Wearable Technologies for Parkinson's Disease: Exploring Their Clinical Potential

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There has been an increasing interest in technological interventions in Parkinson's disease (PD), particularly with regard to wearable technologies. Numerous detailed systematic reviews have recently been published examining the use of wearable technologies for specific aspects of PD, such as diagnosis or monitoring. We do not aim to replicate these: this narrative review is not intended to provide an exhaustive account of all the wearable devices being developed, but rather to help clinicians better understand their broad potential for current and future uses. In this article, we provide a practical and useful overview of wearable technologies used in the (i) diagnosis of PD, (ii) monitoring of PD symptoms and (iii) management/alleviation of PD symptoms.

Keywords

Diagnosis, monitoring, motor symptoms, neurodegenerative disorders, non-motor symptoms, Parkinson's disease, therapeutics, wearable technologies

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Parkinson's disease (PD) is a complex neurodegenerative condition that predominantly affects older people, with a rising prevalence worldwide.[1,2] There are many on-going challenges and unmet needs in PD: difficulties in making an accurate diagnosis (particularly in the early stages of the disease), troubling side effects associated with the available pharmacological treatments, a lack of effective disease-modifying therapies and a need to develop better tools to monitor both motor and non-motor symptoms.[3–6]

There has been an increasing interest in technological solutions to the above-mentioned issues, particularly with regard to wearable technologies.[7] Wearable technology can be defined as a 'device capable of processing and storing information, which has been incorporated into the clothing or accessories that a person uses on their body on a daily basis'; examples of wearable technology used in other areas of medicine include wristband devices for the detection of arrhythmia and body sensors for the detection and prevention of falls.[8–10] With regard to PD, wearable devices can incorporate inertial measurement units, which measure specific force, angular rate and orientation of a body using a combination of accelerometers, gyroscopes and sometimes magnetometers.[11,12] In addition to the physical sensors, vital aspects of wearable technologies are the algorithms used to process, interpret and analyse the raw data to derive meaningful outcomes and, in some cases, make predictions.[13,14]

In PD, there is a growing awareness that wearable technologies may improve the sensitivity, accuracy and reproducibility of capturing complex and fluctuating motor behaviours, with possible applications in diagnosis and for symptom monitoring; there are also potential uses for wearable devices in managing or alleviating motor symptoms (e.g. tremor or freezing of gait [FOG]). In the UK, this interest in wearable technology was reflected in 2023 National Institute for Health and Care Excellence (NICE) guidance (DG51: 'Devices for the remote monitoring of Parkinson's disease'), which conditionally recommended five wearable devices for use in monitoring, with calls to gather further real-world evidence about their use.[15,16] In the USA, numerous wearable devices for use in PD have received approval from the US Food and Drug Administration (FDA).[8]

Numerous detailed systematic reviews examining the use of wearable technologies for specific aspects of PD, such as diagnosis or monitoring, have recently been published.[17–22] We do not aim to replicate these: this narrative review is not intended to provide an exhaustive account of all the wearable devices being developed, but rather to help clinicians better understand the broad potential for current and future uses of wearable technology in PD. In this article, we provide a practically useful overview of wearable technologies used in the (i) diagnosis of PD, (ii) monitoring of PD symptoms and (iii) management/alleviation of PD symptoms. We will consider the potential utility of wearables in each of these areas, the evidence base for some of the currently available devices and those in development and areas for future research. As the scope of this review is focused on wearable technologies, other devices and technology (mobile phones, online applications, ambient sensor technologies, visual-based systems and modified utensils or writing devices) will not be discussed here.

Wearables and diagnosing Parkinson's disease

Despite emerging potential biomarkers, the diagnosis of PD remains clinical and is based largely on standardized clinical diagnostic criteria.[23–25] The Brain Bank Criteria cites bradykinesia as a core feature, with the addition of tremor, rigidity and/or postural instability to be reviewed alongside additional supportive features and exclusion criteria.[26] The International Parkinson and Movement Disorder Society (MDS-PD) criteria, published in 2015 and based on the work of the MDS Task Forces, added additional supportive criteria and altered the exclusion criteria; these criteria have been validated against the gold standard of expert clinical diagnosis.[27,28]

Despite such validated criteria, diagnosis remains challenging, particularly in the early stages of the disease: there is considerable clinical heterogeneity in PD with several identified subtypes; many of the clinical features overlap with other neurological conditions, and biomarkers are not accurate enough as yet to allow definitive diagnosis.[6,29] Clinicopathological studies have found diagnostic accuracy to be as low as 58% in the early stages of the disease; a more recent study using the MDS-PD criteria found the overall diagnostic accuracy to be 87.9% when applied within 5 years of disease onset.[30,31]

Making an accurate diagnosis early in the disease is particularly important regarding the potential development of disease-modifying drugs.[32,33] The concept of prodromal PD – the stage at which individuals do not fulfil the diagnostic criteria but do exhibit signs and symptoms that indicate a higher-than-average risk of developing PD in the future – is relevant here. As a 2019 review concluded, "The most critical gap in the field of PD research is to develop neuroprotective therapy … prodromal PD offers arguably the best opportunity to test neuroprotective therapy, because it is early enough in the neurodegenerative process to meaningfully intervene".[34,35] At present, although there is on-going research in this area, there are no diagnostic criteria in clinical use for prodromal PD.[36]

In the future, increased diagnostic accuracy and prodromal screening may be available with the use of biomarkers (such as serum, dermal or cerebrospinal fluid alpha-synuclein).[37] These are likely to be used within clinical research on prodromal PD and may ultimately form part of revised diagnostic criteria. However, the use of such biomarkers may be costly and challenging to roll out across all healthcare economies, particularly in low- and middle-income countries. An alternative approach to prodromal diagnosis is to assess subtle physical symptoms that may be present before the full clinical manifestation of the disease: for example, several studies have demonstrated abnormal motor functioning during the prodromal phase of PD.[38,39] Therefore, there may be a role for wearable technologies to act as a low-cost tool in the diagnosis of PD – as an adjuvant to clinical criteria to help increase diagnostic accuracy throughout the disease course and make the diagnosis in the prodromal stage.[40]

At present, there is no widespread commercial use of wearable technologies to identify early or prodromal PD outside of research settings. A 2017 systematic review noted a relative lack of high-quality data in early diagnosis, citing only five articles that dealt with the identification of prodromal PD.[21] Studies included in this review used numerous methods, including accelerometers, gyroscopes and force sensors to measure markers such as postural sway, gait and symmetry indices; currently, none of the interventions included in the review have made it outside of the university laboratory.[41–43] The applicability of this research to the identification of early PD is limited as the studies were small, and many of the participants had an established diagnosis of PD. As the authors of the review note, to investigate their use in diagnosing early PD, there is a need to validate these diagnostic devices using patients with minimal motor abnormalities; this represents a recruitment challenge, as such patients often do not present until symptoms are more marked.[21]

More recently, Schalkamp et al. used a wearable accelerometer to assess prodromal PD in the general population.[40] With the use of machine learning, the accelerometer data performed better than other established methods (genetics, lifestyle, blood biochemistry or prodromal signs) at identifying prodromal PD. This finding, that reduced acceleration manifests years before clinical PD diagnosis, suggests the potential of accelerometry as an early marker for PD.

There are still numerous barriers to the widespread adoption of wearables as a diagnostic tool in PD, as explored by Monje et al.[44] These include a lack of external validation, small sample sizes, heterogeneity of data collected, the large number of research devices developed (versus the small number commercially available) and the limitations of the technology (e.g. wrist-worn devices not capturing subtle finger tremor).

In summary, there is promising research to suggest that wearable technologies could help increase the accuracy of PD diagnosis, potentially even providing a robust and relatively cost-effective strategy for diagnosis in the prodromal stage.[38–43] However, this research is still in its early stages, and further research is needed to better validate these devices in larger and clinically appropriate populations.

Wearables for monitoring Parkinson's disease

PD is characterized by diverse and fluctuating movement abnormalities. People living with PD require longitudinal assessment of their symptoms to guide personalized management: in particular, clinicians must have an accurate understanding of how patients' motor symptoms vary throughout the day to effectively guide medication adjustments.[45] This is particularly important given the frequent and variable treatment-related motor complications patients can experience, such as motor fluctuations and dyskinetic movements.

At present, for many patients, disease monitoring is episodic in the form of clinic visits. The efficacy of the management of PD in patients is based on clinicians' global assessments, which may use clinical assessment tools such as the Movement Disorder Society - Unified Parkinson's Disease Rating Scale (MDS-UPDRS) or evaluations such as the Hoehn and Yahr staging.[45] There are significant limitations to the use of MDS-UPDRS for monitoring the progression of PD. The infrequent nature of clinic reviews means that only a brief snapshot of the disease course is captured. Moreover, MDS-UPDRS scoring is subjective (with some inter-rater variability), and the variable nature of PD means symptoms measured in the clinic may not be representative of their motor symptoms in the community.[46,47]

To try to overcome some of the above-mentioned limitations, there has been research on home monitoring, where patients collect data on their symptoms in between clinic visits (e.g. by completing either paper-based or electronic symptom diaries).[48,49] Issues with the use of diaries, such as recall bias, mismatch between patient-subjective self-reporting of function and objective ratings and problems with patients not consistently inputting data due to diary fatigue, have been noted.[50,51] Other methods of home monitoring, such as telemedicine video consultations, suffer the same problems as in-person clinic

Table 1: An overview of wearable devices conditionally approved by the National Institute for Health and Care Excellence for monitoring Parkinson's disease[23,49,56–67]

Device	Description of device	Relevant research to date
PKG	Wrist-worn device, which is used for 6–10 days and provides objective motor measurements of bradykinesia, dyskinesia and tremor. Data are also collected about immobility, medication adherence and tendency to impulsiveness.[23] It is a regulated class IIa medical device and has received clearance to be used in Australia, Europe and the USA	In many studies, the use of PKG data in addition to clinical assessment by doctors led to changes in PD management.[56–58] One study also reviewed PKG acceptability and demonstrated that 82% of participants found the PKG easy to use and 74% found PKG to be somewhat or highly valuable in providing data to manage their PD[56]
STAT-ON	Waist-worn inertial recorder. It measures dyskinesia, 'on' and 'off' periods, gait (including freezing of gait and bradykinesia), falls, energy expenditure and posture. Similar to PKG, the STAT-ON should be worn for at least 5 days. It is a CE safety-marked class IIa medical device, certified for the European market	There is less published evidence regarding the STAT-ON device, with the majority of the evidence focused on diagnostic accuracy.[59,60] There is limited evidence about patient or clinician opinions, which are generally favourable but a lack of evidence regarding the correlation between STAT-ON use and clinical outcomes[61,62]
Kinesia360 and KinesiaU	Kinesia360 is a wrist- and ankle-worn monitoring system linked to a smartphone application, whereas the KinesiaU uses off-the-shelf smartwatch technology paired with the Kinesia application to monitor Parkinson's symptoms. KinesiaU is marketed more at consumers to monitor and manage their own condition, whereas Kinesia360 is aimed at clinicians. Kinesia360 is a class I CE safety-marked and FDA-approved medical device; the KinesiaU motor assessment system is currently cleared for sale in the USA, the UK, the EU and Canada	Diagnostic accuracy is rated as moderate to good with Kinesia360.[63] There were three small studies examining clinical outcomes using the Kinesia systems, and although there were some indications that there may be motor and quality of life improvements, the study cohorts were too small to be definitive[64–66]
PDMonitor	A wearable system consisting of five devices worn on the limbs and the waist. Data on bradykinesia, dyskinesia, tremor, gait (including freezing), postural instability, 'on' and 'off' periods and activity levels are collected. It is a CE safety-marked class IIa medical device, certified for the European market	There is limited published evidence regarding the use of the PDMonitor system, and evidence regarding clinical outcomes is limited to a couple of case reports[49,67]

CE = Conformite Europeenne; FDA = US Food and Drug Administration; PD = Parkinson's disease; PKG = Parkinson's KinetiGraph; STAT-ON = STAT-ON Holter monitor.

visits as they still only provide a snapshot assessment of the patient's symptoms.[52]

Wearable devices for monitoring PD are, at face value, a highly exciting prospect. Technological advancements have produced user-friendly wearables with long battery lives, which can be worn by patients with PD at home during the day to unobtrusively assess motor symptoms. Motor symptoms that can be monitored by wearable devices include bradykinesia, tremors, motor fluctuations, postural instability, gait disturbance and dysarthria.[18,53] Such wearables have the potential to provide more objective and continuous assessments of symptoms compared with symptom diaries or intermittent clinic visits/examinations. They are of particular importance, given the global shortage of neurologists available to perform regular clinical assessments: amongst Medicare patients in the USA living with PD, >40% have not seen a neurologist, and in the UK, published waiting lists for all routine hospital treatments are predicted to reach a peak of 8 million by summer 2024.[54,55] In this sense, the data from wearables may be helpful in improving not only the quality, but also the accessibility of PD disease/symptom monitoring.

Compared with its use in the diagnosis of PD, wearable technology in PD monitoring is a more established field, with several commercially available products in use within healthcare settings. In the UK, the NICE guidance published in January 2023 now conditionally allows healthcare providers to offer devices for remote monitoring of PD.[16] Five devices fall within the guidance: Kinesia 360™ (Great Lakes NeuroTechnologies, Cleveland, OH, USA), KinesiaU™ (Great Lakes NeuroTechnologies, Cleveland, OH, USA), PDMonitor® (PD Neurotechnology Ltd, London, UK), Parkinson's KinetiGraph (PKG; PKG Health Ltd., London, UK) and STAT-ON Holter™ (Sense4Care SL, Barcelona, Spain) (see *Table 1*).[23,49,56–67] A 2022 National Institute for Health and Care Research-commissioned report of the five devices assimilated the evidence to date, including 57 studies of PKG, 15 of STAT-ON, 3 of Kinesia360, 1 of KinesiaU and 1 of PDMonitor.[15]

Many other reviews have examined the use of wearables in PD monitoring in recent years.[18,19,53,68–70] For example, in 2022, a systematic review by Ancona et al. identified 26 studies examining wearable technology to assess motor symptoms at home.[18] They found that the majority of the included studies showed positive results regarding the accuracy and reliability of wearables, but emphasized the need for more research examining the practicality and tolerability of devices. This aligns with other reviews: in 2021, Sica et al. concluded: "characteristics which were ignored by researchers, such as the system's comfort of use, set-up process, instructions for use, support, aesthetics and display, need to be strongly considered".[22] It is important to note that different wearable devices consist of different numbers of sensors, and devices with multiple sensors (e.g. on the arms, legs, sternum and wrist) may be less suitable for long-term use in a home setting compared with those that just involve, for example, a sensor on the wrist. As patient-focused research examining the use of wearable devices in arthritis has highlighted, wearable devices have to be discreet and unobtrusive for patients to tolerate.[71] The limited existing research that has specifically examined wrist-based wearables in PD has found that patients found them acceptable (and indeed preferable to manual self-reporting methods for symptom monitoring).[72,73]

A key question is the extent to which wearable devices for monitoring can effectively guide treatment modifications. There is some limited

evidence in this area: many studies have assessed the degree to which wearables can provide information sufficient to change medical management, generally finding that such data can influence treatment decisions.[56–58,74] A study compared the management of PD by doctors using a combination of objective ambulatory measurement (using the PKG device) and conventional assessment with management using conventional assessment alone.[75] This study demonstrated statistically significant improvements in the MDS-UPDRS scores with the use of the PKG device, suggesting that symptom control is improved when the management of PD is assisted by objective measurement.[75] There is, however, a lack of research investigating the effect of treatment modifications based on wearable sensors alone versus clinician-based decision alone. A 2023 review concluded: "[a]t this stage, we could only consider [wearable sensors] as a potential useful add-tool for PD treatment management, when coupled with clinical evaluation (history taking) but their clinical relevance remains to be proven".[76]

It is important to note that wearable devices for monitoring PD have overwhelmingly focused on motor symptoms.[77] Although motor symptoms are important, non-motor symptoms have been increasingly recognized as having a significant impact on patients' quality of life.[78] As a 2016 review noted, there is "an urgent need for developing unobtrusive systems to monitor nonmotor endpoints in the home and community settings".[7] There is some evidence for associations between bradykinesia and dyskinesia, as measured by wearable devices, and gastrointestinal symptoms, suggesting that wearable sensor motor data may potentially serve as a marker for some non-motor symptoms.[79] Many studies have investigated the use of wearable devices to monitor sleep dysfunction in PD (including rapid eye movement sleep behaviour disorder and nocturnal hypokinesia).[80–84] Regarding autonomic dysfunction, although traditional wearable blood pressure devices are unwieldy, there is potential for wrist-based sensors to provide quantitative assessments of parameters, such as heart rate and blood pressure.[76,77,85,86] There is thus some preliminary research suggesting that monitoring non-motor symptoms using wearables may be feasible, but the impact of such monitoring on treatment or patient outcomes has not been proven.[49,56–67]

Overall, although the application of wearables to PD monitoring is the most mature of the three sectors examined, the evidence base is still relatively limited; there is a particular need for research assessing the feasibility and practicality of wearables for long-term disease monitoring. There is also a need for more research to bridge the gap between the 'big data' acquired with wearable sensor technologies and their limited clinical applications.[7] Moreover, the cost-effectiveness of these devices also needs to be examined in more detail: the devices may represent a significant cost pressure to healthcare economies.[15]

Wearables for managing or alleviating Parkinson's disease symptoms

Once a diagnosis of PD is established, there is a broad consensus about the recognized pharmacological interventions. National guidelines have been developed, summarizing the management strategies (including the role of surgery).[87,88] Despite the general agreement around pharmacological management strategies in PD, there are recognized complications of drugs, such as levodopa (including wearing-off and dyskinesias) or dopamine agonists (impulse control disorders).[89,90] As PD progresses, patients may be suitable for advanced therapies, including deep brain stimulation or levodopa–carbidopa intestinal gel, but these are invasive interventions, and a proportion of patients will be hesitant about such options due to perceived risks.[91] Even when patients are keen to explore advanced therapies, they may be unsuitable for intervention due to comorbidities or other contraindications.

Wearable technologies have the potential to contribute to the management of PD symptoms beyond the above-mentioned treatment approaches, for example, through devices that aim to directly suppress tremor or improve gait.[92–94] Many such non-invasive devices have been developed, with some proven efficacy.[20] A 2022 systemic review concluded that although such non-invasive devices are less effective than invasive devices, such as Deep Brain Stimulation (DBS), they are easier to use and potentially more feasible for widespread use, given the lower risks of complications.[20] Indeed, wearable devices are attractive, as they avoid some of the adverse effects or risks associated with pharmacological treatment or surgery.

A variety of different devices with varying mechanisms of action have been explored. Mechanisms used to control tremors include the following: (i) transcutaneous electrical nerve or muscle stimulation, (ii) passive biomechanical loading to dissipate the energy and dampen the tremor and (iii) orthoses containing elements that exert an active force to counteract the tremor.[95–98] Mechanisms to improve gait and combat FOG include the following: (i) devices that make use of 'cueing' (the use of visual, auditory or tactile stimuli as triggers to help initiate or continue movement), (ii) peripheral mechanical stimulation, intended to correct gait abnormalities and enhance motor performance and (iii) wearable exoskeletons designed to facilitate neurorehabilitation or reduce freezing.[99–105]

A huge array of devices are in various stages of development – for a clinician, it can be challenging to determine which devices have a clear evidence base for use in PD and which are approved for clinical use in various jurisdictions. It is important to note that many of those with initially promising published data are not Conformite Europeenne (CE) marked/FDA approved (so are not available for clinical use), while some that have been approved for clinical use lack published evidence to support their use. Furthermore, some devices have received media attention, even though they are still in the early stages of development and far from being available in a clinical setting (e.g. a non-invasive vibrotactile glove developed at Stanford University used to alleviate motor symptoms).[106,107]

In *Table 2*, we have summarized some examples of wearable devices for the management of symptoms, such as tremor and FOG, which are currently approved for clinical use; this is intended to give an overview of some of the different types of devices available and is not exhaustive.[96,97,108–115]

In general, research in this area is in its remarkably early stages: many of the studies are highly small scale and of variable quality, and many of the devices included in recent reviews are prototypes. Moreover, relatively little research has involved experimental validations of devices with a control group using a sham version of the device. As in other areas discussed earlier, methodological heterogeneity limits the strength of conclusions that can be drawn; for example, different studies often use different methods to quantify tremor reduction, making it difficult to compare the results. There is also a lack of data on the feasibility and acceptability of many of these devices for everyday use for patients – this is particularly notable for some of the larger exoskeletons or orthoses, for which this may be a significant barrier to their use.

Table 2: Examples of wearable devices for reducing tremor or freezing of gait that are currently approved for clinical use[96,97,108–115]

Device	Type of device	Description of device	Relevant research to date
Cala Trio (Cala Health, San Mateo, CA, USA)	Electrical nerve stimulation	An FDA-approved electrical nerve stimulator with two electrodes over the median and radial nerves plus an accelerometer that measures the frequency of the tremor, thereby modulating the stimulation intensity depending on the tremor frequency. The device is currently intended for use in essential tremor rather than in PD	A small case series of 5 patients with PD demonstrated electrical stimulation of the median and radial nerves, leading to a 57% tremor suppression.[96] A larger study involving the use of the device for 3 months in patients with essential tremors demonstrated improvements in upper limb tremors[108]
MotiMove (3F-Fit Fabricando Faber, Beograd, Serbia)	Electrical muscle stimulation	A CE safety-marked multichannel stimulator, which is placed on the forearm and upper arm. This system delivers out-of-phase stimulation by sending electrical current pulses to the flexor and extensor muscles, triggering the depolarization of motor neurons to counteract tremorgenic activity	A study of 7 patients with PD/essential tremor demonstrated a significant decrease in the amplitude of tremor[109]
Tremelo (Five Microns, Fresno, CA, USA)	Biomechanical passive suppression	An FDA-approved wearable sleeve, where springs attached to weights dampen tremors in a similar manner to methods used in stabilizing skyscrapers. The device is currently intended for use in essential tremor rather than in PD	Limited evidence for reduced tremor in an analysis of its use in 2 patients with PD[97]
Gondola (Gondola Medical Technologies, Lausanne Switzerland)	Automated mechanical peripheral stimulation	An FDA-approved and CE safety-marked device applied to the feet, which applies pressure pulses to the head of the big toe and the first metatarsal joint. The overall treatment consists of four repetitions of the stimulation cycle (total: 2 minutes). Currently, patients must visit a Gondola Partner Centre (all in Europe) to access the device	Evidence for increases in stride length and gait speed.[110,111] The Gondola promoted faster walking with longer strides after six to eight stimulation sessions in the study 'Peripheral neurostimulation breaks the shuffling steps patterns in Parkinsonian gait: A double blind randomized longitudinal study with automated mechanical peripheral stimulation' (Foot Mechanical Stimulation for Treatment of Gait and Gait Related Disorders in Parkinson's Disease and Progressive Supranuclear Palsy. [GONDOLAPILOTA]; ClinicalTrials.gov identifier: NCT01815281)[112]
CUE1 (Charco Neurotech, Cambridge, UK)	Vibrotactile stimulation and cueing	A CE safety-marked non-invasive-focused stimulation device attached to the sternum via a medical adhesive patch, which uses a quiet electric motor to produce high-frequency vibrotactile stimulation. It is currently commercially available in the UK (although there is a waiting list due to high demand), with plans to launch in other countries such as the USA and Australia	Case reports show reduced FOG and improved MDS-UPDRS III scores.[113–115] A small feasibility study involving patients with PD demonstrated that the study design was acceptable and that further studies, specifically designed to explore the efficacy of the SVSD, should be designed on a larger scale[113]

CE = Conformite Europeenne; CUE1 = Vibrotactile stimulator; FDA = US Food and Drug Administration; FOG = freezing of gait; MDS-UPDRS = Movement Disorder Society - Unified Parkinson's Disease Rating Scale; PD = Parkinson's disease; SVSD = sternal high frequency vibrotactile stimulation device.

It is also important to note that much research on wearables for tremor suppression has not been specific to PD; for example, tremor control devices have been explored in the management of essential tremors or in tremor disorders more generally.[92,116] Indeed, many clinically approved devices (such as Tremelo and Cala Trio) are intended for use in essential tremors, with only limited evidence for their use in PD.[117,118] Although there may be some overlap in therapeutic effect, it is important to ensure that devices are adequately tested in patients with PD to assess their validity in this population.

In summary, the use of wearables for managing motor symptoms in PD is an emerging area, but the evidence generated to date is generally still of low quality. Although nearly all devices present a low risk of harm, there is not enough evidence to recommend any of the devices discussed be adopted for widespread clinical use.

Conclusion: Current limitations and future directions

There is an undoubted appeal of wearable technology to people with PD. However, devices are often marketed as providing a simple answer to what represents a highly complex situation; there are more than 40 symptoms associated with PD, but most devices focus on measuring or treating only a handful.

A few important limitations in the field need to be acknowledged. Regarding the measuring and monitoring of symptoms, none of the devices discussed earlier are able to quantify all the cardinal features of PD; for example, STAT-ON does not measure tremor, and PKG does not assess gait. There is a general lack of consensus on which symptoms are the most important to focus on (for both diagnosis and monitoring); clarity is required in this area, particularly if the data from wearables are

to be incorporated into diagnostic criteria or treatment guidelines in the future. Moreover, research on wearable devices to detect and monitor non-motor symptoms lags behind.

There is currently a significant gap between the number of devices being developed and the number of devices approved for clinical use. For example, the use of wearables in early diagnosis of PD is a promising field, yet there are no devices in widespread commercial use; a lack of external validation for devices in sufficiently sized and clinically appropriate populations are current barriers to their uses. For wearables used in the management of PD, many devices have been approved for clinical settings, but there is relatively a dearth of high-quality evidence supporting their use.

A challenge for all these wearable technologies concerns a lack of compatibility across platforms. Most wearable systems developed are not compatible with one another; as a 2016 review noted, the development of this technology "is currently advancing in isolated silos rather than as part of concerted actions aimed to implement open platforms".[7] Additionally, the impact that commercially available wristwatches/activity trackers may have on further development in the field needs to be considered. This is exemplified by the advent of StrivePD (Rune Labs, San Francisco, CA, USA), a collaboration between Apple and Rune Labs providing patients the ability to monitor their disease using the Apple smartwatch and a mobile-based application, which was approved by the FDA in 2022.[119] It is possible that dedicated wearable PD-monitoring technology will become obsolete in favour of algorithms in applications linked to the already widely available consumer products such as the Apple watch; this blurring of the divide between what constitutes a medical or wellness device presents challenges for regulation.[120] The challenges and complexities of commercializing wearable technologies more generally have been explored, and for wearables in PD, the interface between more traditional academic research institutions and technology corporations will be important in shaping the field.[121,122]

Overall, although wearable devices have the potential to contribute significantly to the care of people living with PD, for the vast majority of devices, this potential has yet to be fully realized. There has been an exponential growth in the evidence base for wearables in PD over the past 5 years and this is likely to grow further over the next 5 years. Consensus guidelines are required to clarify key areas for researchers and allow common standards when using wearable technology in the diagnosis, monitoring or treatment of PD. ❑

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