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Topical Review

Wearable technologies to measure clinical outcomes in multiple sclerosis: A scoping review

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Abstract: Wearable technology refers to any sensor worn on the person, making continuous and remote monitoring available to many people with chronic disease, including multiple sclerosis (MS). Daily monitoring seems an ideal solution either as an outcome measure or as an adjunct to support rater-based monitoring in both clinical and research settings. There has been an increase in solutions that are available, yet there is little consensus on the most appropriate solution to use in either MS research or clinical practice. We completed a scoping review (using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) guidelines) to summarise the wearable solutions available in MS, to identify those approaches that could potentially be utilised in clinical trials, by evaluating the following: scalability, cost, patient adaptability and accuracy. We identified 35 unique products that measure gait, cognition, upper limb function, activity, mood and fatigue, with most of these solutions being phone applications.

Keywords: Multiple sclerosis, wearable technology, mHealth, biosensors, remote sensing technology, mobile applications

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Introduction

Assessment of new treatments in multiple sclerosis (MS) studies necessitates effective, reliable and validated outcome measures. Most clinical MS outcome measures are rater dependent and are applied episodically.[1] Clinical trials in MS require sensitive outcome measures, that can detect small changes in disability or functional improvement on a frequent basis, which can then reliably reflect long-term changes.[2]

With the advances in technology over the last few decades, it is now possible to explore methods of accurate, sensitive and objective continuous remote monitoring.[3,4] The World Health Organization (WHO) defines mHealth as a medical and public health practice supported by mobile devices, such as mobile phones.[5] Wearable technology is defined as incorporating a microprocessor and an Internet connection. Wearable technology, otherwise often referred to as wearables, are mobile technology solutions that can be worn by the person, as accessories or even embedded in clothing, and often include passive or active tracking capabilities which can be used to assess health and well-being.[6] Our definition of wearable technology encompasses mHealth solutions because the growth of mobile networks (3G, 4G and 5G) has enabled the development of wearables. Wearables evolved from fitness activity trackers to wristwatches and the more robust mobile applications including Bluetooth headsets, smartwatches and smartphones. Common examples of these devices include the Fitbit® activity band and smartphone applications like MapMyRun®. Advancements in wearable technology and phone applications ('apps') enable continuous patient-based monitoring and provide feedback on daily life. The results of daily monitoring using wearable technology could be used either as an outcome measure or as an adjunct to support rater-based assessments. There has been an increase in solutions that are available for those who are diagnosed with chronic illness, especially in regard to neurological disease.[7] Yet, there is little consensus on the most appropriate solution to use in either MS research or clinical practice.

Studies have shown that patients, caregivers and health care professionals find value in using such

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Table 1. Potential advantages and disadvantages of wearable technology in trials.

Advantages	Disadvantages
Continuous or frequent monitoring	Cost of device
Remote monitoring ability	Secure data storage
Less invasive	Local skin irritation
Decreased travel burden for participants	Troubleshooting device
Feedback to the participant	Charging and battery life of devices
Ease of use	Software upgrade incompatibility

devices, especially when they are less invasive in day-to-day situations and provide real-time feedback.[8,9] Currently, there are two randomised controlled trials (RCTs)[10,11] that have utilised wearable technology in people with multiple sclerosis (PwMS); however, there are several more RCTs currently ongoing that utilise wearable technology, for example, the MD3001 (SPI2) trial.[12]

The advantages and disadvantages of wearable technology are summarised in Table 1 above.

Software upgrades could be one of the biggest limitations to wearables produced by commercial entities. The upgrade also applies to device algorithms as manufacturers attempt to improve both parameter estimation and user satisfaction. This leads to a change in not only the appearance and behaviour of the device but also the algorithms used in logging and reporting the data.[13] Maintaining a solution through a trial without a software update is difficult, and if an update is done, it could significantly change any wearable-related outcomes.

The rationale for conducting this scoping review was to understand each solution and its utility in MS. This review was commissioned by the UK MS Society on behalf of the Outcome Measures Working Group (part of the Expert Consortium on Progression in MS Clinical Trials, a UK MS Society initiative). We reviewed wearable technology solutions with a particular interest in their potential to detect changes in function for PwMS in a more reliable and accurate manner, and their suitability for use in a UK-wide multi-centre platform trial.

Objective

The objective was to identify all validated wearable solutions for PwMS and determine suitability for use in a UK-wide multi-centre platform trial by considering the following factors: reproducibility in MS populations, feasibility (including cost), patient adaptability and prior use in an RCT.

Methods

We used a scoping review approach which aims to map the key concepts underpinning a research area, especially where an area has not been reviewed comprehensively before (Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR)).[14]

Our search strategy utilised subject heading searches: 'Multiple Sclerosis' and 'wearable electronic devices', as well as keywords 'wearable technology' and 'electronic devices'. The literature search was conducted using MEDLINE (via PubMed) and Embase (via OVID) databases. This search included articles published from database inception to 30 May 2019. Additional searches looked at authors who have frequently published with different devices as well as forward and backward citation tracking of included papers. The scoping review followed the PRISMA-ScR guidelines.[15]

When examining suitability of a wearable device for use in a UK-wide multi-centre platform trial, we considered several factors: reproducibility (defined as the number of studies examining the solution in MS), feasibility (including cost), patient adaptability and prior use in an RCT. The results of this are shown in Figure 2 and Table 2.

Study eligibility criteria

The inclusion criteria were defined as (1) primary research studies that used wearable technology in a cohort of PwMS of all ages (adult or paediatric), (2) studies from any geographical location and (3) reported in the English language. Exclusion criteria were defined as (1) wearable solutions intended for another health condition, (2) non-wearable solutions, (3) non-primary research such as narrative reviews and (4) abstracts that did not have full-text available.

After screening titles and abstracts, duplicates were removed and the full text of each paper was assessed for eligibility according to the criteria stated above.

Table 2. Summary of unique solutions and their general characteristics.

Wearable in use	Solution type	Cohort (*n*)	Type of study	Purpose	Functional area of assessment	Outcome	Test environment	Additional requirements for solution
ActiGraph wGT3X-BT[10]	Hardware	80 MS	RCT	Used to monitor activity levels in a trial to see effect of core exercise on PwMS	Activity level lower limb	Core exercises helped PwMS increase activity levels	At home	Not available
My eReport France (private app)[11]	Software	180 MS	RCT	Mobile phone application for drug adverse reaction reporting by patients with RRMS in an RCT	Self-management	Study not completed and results not yet available	At home	Apple iPhone, iPad or iTouch and requires iOS 7.1 or later Android OS 3.0 and up
BETACONNECT, myBETAapp[16]	Hardware, software	>100 MS	Interventional	Bayer produced app to assist the BETACONNECT auto injector and to help self-manage symptoms and dose	Injection/ self-management	Shown to be an effective patient self-management tool for disease-modifying therapy alongside auto injector	At home	BETACONNECT auto injector IPhone iOS 9.0 or later Android 4.4 and up
Fitbit Flex[17]	Hardware	95 MS	Interventional	To assess continuous step count activity remotely among PwMS for 1 year and determine how average daily step count is associated with other measures of MS disability	Lower limb	Appears to be feasible to monitor for 1 year. It showed a decrease in average daily step count correlated to worsening of standard ambulatory measures	At home	IPhone iOS 12.2 or higher Android OS 7.0 or higher
Keeogo exoskeleton[18]	Hardware	29 MS	Interventional	An exoskeleton for lower extremity to enable PwMS to benefit from exercise and physical activity	Lower limb	Lower extremity exoskeleton, exercise-mediated benefit to PwMS that improves unassisted gait endurance and stair climbing	At home and in controlled clinic setting	Nil
TEAMS (private app)[19]	Software	10 MS	Observational	A tailored telerehabilitation app: Participant-Centered Development and Usability Study	Activity level	App that allows for PwMS to follow an exercise programme and showed good usability. Currently being studied in an RCT	At home	Android iOS phone or tablet Adjustable floor stand
StepWatch Activity Monitor[20]	Hardware	64 MS	Observational	Understanding walking activity in MS: step count, walking intensity and uninterrupted walking activity duration related to degree of disability	Activity level	Results showed everyday walking in PwMS was not high and that PwMS rarely walk for more than 6 minutes uninterrupted	At home	Nil
Digi-walker SW-200 pedometer, Jawbone UP2, Jawbone UP Move, Fitbit Flex and Fitbit One AND Health app, Health Mate, Moves[21]	Hardware, hardware, hardware, software, software, software	45 MS	Observational	This study examined the accuracy and precision of common smartphone applications and motion sensors for measuring steps taken by MS patients while walking on a treadmill	Activity level	Fitbit One was the best and most precise solutions for measuring steps but more research is needed before inclusion in clinical research	In controlled clinic setting	Additional software required on a smart device

(Continued)

Table 2. (Continued)

Wearable in use	Solution type	Cohort (*n*)	Type of study	Purpose	Functional area of assessment	Outcome	Test environment	Additional requirements for solution
StepWatch Activity Monitor, GT3X+ ActiGraph[22]	Hardware, hardware	63 MS	Observational	Accuracy of StepWatch and ActiGraph accelerometers for measuring steps taken among persons with MS	Activity level	Results showed that the StepWatch was a more accurate choice of accelerometer, especially in those with higher disability levels	In controlled clinic setting	ActiLife 6 software
7164 and GT3X ActiGraph[23]	Hardware	41 MS, 41 HC	Observational	Comparison of ActiGraph activity monitors in persons with MS and controls	Activity level	There was enough discrepancy between the two models to show they are not interchangeable under free-living conditions	At home and in controlled clinic setting	Personal computer with USB 2.0 connection
StepWatch Step Activity Monitor (SAM)[24]	Hardware	9 MS	Observational	Validity of the StepWatch SAM: preliminary findings for use in persons with Parkinson disease and MS	Activity level	Results showed that the StepWatch accurately measured step count for those with MS	In controlled clinic setting	Data are downloaded to a host computer via a docking station
ActiBelt[25]	Hardware	30 MS	Observational	Creating a robust and autonomous measurement device for long-term monitoring of patient activity	Activity level	Preliminary results are promising but the algorithm needs to be modified to allow for more sensitivity	In controlled clinic setting	Nil
Private app[26]	Software	22 MS, 17 HC	Observational	This study illustrated some of the novel approaches that smartphones provide to monitor MS patients in their natural setting	Activity level Cognition Fatigue	Results show the feasibility of and barriers to deploying a smartphone platform to gather passive and active data. Overall positive data show smartphone platform may therefore enable large-scale studies of PwMS	At home	Android HTC 4G Smartphone
MS TeleCoach (Private app)[27]	Software	75 MS	Observational	Assess feasibility of the MS TeleCoach offering telemonitoring of fatigue, telecoaching of physical activity and energy management over a 12-week period	Activity level Fatigue	Intervention was well accepted and shows use of MS TeleCoach as a self-management tool in PwMS suffering from mild disability and moderate to severe fatigue appeared to be feasible	At home	Not available
activPAL3[28]	Hardware	20 MS	Observational	Validity of the activPAL3 activity monitor in people moderately affected by MS	Activity level Lower limb	Good for moderately affected PwMS – slow walking cadence produced large inaccuracies	In controlled clinic setting	ActivPAL Professional Software version 7.2.23
Fitbit Flex, GT3X ActiGraph[29]	Hardware, hardware	99 MS	Observational	Continuous daily assessment of MS disability using remote step count monitoring	Activity level Lower limb	Evaluated in an RMS and PMS cohort and shown to support remote step count monitoring as an exploratory outcome in MS trials	At home and in controlled clinic setting	Fitbit flex software

(Continued)

Table 2. (Continued)

Wearable in use	Solution type	Cohort (*n*)	Type of study	Purpose	Functional area of assessment	Outcome	Test environment	Additional requirements for solution
Phone app (private)[30]	Software	5 MS	Observational	Self-management phone app for PwMS to capture data about symptoms, physical activities, mood and goals	Activity level Mood	Created a low-fidelity prototype and the high-fidelity prototype is being built to be further evaluated	At home	Not available
Floodlight Open[31]	Software	76 MS, 25 HC	Observational	Testing feasibility of remote active testing and passive monitoring using smartphones over 24 weeks. These tests included Cognition (SDMT), Upper Limb (Pinching test and Draw a Shape), Gait and Posture (25FW, 5UTT), Daily mood questionnaires and symptom tracker	Balance Cognition Lower limb Upper limb QoL	Floodlight Open showed strong correlations to the SDMT, 9HPT and 25FW. Older version of the app (FLOODLIGHT) also included the MSIS-29 which had a good correlation; however, this module is unavailable for the Floodlight Open model	At home and in controlled clinic setting	Apple: Requires iOS 11.0 or later. Compatible with iPhone, iPad, and iPod touch Android: Requires OS 7.0 and up
MSPT[32]	Software	51 MS, 49 HC	Observational	The Multiple Sclerosis Performance Test and iPad-based disability assessment tool. Includes five performance modules: Walking speed to simulate walking speed test (WST), balance test, Manual Dexterity Test for upper limb function, Processing Speed Test to simulate the SDMT, low-contrast letter acuity test designed to simulate the Sloan LCLA test	Balance Cognition Lower limb Upper limb Visual	Well accepted by patients and strong correlations to their respective standard neurological test. Currently being tested for use in a clinical setting	In controlled clinic setting	Apple iPad (no other details)
MSiDMT (private)[33]	Software	40 MS	Observational	iPad-based SDMT test, testing correlation of the iPad solution to the SDMT	Cognition	There was a strong correlation between the MSiDMT and the SDMT and it was well accepted by PwMS	In controlled clinic	Apple iPad (no other details)
Level Test (private app)[34]	Software	29 MS	Observational	Smartphone embedded sensors to measure various neurological functions using gamification	Cognition	Measured outcomes showed moderate correlations with various clinical scales and components of neurological examination. Certain level tests discriminated MS from HC	In controlled clinic setting	Android 8.1 Oreo OS and up
Activity monitor (private)[35]	Hardware	21 MS	Observational	Examine the impact of MS disability on physical activity behaviours involving ambulation	Lower limb	The activity monitor showed that daily step strongly related to gait and balance measures. EDSS and MSWS scores also strongly related to daily step count	At home and in controlled clinic setting	Nil

(Continued)

Table 2. (Continued)

Wearable in use	Solution type	Cohort (*n*)	Type of study	Purpose	Functional area of assessment	Outcome	Test environment	Additional requirements for solution
MIMU (MTw, Xsens)[36]	Hardware	20 HC and 10 MS	Observational	Using sensors to try and detect gait characteristics while ascending stairs	Lower limb	Detected MS-specific gait patterns that would not be picked up otherwise	In controlled clinic setting	Parameters computed from MIMU signals using MATLAB
x-IMU(x-io)[37]	Hardware	17 MS, 23 HC	Observational	Quantifying mobility impairment in MS, with a thigh-derived inertial sensor metric to assess the sit-to stand and stand-to-sit transitions in the Timed Up and Go task	Lower limb	Shown to be effective at differentiating between HC and MS	In controlled clinic setting	Micro SD cards to transfer data to a computer Binary file converter software
Dynaport sensor, OPAL sensors[38]	Hardware, hardware	14 MS	Observational	Using sensors to quantify gait characteristics and gait deficits from prolonged daily living measurements	Lower limb	Validated a method to quantify walking in real life in PwMS	At home and in controlled clinic setting	Nil
OPAL sensors[39]	Hardware	12 MS, 12 HC	Observational	Using sensors, to quantify head and pelvis movement patterns that occur in PwMS with disability and determine how these secondary gait compensations impact on gait stability	Lower limb	Efficient way to screen for excessive compensatory movements and provides information that impacts mobility, stride time, gait stability. Good for identifying high risk of falls	In controlled clinic setting	Custom software in MATLAB and developer protocols
Garmin forerunner 230[40]	Hardware	73 MS	Observational	Evaluate the agreement between patients' and neurologists' estimates of maximum walking ability and patients' mean maximum walking ability measured in daily life using GPS smartwatch	Lower limb	Confirmed patient estimate of distance walked is poor and shows that remote monitoring is a good way forward	At home	Not available
BioStampRC[41]	Hardware	30 MS	Observational	A machine learning approach for gait speed estimation using skin-mounted wearable sensors	Lower limb	Results support the use of wearable accelerometer arrays for estimating walking speed in normal subjects and their extension to MS patient cohorts with gait impairment	In controlled clinic setting	BioStampRC Investigator Application
OPAL sensors[42]	Hardware	52 MS, 21 HC	Observational	Validation study of the Instrumented Push and Release Test to quantify postural responses in persons with MS	Lower limb	Demonstrated strong agreement and correlation between sensor-based metrics and gold standard laboratory measurements. Several metrics were shown to be different between PwMS and HC	In controlled clinic setting	Custom MATLAB algorithm
BioStampRC, GT3X ActiGraph[43]	Hardware	45 MS, 15 HC	Observational	Monitoring gait in MS with novel wearable motion sensors	Lower limb	Results showed that the BioStamp is the most accurate device	In controlled clinic setting	Custom-developed MATLAB algorithm

(Continued)

Table 2. (Continued)

Wearable in use	Solution type	Cohort (*n*)	Type of study	Purpose	Functional area of assessment	Outcome	Test environment	Additional requirements for solution
G-sensor[44]	Hardware	105 MS, 47 HC	Observational	This study aims to verify the feasibility of using wearable accelerometers in an ambulatory environment to assess spatiotemporal parameters of gait in PwMS, as well as the correlation of objective data with patient-reported outcomes	Lower limb	Wearable accelerometers are a useful tool for assessing gait performance in PwMS in a clinical setting, especially in mild to moderate disability	In controlled clinic setting	BTS Bioengineering G-Studio® computer software
OPAL sensors[45]	Hardware	5 MS, 13 HC	Observational	To determine whether gyroscopic corrections improve wearable sensor data prior to measuring dynamic sway in the gait of PwMS	Lower limb	The visualisation of asymmetric pelvic sway in PwMS illustrates the potential to better understand their mobility impairments for reducing fall risk	In controlled clinic setting	Custom software
MSdialog, app[46]	Software	76 MS	Observational	A web- and mobile-based software application, captures data on self-administration of subcutaneous interferon β-1a, clinical outcomes and patient-reported outcomes in patients with MS outside the clinic	Self-management	Well accepted by users and user retention was high over 6 weeks. PwMS found it easy to use and superior to previous methods for tracking health	At home	MSdialog web-based software and optional phone- and tablet-based application
FAMOS (private)[47]	Hardware	17 MS, 9 HC	Observational	A wireless body measurement system to study fatigue in MS	Fatigue	Preliminary results show significant differences between fatigued PwMS and HCs. This provides a new approach to study fatigue in MS but needs to be validated through larger clinical trials	At home	Custom LabVIEW software
iPad visual scale (private)[48]	Software	52 MS, 52 HC	Observational	To explore the reliability and feasibility of electronic visual analogue scales in PwMS and health individuals	Fatigue QoL	Reliable and useful for PwMS to register fatigue, pain, anxiety and QOL	In controlled clinic setting	Smartphone (Huawei Ascend G6) Tablet (Samsung Galaxy Tab S 10.5)
Phone app (private)[49]	Software	76 MS, 19 HC	Observational	Two smartphone tests of fine finger movements to see if correlated with neurological examination	Upper limb	Good correlation with 9HPT and captured richer data than traditional measures	At home and in controlled clinic setting	Android 8.1 Oreo OS and up

MS: multiple sclerosis; HC: healthy control; RMS: relapsing multiple sclerosis; RRMS: relapsing remitting multiple sclerosis; PMS: progressive multiple sclerosis; PwMS: people with multiple sclerosis; RCT: randomised controlled trial; SDMT: Single Digit Modality Test; 25FW: 25 Foot Walk; 5UTT: 5 U-Turn Test; MSIS-29: Multiple Sclerosis Impact Scale; WST: Walking Speed Test; EDSS: Expanded Disability Status Scale; MSWS: Multiple Sclerosis Walking Scale; QoL: quality of life; 9HPT: 9-Hole Peg Test; Sloan LCLA: Sloan Low-Contrast Letter Acuity; GPS: Global Positioning System.

Data extraction

The data to be extracted for each article were determined in consultation with the second author (G.P.) and a data extraction form was created. Descriptive characteristics were extracted where available for (1) wearable device, (2) cohort, (3) type of study, (4) purpose, (5) functional area of assessment and (6) outcome.

Developers of the wearable technology were separated into the following categories:

- Health care–related agency: Hospitals, clinics or government organisations directly related to health care
- Pharmaceutical company: entities with commercial purposes to research, develop, market or distribute drugs in the context of health care
- Educational organisation: any educational organisations such as universities, colleges, libraries or schools not directly related to health care
- Small and medium enterprises: start-ups, software developing companies or any other private organisation that identified themselves as an enterprise and not individuals

Results

The searches yielded 1880 potentially relevant articles. Removing duplicates and applying the eligibility criteria resulted in a total of 35 unique MS wearable technology solutions, which included 3 unique solutions that were yielded from conferences and scientific meetings. Figure 1 describes the PRISMA flow diagram.

The list of the included wearable technology solutions and the frequency with which they appeared in validated studies is shown in Figure 2. A majority of the solutions that were used in studies in PwMS were applications (apps), accelerometers and activity monitors. The older studies predominantly focused on measuring activity, walking or gait since activity monitors, accelerometers and gyroscopes were the most readily available and advanced technology at the time. This result is not unexpected because the nature of MS disease progression would require sensors focused on assessments based on activity and function, both easily derived from accelerometers. Within the solutions available for monitoring activity levels, there is great variability between the outcomes available. Certain solutions provide a basic step count for example, Fitbit, whereas others provide additional metrics such as stride length and gait characteristics. It is important to determine the key outcome measures of interest to best guide which wearable to use. Included are four unique app solutions for cognition, which were all created more recently, as apps are becoming an easier wearable technology to develop and deploy. There were a handful of wearables that focused on fatigue, mood, quality of life (QoL) and self-management.

A summary of the general characteristics of the unique wearable technology solutions found is shown in Table 2.

There is significant variability in the per-unit cost of each product, and the decision as to which wearable to use depends largely on the study budget and outcomes of interest. Costs may vary significantly when using a physical wearable sensor compared to a smartdevice application. Aside from per-unit cost, other considerations include repair or replacement of faulty devices, annual maintenance charges, software package costs, return of devices, charging capabilities and collection of data (postage vs. remote upload). Physical wearable sensors risk being ‘phased out’ and being replaced with newer models that have not been tested in an MS population. Applications may alleviate this problem by sending out software updates, which the user can download. Users could however face problems if this update exceeds the smart device support capability.

There does seem to be a shift towards developing more validated wearable technology solutions for MS and focusing on health care adoption to make sure that dissemination of the solutions is more successful and reaches a wider population. This is seen by the increase in the number of publications related to the subject of wearable technology in MS. In addition, as a result of an increased number of solutions being validated, wearable technologies are now becoming more utilised in RCTs. At the time of writing this review, we had identified two RCTs that utilise wearable technology; however, we are aware of at least one other RCT which was published using wearable technology in MS.[50] We believe that this study did not appear in our literature search, because the term ‘wearables’ or ‘mHealth’ is not used in the paper nor is it referred to in the keywords or subject headings. We acknowledge that our search terms may have excluded other studies involving wearable technology, in MS. We are also aware of several other RCTs that are currently being run, that employ wearable technology such as the SPI2 and TEAMS studies.[51,52]

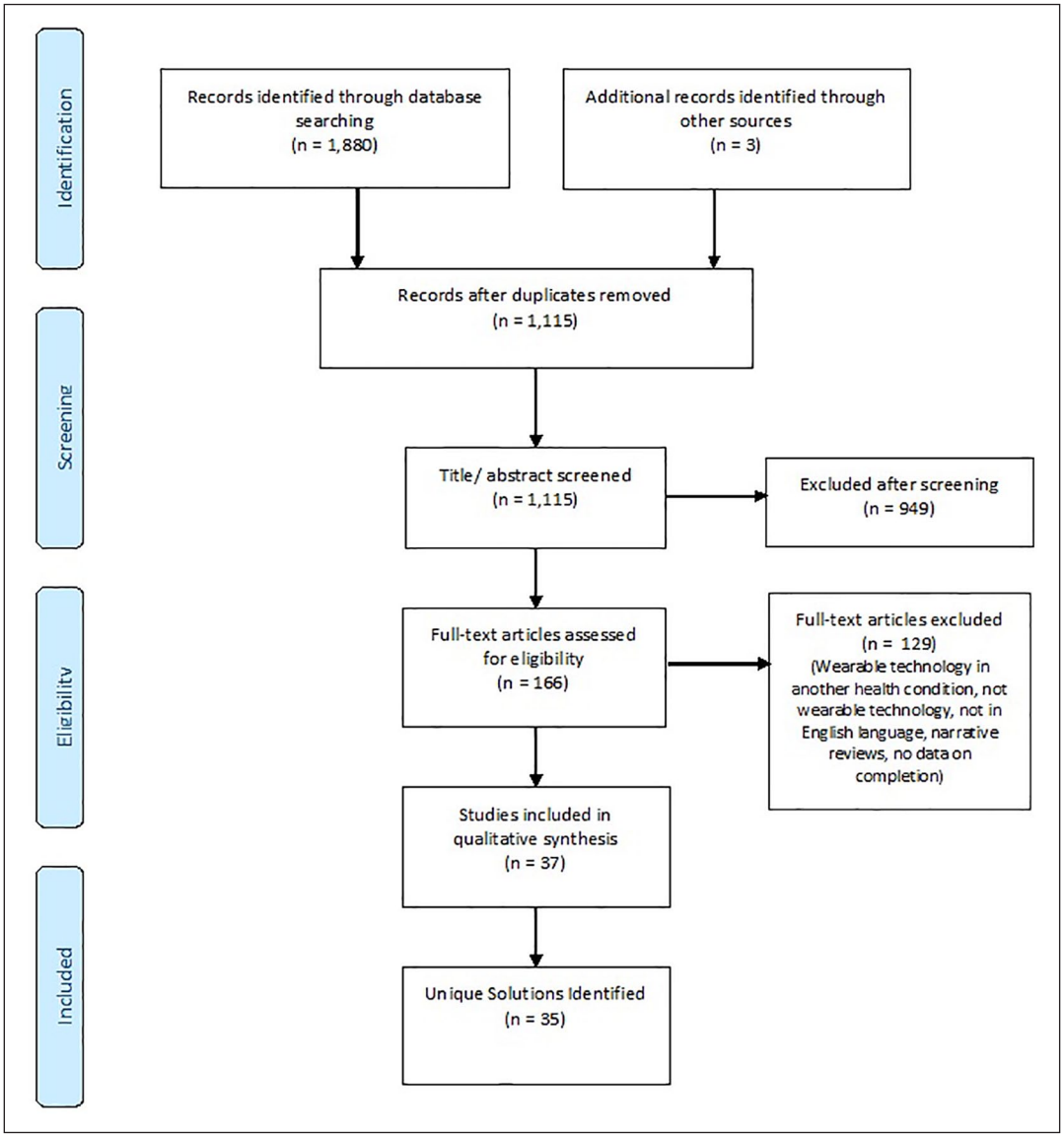

Figure 1. PRISMA flow diagram.[53]

While doing this review, we identified 10 (27%) solutions that we classed as 'private' solutions as they had been created, tested and not available to the public, as shown in Table 2. This seems to have happened for various reasons, including not having the necessary resources to further validate or improve the solution or not having enough resources to gain regulatory approval. All the identified solutions that are private and unavailable were created by health care or educational organisations. Ideally, independent validation prior to clinical or research use seems appropriate; however, this may not be feasible due to on-going costs. When comparing this to the solutions created or funded by pharmaceutical companies, for example, the FLOODLIGHT app and the MSPT, it was shown that 98% of the solutions created by pharmaceutical companies were successfully implemented and disseminated, as they had enough resources to manage the on-going cost and effort required to gain regulatory approval and market the products.

Wearables are gaining importance in MS; however, there are many lessons to be learnt from its use in other chronic neurological disorders, such as Parkinson's disease.[54] While the promise of unsupervised assessments is alluring, and could save time and cost, using these devices in clinical and research settings is far from seamless due to several issues. Many wearable devices have not been validated or approved for clinical use in people with Parkinson's disease. In addition, as gold standards are variable and sometimes scarce, unsupervised patient monitoring also brings

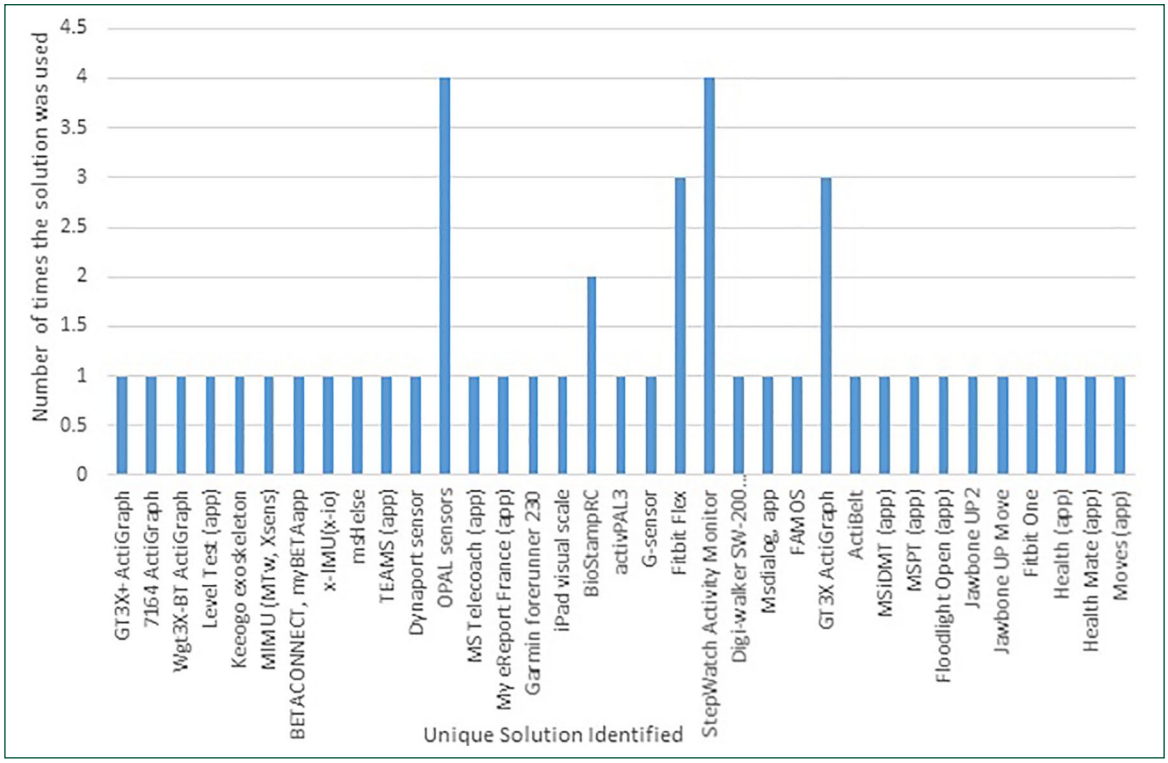

Figure 2. Unique devices and frequency of appearance.

new challenges (e.g. using a patients' diary to validate devices capturing motor fluctuations).[55,56]

Limiting factors to consider when developing wearable technology are adherence and usability by both the participant and the researcher. PwMS have shown a high level of acceptance when using smartphone applications (apps), although this may wear off as the disease progresses due to increased disability (e.g. decreased hand dexterity).[8] Factors to consider when designing a solution are convenience, placement of the wearable device, appearance of the sensor and feedback of results to the PwMS. Patient feedback is extremely important in keeping PwMS interested and engaged in their own health. Many solutions have opted for patient-friendly readouts, while more complex data and parameters are available to the respective clinicians and researchers.[57] With regard to usability by the researcher, issues to consider include troubleshooting hardware and software, technical support and ease of implementation with the participant.

Another limiting factor, from a UK perspective, was the approach from regulatory bodies. Stricter guidelines determined what was seen as a medical device or classed as an observational tool. New guidelines which have recently come into effect, such as the new Evidence Standards Framework by the National Institute for Health and Care Excellence (NICE) in March 2019 and the Regulation (EU) 2017/745 by the European Parliament (May 2020), will also work to create stricter guidance for patient safety, security monitoring and data security. Many solutions that are available elsewhere have struggled to implement themselves outside of research in the United Kingdom due to these guidelines.

Limitations

Although we used a detailed process to search and document the currently validated solutions in MS, there were several limitations. The nature of this scoping report was web search based and, thus, relied on university subscription to journals to access the papers, although only 5 of 1115 titles screened could not be accessed in this way. The inclusion of only English language papers may also be considered a limitation.

Conclusion

In the coming years, we can expect to see more sensitive and comprehensive measures being developed, with the idea of using wearable solutions perhaps as

the gold standard to measure outcome measures in studies and clinical practice. However, at present, guidelines on what wearable technology should be used in clinical practice and research are absent, and this is an area that will require considerable attention and stringency.

While doing the review, we came across many unvalidated solutions available for PwMS across a range of outcome measures, most of them being phone or iPad solutions. We classed a solution as 'unvalidated' if there was an inability to demonstrate test–retest reliability and/or failure to demonstrate difference between healthy controls and PwMS. In comparison, the validated solutions are rather limited, but are most advanced particularly in measurements of gait (characteristics) and balance. These solutions often provide the greatest accuracy and acceptance rate, as gait is one of the earliest outcome measures explored in MS wearable solutions.

Also with the advances in mobile technology, more solutions are focusing on utilising common wearables such as smartphones, smartwatches and tablets, to increase accessibility and minimise costs to the user. Looking forward, there is also a change occurring from single-measure solutions to multi-measure and multi-sensor solutions, such as the Floodlight Open app, which utilises multiple sensors within a smartphone to remotely measure gait, cognition and upper limb function.

As development in wearable technology in MS is still on-going, we can expect to see newer solutions focusing on other areas with technology advancements that allow for more upper body and cognitive measures. There is a dearth of validated solutions available for fatigue, mood and pain.

The future of wearable technology in MS therefore looks promising with the potential to become a primary, co-primary or adjunctive monitoring tool in research and clinical practice.

Declaration of conflicting interests

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