

Use of Wearable Devices in Health Monitoring: A Review of Recent Studies

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1 INTRODUCTION

About 15% of the world's population lives with a disability according to the annual world report on disability [45]. Moreover, 100 to 190 million individuals face significant difficulties in functioning. For instance, about 70 million people suffer from movement disorders, such as Parkinson's disease (PD), essential tremor (ET), epilepsy, and stroke [14]. State-of-the-art methodologies for diagnosis, treatment, and rehabilitation of this population rely on evaluations by medical professionals in a clinical environment [19]. However, as soon as patients leave the clinic it is not possible to monitor their symptoms due to lack of standard approaches [19]. Recent work suggests that *wearable internet-of-things (IoT) devices* that combine sensing, processing, and wireless communication can help in improving the quality of life of this population [18, 22, 32, 38].

Wearable sensors and mobile health applications are emerging as attractive solutions to augment clinical treatment and enable telepathic diagnostics [1, 14, 19]. Wearable devices have been recently used for monitoring of patients in a free-living home environment [28]. This capability allows doctors to understand the progression of symptoms over time [12]. Wearable devices have also shown promising results in the diagnosis and management of many movement disorders. For example, studies in [36, 44] use wearable sensors and machine learning algorithms to identify ET in patients. Similarly, Ryvlin et al. employ wearable devices to identify biomarkers that enable detection of generalized tonic-clonic seizures in patients with epilepsy [41]. Wearable technology has also been widely used in the diagnosis and treatment of PD patients [11, 48]. Despite these promising results, widespread adoption of wearable sensors and devices has been limited. Instead, they have been primarily used in research studies that occur in a more controlled environment.

This review summarizes how wearable devices are used in health monitoring. Specifically, it overviews the use of wearable devices in diagnosis, monitoring, and rehabilitation of movement disorders. Then, it discusses the major challenges and potential solutions to the adoption of wearable devices.

2 WEARABLE DEVICES IN HEALTH MONITORING

State-of-the-art methods for assessment and treatment of movement disorders are based on the tests performed in clinical examinations during which patients perform specific tasks. Diagnosis and evaluation of disease progression by visual inspection is sub-optimal as it can be affected by subjectivity of the clinician. Therefore, recent studies have explored the usage of wearable devices in the diagnosis and treatment of movement disorders [37, 39, 43]. To study the trends in the usage of wearable devices for movement disorders, we present a review of recent research in the following application areas: Diagnosis, prognosis/monitoring, predicting response to treatment, and therapy/rehabilitation.

Diagnosis/Early Diagnosis: Recent research on the diagnosis of movement disorders focuses mainly on assessing gait and tremor as these are some of the most commonly observed symptoms. The work in [47] employs an accelerometer to differentiate PD patients with gait disorder from healthy controls. Similarly, Zhang et al. [48] use data from wearable accelerometers and electromyography (EMG) sensors to develop a posture assessment system to differentiate between the tremor observed in ET and PD. Raethjen et al. study corticomuscular coherence of Parkinsonian tremor with the help of electroencephalogram (EEG) and EMG sensors [37]. Smartphones have also been used to aid in the diagnosis of ET and PD [44].

In addition to gait and tremor, many studies focus on diagnosis using non-motor symptoms, such as speech disorders and sleep disorders. For instance, Campos-Roca et al. use an acoustic data set from 40 healthy subjects and 40 PD patients to classify PD patients from the control subjects [10].

In summary, research on movement disorder diagnosis using wearable devices focuses on one of the following problems:

- Early diagnosis of PD patients
- Differentiate patients with PD from healthy controls or patients with a different neurological disorder
- Differentiating tremors caused by PD and ET

Prognosis/Monitoring the Severity of Symptoms: Objective measures are required for analysis of disease progression in patients since feedback from diaries and memory is subject to low compliance and recall bias [31]. Therefore, recent research has considered the following problems related to monitoring of patients:

- *Home-based or remote monitoring of patients:* Bächlin et al. developed a wearable system that uses accelerometers to detect freezing of gait events in PD patients [2]. Similarly, the study in [4] uses an accelerometer and a smartphone to analyze gait, dyskinesia, and motor states in real-time. Pulliam et al. [36] propose a system for continuous in-home monitoring of ET. A system for the detection of seizures in epilepsy patients is proposed in [5].
- *Evaluating the progression of movement disorders in patients:* Contreras et al. [12] propose a system that uses smartphones to analyze the severity of tremors in PD patients. The authors conclude that the proposed system can be used to evaluate the progression of PD in stages 3 and 4. Non-motor symptoms have also been used to monitor the progression of PD [29]. These studies use sensor data to analyze the emotional states of patients to better understand non-motor symptoms, such as anxiety and depression.
- *Evaluating the severity of symptoms in a patient:* Symptoms, such as tremor, can greatly affect the quality of life of patients. Therefore, recent studies have used wearable devices to evaluate the severity of tremor. Specifically, the works in [12, 36] use wearable sensors, such as gyroscope, to measure tremor amplitudes. For instance, Pulliam et al. use motion sensors to quantify the intensity of tremor in ET patients. Furthermore, the authors in [49] use four inertial sensors to assess bradykinesia and hypokinesia in PD patients.

Predicting Response to Treatment: Levodopa is one of the most commonly used medication to manage the symptoms of PD [40]. The dosage of Levodopa required varies as a function of the severity of symptoms. Currently, doctors measure the efficacy of treatment based on patients' diaries and observations. However, these inputs are highly subjective. Therefore, researchers employ wearable devices to analyze how patients are responding to treatment [34, 40]. Ruanola et al. [40] use recordings from a wireless EMG sensor mounted at the forearm to measure the effect of Levodopa in advanced PD patients. Wearable devices are also being used to understand how patients react to treatment in ET. Specifically, wearable technology can be used to monitor side-effects of ET treatment, such as heart problems [24].

Therapy and Rehabilitation: Wearable devices are also used for physiotherapy and other types of feedback in patients. For example, auditory cues and vibration-based devices have been used to help patients who experience freezing of gait [11, 43]. These methods are useful in alleviating symptoms like tremor and freezing of gait. For instance, Chomiak et al. [11] employ the sensors in an iPod touch to calculate the step height in walking. This data is then used to trigger auditory feedback to patients. Their results show that such a system is useful for stepping in place training. Similarly, Vidya et al. [43] use vibration motors on patients' wrists to reduce hand tremor. In summary, these studies show that wearable devices can be used effectively for therapy and rehabilitation in patients.

The study in [15] classifies 778 articles related to PD into one of the four application areas above. Figure 1 shows the composition of application areas for the 778 papers. We observe that the highest percentage (37%) of papers focus on diagnosis or assisting in the diagnosis of Parkinson's Disease. This is followed by the "Prognosis/Monitoring the Severity of Symptoms" category that has 36% of the papers. The other two application areas have a lower percentage of studies in the period 2008–2018. Specifically, 18% of the studies focus on therapy and rehabilitation of patients and 9% of the studies are classified in the category of predicting response to treatment. The lower number can be attributed to the fact that it is generally harder to predict the response to treatment as it requires monitoring as well.

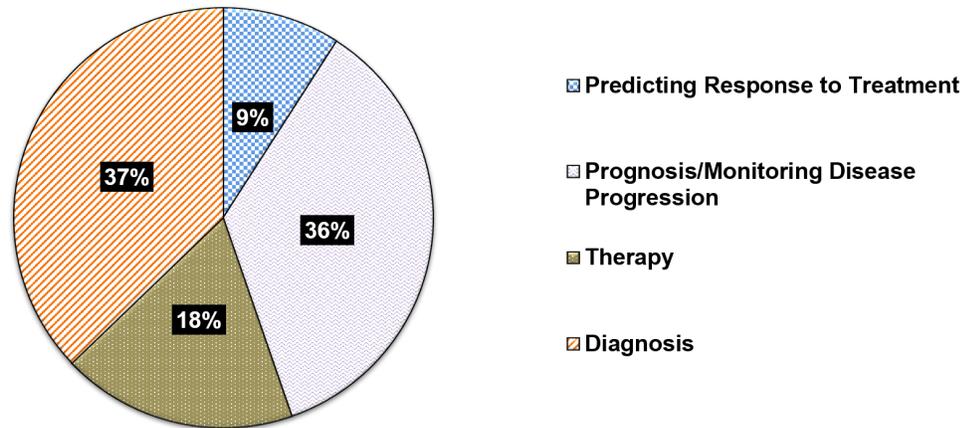


Fig. 1: Percentage of publications on Parkinson's disease between 2008-2018 by application area

In summary, this review shows that wearable devices are making a high impact on movement disorders research by enabling patients and doctors to obtain more objective measures for the diagnosis and improving home monitoring of patients.

3 WEARABLE CHALLENGES AND SOLUTIONS PROPOSED IN THE LITERATURE

The PD case study shows that wearable devices offer a great potential to improve the quality of life of patients. However, the current application of wearable devices is mainly limited to research studies. Recent research has focused on identifying the reasons that hinder the widespread adoption of wearable devices despite their potential in improving healthcare [19, 21, 23, 31]. The International Movement Disorders Task force states that non-compatible platforms, and limited applicability of "big data" acquired from the wearable devices as some of the reasons for lack of adoption [19]. Another study by Ozanne et al. [31] reports that many social and technical issues contribute to limited adoption by patients. According to surveys in [31], participants fear that bulky and rigid devices may lead to unwanted attention and a feeling of being watched. Instead, users prefer devices that are stretchable and flexible such that they can easily be worn under clothes. The surveys also highlight technical challenges, such as inconclusive recordings, privacy of data, and need for frequent recharging. Similarly, the review in [23] describes the needs of participants with various movement disorders. PD patients have typically expressed a need for wearable devices to assist in physiotherapy, while epilepsy patients want features that improve seizure management. The study in [27] states that about 32% of users stop using wearable devices after 6 months and addressing some of the issues above can enable a higher adoption rate for these devices. Therefore, a significant amount of research efforts focus on addressing one or more of these challenges [1, 6, 30]. In what follows, we overview recent research in the following areas:

- 1) Wearable IoT devices using Flexible Hybrid Electronics,
- 2) Energy-neutral operation through optimal energy harvesting and management,
- 3) New wearable applications that provide meaningful data to their users.

3.1 Wearable IoT Devices using Flexible Hybrid Electronics (FHE)

One of the major challenges faced by existing wearable devices is that they are typically rigid, which leads to patients stopping their use after a few weeks or months [31]. Flexible and stretchable electronics is emerging as an attractive technology to enable wearable devices. They can be used in applications such as electronics shirts and jackets [9]. However, the performance of pure flexible electronics is still much lower than that of conventional CMOS technologies. Flexible hybrid electronics has emerged as an attractive solution to bridge the gap between flexible electronics and CMOS technology [20, 26]. FHE technology has been used in developing health monitoring devices. For instance, Poliks et al. [35] use

it to propose a wearable EEG monitor that can monitor a user, process the signal and transmit the data to a host. The work in [46] proposes a skin temperature monitor and an electrocardiogram (ECG) sensor using the FHE technology. We use FHE technology to propose an open-source wearable device that can help alleviate non-compatibility among wearable devices [6]. Our device integrates a TI-CC2650 microcontroller, inertial motion units, and multiple communication protocols to enable monitoring of movement disorders. We envision that the wearable prototype and extensions to it can be used to create an open-source hardware/software ecosystem for health monitoring by bringing health professionals and researchers together.

3.2 Energy-Neutral Operation

Energy limitation is one of the major challenges faced by wearable IoT devices. Large and inflexible batteries are not suitable for wearable use, whereas flexible printed batteries have limited capacities. Moreover, frequent recharging is cumbersome for patients suffering from functional disability [19]. Therefore, ensuring a long lifetime is one of the most critical requirements for the success of wearable devices. Dagdeviren et al. [13] propose a piezoelectric generator that is able to harvest energy from movements of the heart, lung, and diaphragm. This device can be easily integrated into a wearable health monitoring device to harvest energy from the human body. Similarly, solar energy harvesting for wearable devices has been studied in [33]. Ambient energy harvesting necessitates the development of algorithms to efficiently manage the harvested energy such that device lifetime can be maximized. To this end, Kansal et al. [25] propose the concept of energy-neutral operation where the energy by the device in any given period is equal to the harvested energy. Algorithms for energy-neutral operation are proposed in [8, 25]. These algorithms enable energy-neutral operation by maximizing the harvested energy and allocating it optimally.

3.3 Applications Areas for Wearable Devices

High impact applications using wearable devices are instrumental to the success of wearable devices [23]. Therefore, recent research has focused on developing meaningful applications using wearable devices. One of the most commonly implemented use cases is the monitoring of physical activity [17]. These devices help users in tracking their activity and in achieving fitness goals. Furthermore, human activity recognition has been a popular research area due to its applications in movement disorders. Human activity recognition using wearable devices has been proposed in [3, 7]. Another popular application is using wearable devices for vital sign monitoring, as surveyed in [16]. Sleep monitoring using wearable devices has also received attention recently due to its potential benefits in improving user wellness [42]. In conclusion, these application areas along with FHE technology and energy-neutral operation have the potential to significantly improve the adoption rates of wearable devices.

4 CONCLUSION

Wearable devices offer great potential to improve the quality of life for patients and the general population. This article presented a review of how wearable technology is being used in the diagnosis, monitoring, rehabilitation of movement disorder patients. Then, it discussed the major challenges that hinder the widespread adoption of wearable devices. Finally, it presented new proposals that aim to improve the adoption of wearable devices. Specifically, it focused on flexible hybrid electronics, energy-neutral operation, and health applications. We envision that these solutions will lead to wider adoption of wearable devices.

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