaining confidentiality and compliance with regulations such as HIPAA. Ensuring that different devices and systems can communicate effectively is essential for the seamless exchange and use of data [38]. The integration of MAN sensors in healthcare is expected to evolve with technological advances. Key trends include:

AI algorithms can analyze data from multiple sensors to predict health problems and suggest preventative measures. 5G technology is expected to improve the speed and reliability of data transmission and enable more sophisticated surveillance solutions. Patients will have greater access to their health data, enabling them to actively participate in their care and decision-making processes [38]. By enabling continuous monitoring and efficient data management, MAN sensors play a vital role in modern healthcare [36]. Their integration into medical practices improves patient outcomes and increases the overall efficiency of health care delivery systems. As technology advances, the capabilities and applications of MAN sensors in the medical field continue to expand, offering new opportunities for better health management [38,39].

4. Challenges and future

Wearable sensors for Parkinson’s disease are poised for significant advancements in the future. Continuous technological improvements are expected to enhance their accuracy, cost-effectiveness, and comfort, making them common tools for diagnosis and management. However, these sensors collect sensitive personal data, raising critical concerns regarding data privacy and security. To protect patient information, robust privacy and cybersecurity policies must be established. Some patients may hesitate to adopt wearable sensors; thus, increasing awareness and education about their benefits can help alleviate skepticism and promote acceptance. Additionally, the high cost of these devices presents a barrier, which could be mitigated through subsidies to make them more affordable for all patients. The role of wearable sensors in managing Parkinson’s disease illustrates the transformative potential of technology in enhancing health and quality of life. These sensors—whether external or implanted—will provide real-time insights into individual health status, continuously monitoring vital signs such as heart rate, blood pressure, glucose levels, and blood oxygen. This capability will empower healthcare providers to deliver personalized treatments and implement preventive measures before diseases develop. The integration of the Internet of Things (IoT) and advanced communication networks like 5G will facilitate remote patient monitoring, allowing healthcare professionals to track patients’ health from home with real-time data, reducing the need for frequent hospital visits. Looking ahead, we anticipate a shift towards more implantable devices that will enable continuous health parameter monitoring, crucial for managing conditions such as diabetes and chronic pain. By combining data from body sensors with artificial intelligence, healthcare delivery will become increasingly precise, with AI analyzing sensor data to predict diseases and optimize patient management strategies. As reliance on body sensors and the accumulation of personal health data increase, the demand for strong data security and privacy measures will be vital. We foresee advancements in cybersecurity technologies tailored to protect health information. In summary, body sensors represent a transformative advancement in healthcare, promising a future that is smarter, more accurate, and efficient, ultimately enhancing quality of life and reducing medical costs. **Figure 10** generally shows the performance of wearable sensors in the future. Data collected by wearable sensors may contain sensitive patient information. The use of data encryption and security protocols is essential to protect this information. The high cost of producing advanced sensors is a barrier to their widespread use in developing countries. It is suggested that governments and insurers cover part of the costs to increase patient access. Patients may be reluctant to use these technologies due to unfamiliarity with them or concerns about their accuracy. Extensive education and outreach programs can reduce these resistances [21,40].

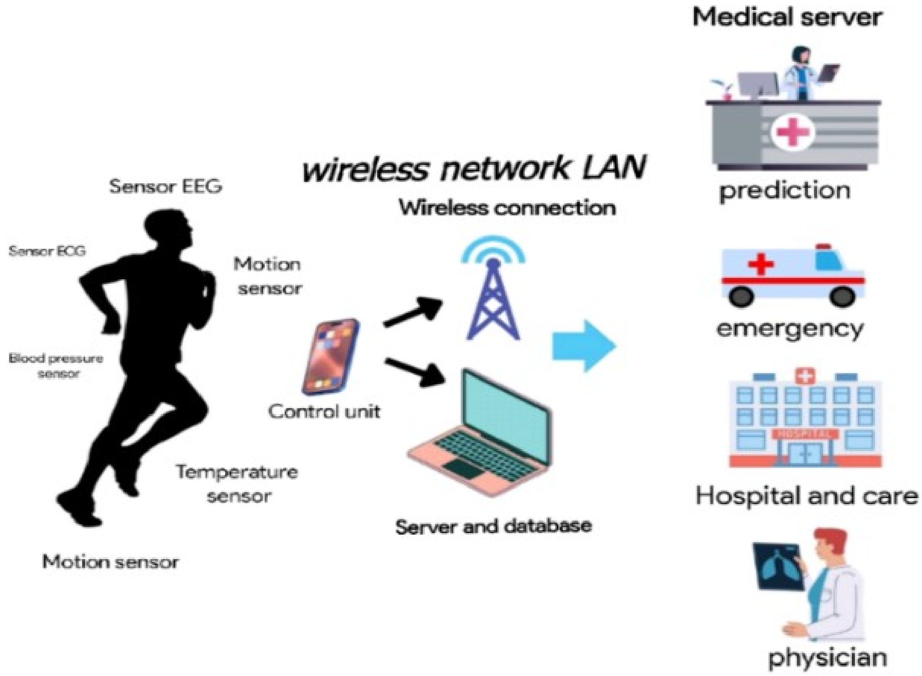

Figure 10. wearable sensors in the future.

5. Conclusion

In conclusion, wearable sensors represent a groundbreaking advancement in the management of Parkinson's disease, offering high sensitivity and accuracy in monitoring key motor symptoms such as gait parameters, including speed, stride length, and walking patterns. Their non-invasive nature and reliability make them ideal for both rehabilitation and home monitoring, enhancing patient independence and quality of life. This review highlights the diverse types of wearable sensors, their integration with IoT and neural networks, and their practical applications in real-time data analysis. Motion sensors, in particular, stand out for their effectiveness and affordability, providing valuable insights into tremors and gait fluctuations. With an accuracy rate of 70%–80%, these devices can monitor clinical efficacy before and after therapeutic interventions, allowing for personalized care strategies. However, the current landscape of wearable sensors is varied, with discrepancies in sensor placements and selected parameters. Future research must focus on standardizing measurement settings and selecting the most informative spatiotemporal parameters to improve comparability across studies. As technology continues to evolve, the integration of advanced features such as artificial intelligence and 5G connectivity will enhance the capabilities of these sensors, facilitating remote monitoring and timely interventions while addressing concerns about data privacy and security. Ultimately, wearable sensors hold immense promise in transforming the management of Parkinson's disease, providing both physicians and patients with powerful tools for effective disease management and improved health outcomes.

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References

1. Brognara L, Palumbo P, Grimm B, Palmerini L, et al. Assessing gait in Parkinson's disease using wearable motion sensors: A systematic review. Diseases. 2019; 7(1): 18.
2. Albán-Cadena AC, Villalba-Meneses F, Pila-Varela KO, et al. Wearable sensors in the diagnosis and study of Parkinson's disease symptoms: A systematic review. Journal of Medical Engineering & Technology. 2021; 45(7): 532–545.
3. Di Biase L, Di Santo A, Caminiti ML, et al. Gait analysis in Parkinson's disease: An overview of the most accurate markers for diagnosis and symptoms monitoring. Sensors. 2020; 20(12): 3529.
4. Machrowska A, Karpiński R, Maciejewski M, et al. Application of Recurrence Quantification Analysis in the Detection of Osteoarthritis of the Knee with the Use of Vibroarthrography. Adv. Sci. Technol. Res. J. 2024; 18: 19–31.
5. Karpiński R, Krakowski P, Jonak J, et al. Comparison of selected classification methods based on machine learning as a diagnostic tool for knee joint cartilage damage based on generated vibroacoustic processes. Applied Computer Science. 2023; 19(4): 136–150.
6. Pulliam CL, Heldman DA, Orcutt TH, et al. Motion sensor strategies for automated optimization of deep brain stimulation in Parkinson's disease. Parkinsonism & related disorders. 2015; 21(4): 378–382.
7. Asci F, Vivacqua G, Zampogna A, et al. Wearable electrochemical sensors in Parkinson's disease. Sensors. 2022; 22(3): 951.
8. Machrowska A, Karpiński R, Maciejewski M, et al. Application of eemd-dfa algorithms and ann classification for detection of knee osteoarthritis using vibroarthrography. Applied Computer Science. 2024; 20(2): 90–108.
9. Monje MH, Foffani G, Obeso J, Sánchez-Ferro Á. New sensor and wearable technologies to aid in the diagnosis and treatment monitoring of Parkinson's disease. Annual Review of Biomedical Engineering. 2019; 21(1): 111–143.
10. Muthukrishnan N, Abbas JJ, Krishnamurthi N. A wearable sensor system to measure step-based gait parameters for parkinson's disease rehabilitation. Sensors. 2020; 20(22): 6417.
11. Shawen N, O'Brien MK, Venkatesan S, et al. Role of data measurement characteristics in the accurate detection of Parkinson's disease symptoms using wearable sensors. Journal of Neuroengineering and Rehabilitation. 2020; 17: 1–14.
12. Sotirakis C, Su Z, Brzezicki MA, et al., Identification of motor progression in Parkinson's disease using wearable sensors and machine learning. Parkinson's Disease. 2023; 9(1): 142.
13. Sica M, Varnosfaderani OT, Crowe CC, et al. Design of a multi-sensors wearable system for continuous home monitoring of people with Parkinson's. IEEE Access. 2024.
14. LeMoyne R, Mastroianni T, McCandless C, et al. Implementation of a smartphone as a wearable and wireless accelerometer and gyroscope platform for ascertaining deep brain stimulation treatment efficacy of Parkinson's disease through machine learning classification. Advances in Parkinson's Disease. 2018; 7(2): 19–30.
15. Romero LE, Chatterjee P, Armentano RL. An IoT approach for integration of computational intelligence and wearable sensors for Parkinson's disease diagnosis and monitoring. Health and Technology. 2016; 6: 167–172.
16. De Oliveira APS, de Santana MA, Andrade MKS, et al. Early diagnosis of Parkinson's disease using EEG, machine learning and partial directed coherence. Research on Biomedical Engineering. 2020; 36: 311–331.
17. Oh SL, Hagiwara Y, Raghavendra U, et al. A deep learning approach for Parkinson's disease diagnosis from EEG signals. Neural Computing and Applications. 2020; 32: 10927–10933.
18. Chen M, Sun Z, Xin T, et al. An interpretable deep learning optimized wearable daily detection system for Parkinson's disease. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2023.
19. Prakash P, Kaur R, Levy J, et al. A deep learning approach for grading of motor impairment severity in Parkinson's disease. In: Proceedings of the 2023 45th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC); 24–27 July 2023; Sydney, Australia.
20. Shcherbak A, Kovalenko E, Somov A. Detection and classification of early stages of Parkinson's disease through wearable sensors and machine learning. IEEE Transactions on Instrumentation and Measurement. 2023; 72: 1–9.

21. Patel S, Lorincz K, Hughes R, et al. Monitoring motor fluctuations in patients with Parkinson's disease using wearable sensors. IEEE transactions on Information Technology in Biomedicine. 2009; 13(6): 864–873.
22. Saikia A, Hussain M, Barua AR, Paul S. EEG-EMG correlation for Parkinson's disease. International Journal of Engineering and Advanced Technology. 2019; 8(6): 1179–1185.
23. Bikias T, Iakovakis D, Hadjidimitriou S, et al. DeepFoG: An IMU-based detection of freezing of gait episodes in Parkinson's disease patients via deep learning. Frontiers in Robotics and AI. 2021; 8: 537384.
24. Gonçalves HR, Rodrigues A, Santos CP. Gait monitoring system for patients with Parkinson's disease. Expert Systems with Applications. 2021; 185: 115653.
25. Antonini A, Reichmann H, Gentile G, et al. Toward objective monitoring of Parkinson's disease motor symptoms using a wearable device: Wearability and performance evaluation of PDMonitor®. Frontiers in Neurology. 2023; 14: 1080752.
26. Mughal H, Javed AR, Rizwan M, et al. Parkinson's disease management via wearable sensors: A systematic review. IEEE Access. 2022; 10: 35219–35237.
27. Zhang H, Li C, Liu W, et al. A multi-sensor wearable system for the quantitative assessment of Parkinson's disease. Sensors. 2020; 20(21): 6146.
28. Schepers M, Giuberti M, Bellusci G. Xsens MVN: Consistent tracking of human motion using inertial sensing. Xsens. Technol. 2018; 1(8): 1–8.
29. Kim YW, Cho WH, Joa KL, et al. A new auto-scoring algorithm for balance assessment with wearable imu device based on nonlinear model. Journal of Mechanics in Medicine and Biology. 2020; 20(10): 2040011.
30. Milano F, Cerro G, Santoni F, et al. Parkinson's disease patient monitoring: A real-time tracking and tremor detection system based on magnetic measurements. Sensors. 2021; 21(12): 4196.
31. Lu R, Xu Y, Li X, et al. Evaluation of wearable sensor devices in Parkinson's disease: A review of current status and future prospects. Parkinson's Disease. 2020; 1: 4693019.
32. Heijmans MHM. Track and treat Parkinson's disease using wearable sensors and MRI [PhD thesis]. Maastricht University; 2021.
33. Jauhiainen M, Puustinen J, Mehrang S, et al. Identification of motor symptoms related to Parkinson disease using motion-tracking sensors at home (KÄVELI): Protocol for an observational case-control study. JMIR Research Protocols. 2019; 8(3): e12808.
34. Moreau C, Rouaud T, Grabli D, et al. Overview on wearable sensors for the management of Parkinson's disease. NPJ Parkinson's Disease. 2023; 9(1): 153.
35. Caballol N, Bayés À, Prats A, et al. Feasibility of a wearable inertial sensor to assess motor complications and treatment in Parkinson's disease. PloS One. 2023; 18(2): e0279910.
36. Hasan K, Biswas K, Ahmed K, et al. A comprehensive review of wireless body area network. Journal of Network and Computer Applications. 2019; 143: 178–198.
37. Preethichandra DMG, Piyathilaka L, Izhar U, et al. Wireless body area networks and their applications—A review. IEEE Access. 2023; 11: 9202–9220.
38. Poongodi T, Rathee A, Indrakumari R, Suresh P. IoT sensing capabilities: Sensor deployment and node discovery, wearable sensors, wireless body area network (WBAN), data acquisition. Principles of Internet of Things (IoT) Ecosystem: Insight Paradigm. 2020; 127–151.
39. Dziadak B, Makowski Ł, Kucharek M, Jóśko A. Energy harvesting for wearable sensors and body area network nodes. Energies. 2023; 16(4): 1681.
40. Dinov ID, Heavner B, Tang M, et al. Predictive big data analytics: A study of Parkinson's disease using large, complex, heterogeneous, incongruent, multi-source and incomplete observations. PloS One. 2016; 11(8): e0157077.