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Tools and Devices – Review

Physical Activity Monitoring in Patients with Neurological Disorders: A Review of Novel Body-Worn Devices

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Keywords
Wearable sensor · Activity monitor · Mobility · Motor activity · Physical activity

Abstract
Aim: The aim was to conduct a systematic review to examine the literature reporting the validity and reliability of wearable physical activity monitoring in individuals with neurological disorders. ***Method:*** A systematic search of the literature was performed using a specific search strategy in PubMed and CINAHL. A search constraint of articles published in English, including human participants, published between January 2008 and March 2017 was applied. Peer-reviewed studies which enrolled adult participants with any neurological disorder were included. For the studies which sought to explore the validity of activity monitors, the outcomes measured using the monitor were compared to a criterion measure of physical activity. The studies' methodological quality was assessed using an adapted version of the Quality Assessment of Diagnostic Accuracy Studies (QUADAS) framework. Data extracted from each study included the following: characteristics of the study participants, study setting, devices used, study protocol/methods, outcomes measured, and the validity/reliability of measurement produced. ***Results:*** Twenty-three studies examining the validity and reliability of 16 different monitors were included. The identified studies comprised participants with a range of different disorders of neurological origin. The available evidence suggests that biaxial or triaxial accelerometer devices positioned around the ankle produce the most accurate step count measurements in patients with neurological disorders. The findings regarding the reliability and validity of activity counts and energy expenditure are largely inconclusive in this population. ***Discussion:*** Ankle-worn biaxial or triaxial accelerometer-type devices provide the most accurate measurement of physical activity. However, further work is required in this field be-

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fore wearable activity monitoring can be more widely implemented clinically. Standardised activity monitoring protocols are required for implementing these devices in clinical trials and clinical practice, and consensus is required as to the reporting and interpretation of derived variables.

Introduction

Regular physical activity is essential for health and well-being and has been shown to contribute to the prevention of many illnesses [1–4], as well as being a vital element in the treatment, rehabilitation, and management of many conditions [5–7]. Physical activity is defined as "any bodily movement produced by skeletal muscles that results in the expenditure of energy" [8] and can be quantified either in terms of mobility (e.g., number of steps) or energy expenditure. Mobility is central to our quality of life. Mobility limitation is often the first noticeable sign of declining function and is associated with reduced independence and disability [9], longer hospital stays [10], nursing home placement [11], and mortality [9]. Measuring physical activity, and particularly mobility, allows clinicians to understand a patient's functional ability and to decide upon treatment or prognosis. Physical activity and mobility have traditionally been assessed by questionnaires, surveys, and activity diaries. These assessment methods are easy to administer to large groups and can be performed at low cost [12]. However, the subjectivity of these tests means that they have limitations [13]. They may lack the precision needed to detect small changes in physical activity and mobility, and the granularity to characterise daily fluctuations in disease severity. They may also be vulnerable to error caused by manual input either by the patient or the investigator/clinician.

The proliferation of unobtrusive, wearable devices has made it easier to capture objective data relevant to physical activity and mobility. Wearable monitors, which are used to estimate physical activity and mobility, can be broadly classified into one of three types: pedometers, accelerometers, and multisensor systems. Pedometers (e.g., Yamax Digi-Walker) estimate the number of steps taken through mechanical (using a spring-mounted level arm) or digital measurements in only the vertical plane [14]. Accelerometers (e.g., RT3 accelerometer) detect acceleration in one (uniaxial), two (biaxial), or three (triaxial) directions and can determine the quantity and intensity of movement [14]. Multisensor systems (e.g., SenseWear Armband) combine accelerometry with other sensors measuring data such as heart rate, galvanic skin response, or temperature, yielding more data to base physical activity estimations upon.

Using body-worn activity monitors may provide a more robust, objective, and detailed method of assessing physical activity and mobility than traditional assessment methods such as questionnaires and standardised tests. The objective data provided may support the clinical decision-making process, assisting clinicians to better visualise changes in motor function. Furthermore, utilising wearable activity monitors permits continuous patient monitoring by allowing data collection in the patient's own home [15]. These out-of-clinic data may provide a more accurate representation of the patient's ability, as some patients perform better in the clinical environment when under the observation of a clinician [16], while others perform better in the familiar environment of their own home. This approach also has the potential to reduce the burden on both the patient and the clinical site by decreasing the utilisation of valuable resources.

Recent years have witnessed a significant growth in the array of activity monitors with considerable clinical potential. However, despite their potential, they have not yet been widely employed in clinical practice. This may be due to the fact that there is relatively little

evidence regarding the accuracy of these activity monitors, and the lack of regulatory approval for many devices. Clinicians may also have concerns related to data privacy and the security of the data produced by these devices. Other cited barriers to their clinical utilisation include the lack of understanding of how to summarise the data gathered to produce meaningful outcome measures that can inform the clinical decision-making process, and also the lack of standards for implementing these devices clinically [17].

A number of reviews have been published which have examined the validity and reliability of using wearable sensors to measure physical activity in chronic lung disease and in stroke patients [14, 18, 19]. The studies included in these reviews were highly heterogeneous in terms of the type of activity monitor used, the activity monitor outcome reported, and the methods used for data collection and analysis. Nonetheless, the evidence presented suggests that multiaxial accelerometer or multisensor devices appear to produce the most valid and reliable data about physical activity in chronic disease populations [14, 18, 19]. A recent systematic review concluded that remote physical activity monitoring is feasible in individuals with neurological diseases, including those with moderate-to-severe disability [20]. Another recent review which evaluated a range of wearable and non-wearable devices for objectively measuring a range of motor symptoms in Parkinson disease (PD) highlighted that while a number of devices can be recommended, further clinimetric testing and clinical validation are required [21]. As yet, no review has broadly summarised the evidence regarding the validity and reliability of wearable activity monitoring in patients with neurological conditions for clinical use. The validity and reliability of activity monitoring in other populations may not translate easily to individuals with neurological diseases, as activity monitoring in individuals with neurological diseases may be complicated by a wide range of neurological impairments such as gait abnormalities [22], weakness [23], spasticity [24], or tremor [25]. For example, it has been demonstrated that gait parameters such as speed and distance can be accurately estimated using a triaxial accelerometer device in healthy adults [26], but the accuracy is not as high in individuals with PD while using the same device [27]. Therefore it is important to explore the validity and reliability of activity monitors in this population before these monitors can be widely implemented in clinical trials and practice.

The aim was to conduct a systematic review to examine the literature reporting on the validity and reliability of activity monitoring in individuals with neurological disorders. This review sought to explore the range of activity monitors that have been evaluated in clinical research studies and to explore the outcome measures of physical activity produced by these monitors. The focus of this review was on the clinical application of activity monitors and was not concerned with studies reporting early developments or validations of algorithms for activity monitoring devices.

Materials and Methods

This review was conducted and is reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [28].

Data Sources

The PubMed and CINAHL electronic databases were searched to retrieve relevant articles. These databases were chosen based on the method used in previous literature reviews published in the field [14, 19, 29]. Pilot searches conducted in other electronic databases did not yield applicable results. A search constraint of articles published in the English language, including human participants, between January 2008 and March 2017 was applied. Due to

Table 1. Study inclusion/exclusion criteria

	Inclusion	Exclusion
Study type	Peer-reviewed original papers that evaluated the validity and/or reliability of a wearable activity monitor	Review articles Case reports/intervention studies using an activity monitor as a component of an intervention or to measure the impact of an intervention Papers that evaluated the validity of physical activity classification models/ algorithms or papers that outlined algorithm development
Outcomes measured	Measurements which quantify the amount/ level of physical activity/mobility, e.g., step counts, distance, intensity of physical activity, walking speed, and energy expenditure	Measurements of postural control Posture classification measurements
Population	Adult participants with a neurological condition/disorder, i.e., any disease of the brain, spine, and the nerves that connect them	Healthy volunteers, paediatric participants (<18 years of age), athletic populations
Sensor types	Any consumer, research, or medical-grade wearable sensor used to measure physical activity	Smartphone applications, ambient sensors
Comparison	Comparison with criterion measure of physical activity/mobility	No comparator

the rapid development of technology in this field, this time frame was selected so as to limit the activity monitors studied to those which are still commercially available.

Search Strategy

The search in PubMed for relevant studies was performed using the free-text and MeSH terms outlined in Appendix 1. The search terms used in the PubMed search were modified for the CINAHL database. The citation lists from all the included studies were also searched, and a search of breadcrumb-related articles was also performed. The search strategy used was developed in consultation with a librarian.

Study Selection

The focus of this review was on an examination of the validity and/or reliability of the range of activity monitors that have been clinically utilised to quantify physical activity and mobility in patients with neurological disorders. Validity and reliability measures are referred to as psychometric properties. Validity refers to how well a test measures what it is purported to measure. Criterion validity was explored in this study, i.e., comparing the activity monitor measurement to a criterion measure of physical activity/mobility. Reliability is the degree to which an assessment tool produces stable and consistent results. The reliability or validity of an assessment tool is indicated by a coefficient, such as the intraclass coefficient or Pearson's

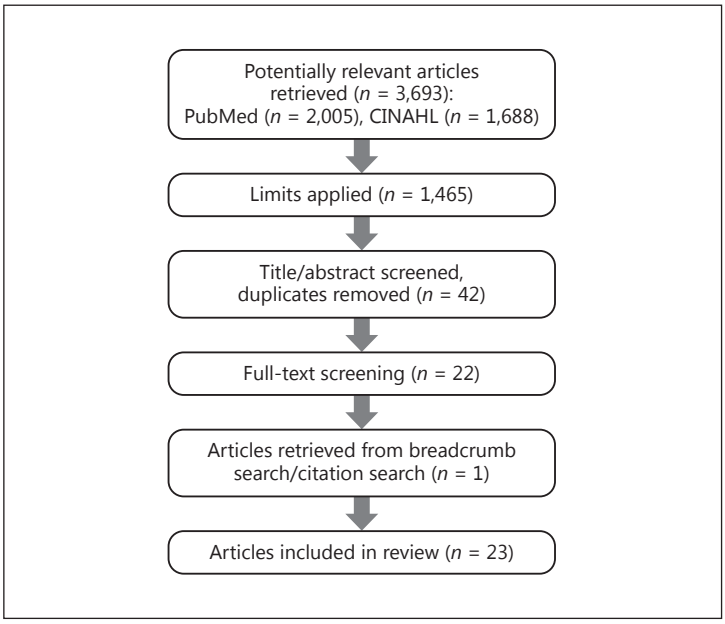

Fig. 1. Flow chart of the review process.

correlation coefficient (where values ≥0.90 generally indicate excellent, 0.75–0.90 good, 0.50–0.75 adequate, and <0.50 poor results [30]).

Validation and reliability studies of physical activity monitors are highly heterogeneous. Therefore the inclusion/exclusion criteria outlined in Table 1 were applied for the selection of studies included in this review. Studies performed in laboratory, clinical, or free-living (home/community) environments were included. The abstracts and titles of the studies identified from the search process were assessed and screened by the authors in order to decide whether they were suitable for inclusion [19]. The full-text articles of all potentially relevant studies were then retrieved and assessed for inclusion by the authors based on the defined study inclusion/exclusion criteria.

Data Extraction

Data extracted from each study included the following: characteristics of the study participants, study setting, devices used (make, model, size, weight, and manufacturer), study protocol/methods, outcomes measured, and the validity/reliability of measurement produced. The methodological quality of the validation studies included in this review was assessed using an adapted version of the Quality Assessment of Diagnostic Accuracy Studies (QUADAS) framework [18, 31]. Due to the heterogeneity of the included studies, a meta-analysis was not possible.

Results

A total of 3,693 potentially relevant articles were retrieved from the literature search performed in the PubMed and CINAHL electronic databases. Figure 1 depicts the study flow throughout the review process. Following a review of the title and abstract and a removal of duplicates, 42 articles remained. The list was subsequently reduced to 22 articles following a review of the full text. One article was retrieved from the citation search/breadcrumb search of the included articles. This yielded a final total of 23 articles for inclusion in this review.

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Table 2. Studies included in the systematic review

	Population and setting	Device	Aim and methods	Endpoints	Findings
Bania [51]	10 participants with spastic diplegic CP (6 male, age: 18.6±2.7 years) were included in the validation study 24 participants with spastic diplegic CP (11 male, age: 18.7±2.9 years) were included in the retest reliability study Clinical setting	An activPAL monitor was placed mid-thigh on the frontal aspect of the thigh	To determine the criterion validity and the retest reliability of the activPAL in adolescents and young adults with diplegic CP Criterion validity study The participants were recorded with a video camera for 12 min, during which they were asked to stand up and sit down twice, as well as to complete a 6MWT Criterion: an observer, blinded to the activPAL output, watched the videos and counted the number of steps and the time spent in sitting and standing Retest reliability study The participants wore the activPAL monitor for 7 days, and for another 7 days 12 weeks later. They were advised to wear it at all times except during bathing and swimming A daily log was also given to the participants in which to note their activities during the 7-day period	Time spent standing Time spent sitting Step count (steps/day)	*Criterion validity* Time standing: R^2 0.97; MD (SD) –0.06 (0.2); 95% LOA –8.6 to 2.6 Time sitting: R^2 0.96; MD (SD) 0.5 (0.5); 95% LOA 1.3 to 20 Step count: R^2 0.99; MD (SD) –13.8 (11.8); 95% LOA 3.3 to 0.8 *Retest reliability* Time standing: ICC 0.60; MD (SD) –0.31 (1.10); 95% CI –0.081 to 0.19 Time sitting: ICC 0.66; MD (SD) 0.37 (1.28); 95% CI –0.021 to 0.95 Step count: ICC 0.87; MD (SD) –411 (1,301); 95% CI –1,044 to 142
Dijkstra et al. [27]	32 PD patients (17 male, age: 67.3±6.6 years, BMI: 26.7±4.0) Research laboratory	A DynaPort was placed in a belt and positioned between and above the posterior superior iliac spines A Yamax Digi-Walker (SW-200) was attached to the belt at the left and the right hip	To determine the accuracy of an accelerometer system for detecting walking periods and steps in subjects with PD during controlled indoor walking tasks 8 walking tasks: (1) walking 15 m at the preferred walking speed; (2) walking 15 m slower than preferred; (3) walking 15 m faster than preferred; (4) walking 10 m at one's own pace; (5) walking 5 m at one's own pace; (6) walking 3 m at one's own pace; (7) walking 15 m at the preferred speed while counting backward from 100 to 0 in steps of 5; and (8) walking 15 m at the preferred speed while carrying a tray with two cups filled with water. All tasks were videotaped. The gait characteristics as observed on video were taken as the gold standard	Gait duration Step count	*Gait duration during all tasks* Absolute percentage error DynaPort: 11.1±4.5 *Step counts during all tasks* Absolute percentage error (ICC) DynaPort: 6.9±3.0 (0.98) Left Digi-Walker: 11.1±9.0 (0.87) Right Digi-Walker: 16.3±13.7 (0.75)

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Table 2 (continued)

	Population and setting	Device	Aim and methods	Endpoints	Findings
Downs et al. [53]	12 female participants with Rett syndrome (age: 12.9±8.0 years) Home environment	A StepWatch activity monitor was attached around the right ankle proximal to the lateral malleolus with an elastic and Velcro strap	To assess the accuracy of the StepWatch activity monitor and investigate relationships between daily step counts, gross motor skills, and age Data collection comprised two parts: 1. The participants were videotaped while performing normal walking activities in indoor and outdoor settings for periods of up to 30 min. Gross motor skills were assessed with the Gross Motor Scale for Rett syndrome 2. The participants wore the StepWatch during 7 consecutive days. Caregivers recorded the time the StepWatch was fitted in the morning and when removed at bedtime	Step count	Step count: MD 0 steps/min; LOA –10 to 10 Agreement did not differ with the level of general (p = 0.389) or complex gross motor skills (p = 0.221) The participants were less active than their healthy peers (difference 6,086 steps/day; p = 0.001), and physical activity was significantly greater in those who were younger and with greater levels of motor skills
Elsworth et al. [32]	43 adults with neurological conditions (n = 20 stroke, n = 16 MS, n = 5 muscular dystrophy, n = 1 SCI, n = 1 TBI; 26 male, 17 female, age: 54±13 years, BMI: 26±4)[a] Clinical setting	A Yamax Digi-Walker (SW-200) was positioned midway between the iliac crest and umbilicus over the right leg in line with the midline of the thigh	To assess the accuracy of a pedometer in measuring step counts in neurologically impaired individuals walking at a self-selected walking speed The participants were asked to walk along a 16-m walkway in a quiet corridor at their normal speed using walking aids as required for a period of 2 min. An observer manually recorded the participants' step counts using a manual step counter	Step count	All: MD (SD) 27 (11); ICC (95% CI) 0.73 (0.23 to 0.93); p = 0.003 Stroke: MD (SD) 31 (113); ICC (95% CI) 0.58 (0.20 to 0.81); p = 0.026 MS: MD (SD) 23 (81); ICC (95% CI) 0.84 (0.60 to 0.94); p = 0.044 Muscular dystrophy: MD (SD) 7.2 (176); ICC (95% CI) 0.38 (–0.62 to 0.91); p = 0.866 SCI step count difference: 130 steps TBI step count difference: 5 steps

Table 2 (continued)

	Population and setting	Device	Aim and methods	Endpoints	Findings
Fulk et al. [42]	30 stroke participants (15 male, age: 61.6±10.4 years) and 20 TBI participants (19 male, 1 female, age: 40.3±11.6 years) Research laboratory	A Fitbit Ultra and Yamax Digi-Walker (SW-701) were worn on the belt or waistband on the side of the less affected leg A Nike FuelBand was worn on the wrist of the less affected arm A StepWatch Activity Monitor was strapped above the lateral malleolus of the less affected leg	To examine the accuracy of two commercial activity monitors, the Fitbit Ultra and the Nike FuelBand, in identifying stepping activity in people with stroke and TBI and to compare the accuracy of these two activity monitors with that of the StepWatch Activity Monitor and the Yamax Digi-Walker The participants wore all four activity monitors simultaneously and performed the 2MWT, during which they were videotaped. A researcher counted the steps taken by the participants from the video record	Step count	*All participants* StepWatch: MD (95% CI) 4.7 (1.11 to 8.35); ICC (95% CI) 0.97 (0.92 to 0.99) Fitbit Ultra: MD (95% CI) –9.7 (–0.12 to –19.28); ICC (95% CI) 0.73 (0.56 to 0.83) Digi-Walker: MD (95% CI) –28.8 (–12.66 to –43.50); ICC (95% CI) 0.42 (0.14 to 0.63) Nike FuelBand: MD (95% CI) –66.2 (–43.63 to –88.67); ICC (95% CI) 0.20 (–0.076 to 0.46)
Hale et al. [33]	47 participants (17 male, age: 63.7±15.5 years; MS n = 11, PD n = 7, stroke n = 20, controls n = 9) Home environment	An RT3 accelerometer was attached to the waistbelt in a central back position	To investigate the reliability of a triaxial accelerometer to measure physical activity in adults with and without neurologic dysfunction The participants wore the RT3 during waking hours (except while bathing, swimming, or lying in bed) for 7 consecutive days while maintaining their typical weekly schedules. They were instructed to complete a daily activity log. After 7 days a 7-day recall questionnaire was administered. 8 weeks later the procedure was repeated, using the same RT3 unit. The mean daily data for the first 3 days and for 7 days of measuring were calculated	Activity count	*Test-retest reliability activity counts over the two test periods* All: ICC (95% CI) 0.85 (0.74 to 0.91); p = 0.00; SEM 23% *Activity counts* 7-day: 124,831±74,373; 3-day: 132,252±92,394; p = 0.03 RT3 data correlation with the 7-day recall questionnaire (R = 0.01, 1%)
Hiremath and Ding [49]	24 paraplegic participants (19 male, age: 41.4±11.4 years) Research laboratory	An SWA was worn on the right upper arm over the triceps muscle An RT3 was secured around the waist with a belt clip holster	To evaluate the performance of the SWA and RT3 activity monitors in estimating EE in manual wheelchair users with paraplegia for a variety of physical activities The activity session consisted of resting and three 8-min activity routines: wheelchair propulsion, arm ergometer exercise, and deskwork. The criterion of EE was measured with a K4b2 portable metabolic cart	EE	*SWA* Absolute percentage error in EE range: 24.4 to 125.8% ICC (LOA) 0.62 (0.49 to 0.73); p < 0.05 (for all activities) *RT3* Absolute percentage error in EE range: 22.0 to 52.8% ICC (LOA) 0.64 (0.51 to 0.73); p < 0.05 (for all activities)

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Table 2 (continued)

	Population and setting	Device	Aim and methods	Endpoints	Findings
Kayes et al. [34]	31 participants with MS (10 male, median age: 50 years, range: 34–80) Research laboratory	An Actical accelerometer was mounted onto waistbands and fitted around the participants' waists over the iliac crest of the left hip	To explore the test-retest reliability and validity of the Actical accelerometer in people with MS The participants were scheduled to attend 2 testing sessions, 7 days apart. They completed a series of 6 activities (reading newspaper, washing, vacuuming, stair climbing, 30-s chair stand test, and 6MWT) while wearing the Actical and a Polar heart rate monitor. The Borg RPE was used to measure self-reported activity intensity	Activity count	*Test-retest reliability* ICC (95% CI), bias, *p* value (95% LOA) Newspaper reading: 0.00 (0.00 to 0.37), 0.4, $p = 0.48$ (±16) Washing: 0.38 (0.07 to 0.70), 2.7, $p = 0.84$ (±145) Vacuuming: 0.75 (0.58 to 0.91), 7, $p = 0.73$ (±247) Stairs: 0.85 (0.76 to 0.95), 96.3, $p = 0.26$ (±1,065) Chair stand: 0.87 (0.77 to 0.96), 31.8, $p = 0.74$ (±1,192) 6MWT: 0.90 (0.83 to 0.97), –139, $p = 0.33$ (±1,330) *Validity* Estimate (95% CI), *p* value Newspaper reading: 0.097 (–0.211 to 0.018), $p = 0.10$ Washing: 0.02 (–0.002 to 0.042), $p = 0.07$ Vacuuming: 0.019 (0.007 to 0.030), $p = 0.002$ Stairs: 0.002 (–0.001 to 0.005), $p = 0.16$ Chair stand: 0.005 (0.002 to 0.009), $p = 0.005$ 6MWT: 0.004 (0.002 to 0.006), $p < 0.001$

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Table 2 (continued)

	Population and setting	Device	Aim and methods	Endpoints	Findings
Klassen et al. [43]	43 participants after stroke (30 male, age: 65±10.66 years) Research laboratory	A Fitbit One was positioned on each participant's non-paretic side on a waistband and ankle strap (above the lateral malleolus)	To examine the effect of walking speed on the accuracy of an accelerometer-based activity monitor in ambulatory individuals after stroke and to compare the effect of position (waist vs. ankle) on the accuracy of an accelerometer-based activity monitor The participants walked a distance of 15 m for 8 walking trials: 1 trial at a self-selected walking speed and 7 trials from 0.3 to 0.9 m/s in 0.1 m/s increments. Each trial was videorecorded, and two independent viewers counted the actual number of steps from the video recordings of each trial	Step count	*Fitbit ankle* Percentage error (SD) [95% CI] 0.3 m/s: 15.8 (22.3) [9.1 to 22.7] 0.4 m/s: 5.5 (10.3) [2.4 to 8.6] 0.5 m/s: 4.5 (6.7) [2.4 to 6.6] 0.6 m/s: 4 (4.9) [2.4 to 5.6] 0.7 m/s: 4.9 (8.2) [2.1 to 7.7] 0.8 m/s: 6.9 (11.7) [2.8 to 11.0] 0.9 m/s: 4.9 (8.3) [1.8 to 8] *Fitbit waist* Percentage error (SD) [95% CI] 0.3 m/s: 84.6 (30.5) [75.5 to 93.7] 0.4 m/s: 59.1 (40.1) [47.1 to 71.1] 0.5 m/s: 38.3 (33.2) [28.0 to 48.6] 0.6 m/s: 16.6 (17.8) [10.8 to 22.4] 0.7 m/s: 11.8 (17.0) [6.1 to 17.5] 0.8 m/s: 10.1 (13.6) [5.4 to 14.8] 0.9 m/s: 7.7 (8.9) [4.3 to 11.1] *Paired* t *test* Fitbit ankle vs. Fitbit waist: 0.3 m/s: $p < 0.001$ 0.4 m/s: $p < 0.001$ 0.5 m/s: $p < 0.001$ 0.6 m/s: $p = 0.002$ 0.7 m/s: $p = 0.21$ 0.8 m/s: $p = 0.84$ 0.9 m/s: $p = 0.58$
Learmonth et al. [35]	82 participants with MS (20 male, age: 49.2±9 years) Home environment	An ActiGraph GT3X was worn around the waist	To determine the reliability, precision, and clinically important change of accelerometry in participants with MS The participants wore the ActiGraph for 7 days during waking hours exclusive of bathing or swimming. The same procedure was repeated 6 months later	Activity count Step count	Activity count: ICC 0.883; 95% CI 0.815 to 0.926; SEM 28,450; CV 17%; MDC 78,860 Step count: ICC 0.907; 95% CI 0.853 to 0.94; SEM 726; CV 16%; MDC 2,011

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Table 2 (continued)

	Population and setting	Device	Aim and methods	Endpoints	Findings
Lord et al. [47]	12 people with PD (4 male, age: 70.5±3.3 years)[a] Research laboratory	The Vitaport activity monitor consists of a portable data recorder attached to a belt worn around the waist, with 5 accelerometers attached to the body: 1 on each leg positioned on the lateral aspect of the mid-thigh, and 3 on the lower third of the sternum	To test the concurrent validity of the Vitaport activity monitor by comparing it to the GAITRite in controls and people with PD, to establish the use of the Vitaport activity monitor during a functional walk test, and to estimate the measurement error of the Vitaport activity monitor under these conditions Four different walking tasks were performed: simple walking, dual motor task, dual cognitive task, and multiple task. Spatial and temporal variables of gait were measured using a GAITRite electronic walkway and the Vitaport activity monitor	Gait speed Step length Step frequency	*Gait speed* MD (SD) [95% CI]; ICC Simple walk: –0.06 (0.04) [–0.06 to –0.3]; 0.99 Dual motor: –0.00 (0.09) [–0.06 to 0.5]; 0.91 Dual cognitive: –0.07 (0.05) [–0.10 to –0.04]; 0.97 Multiple task: 0.01 (0.08) [–0.06 to 0.03]; 0.94 *Step length* MD (SD) [95% CI]; ICC Simple walk: –0.03 (0.02) [–0.04 to –0.01]; 0.97 Dual motor: 0.00 (0.04) [–0.02 to 0.03]; 0.85 Dual cognitive: 0.03 (0.03) [–0.05 to –0.01]; 0.92 Multiple task: 0.00 (0.02) [–0.01 to 0.02]; 0.93 *Step frequency* MD (SD) [95% CI]; ICC Simple walk: 0.15 (0.04) [0.12 to 0.18]; 0.98 Dual motor: 0.14 (0.07) [0.09 to 0.19]; 0.96 Dual cognitive: 0.15 (0.04) [0.12 to 0.18]; 0.98 Multiple task: 0.11 (0.11) [0.03 to 0.18]; 0.92
Motl et al. [36]	567 participants with MS (93 male, age: 47±10 years) Home environment	An ActiGraph 7164 was worn on a belt around the waist above the non-dominant hip	To estimate the reliability of objective measures of physical activity over a period of 6 months in persons with MS The participants wore the ActiGraph during waking hours, except while bathing, showering, or swimming, for 7 days and then completed a battery of questionnaires that contained the Godin Leisure-Time Exercise Questionnaire (GLTEQ) on the eighth day. The same procedures were completed at baseline and 6 months later at follow-up	Activity count Minutes of MVPA	*Activity counts/day* Significant change in over 6 months; $t(474) = 3.92$, $p = 0.0001$, $d = 0.18$; ICC 0.84 (95% CI 0.81 to 0.87); value significantly different from 0; $F(1, 474) = 6.53$, $p = 0.0001$ *Minutes of MVPA/day* Significant change over 6 months, $t(474) = 5.38$, $p = 0.0001$, $d = 0.30$; ICC 0.84 (95% CI 0.80 to 0.87); value significantly different from 0; $F(1, 474) = 6.09$, $p = 0.0001$

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	Population and setting	Device	Aim and methods	Endpoints	Findings
Motl et al. [37]	51 participants with MS (8 male, 43 female, age: 53.1±11.3 years) Research laboratory	An actibelt accelerometer was attached to the participants' waist with a special buckle	To determine the accuracy of the actibelt for measuring walking speed during the 6MWT among persons with MS The participants performed a 6MWT in a rectangular, carpeted corridor. The distance traveled (m) was recorded using a measuring wheel and was then converted into actual walking speed (m/s) for comparability with the actibelt output	Walking speed	The actibelt significantly overestimated walking speed (–0.12±0.17 m/s, $p < 0.0001$). The overestimation was more pronounced in participants with moderate (–0.10±0.16 m/s) and severe (–0.26±0.12 m/s) disability. No significant overestimation was seen in those with mild disability (–0.02±0.11) Overall standard error of the estimate: 0.10 m/s (95% CI 1.10 to 1.50)
Motl et al. [38]	24 participants with MS (4 male, age: 43.5±12.2 years)[a] Research laboratory	An ActiGraph 7164 was worn on an elastic belt that was positioned on the participants' right hip	To examine the accuracy of the ActiGraph accelerometer for measuring steps taken during controlled conditions by persons with MS compared with a sample of individuals without MS The participants performed three 6MWT on a treadmill, at 54, 80, and 107 m/min. There was a 6-min period of rest between walking periods. The actual number of steps taken was counted by observation using a hand-held tally counter	Step count	Percent error rate (SD) [95% CI] 54 m/min: 4.1 (9.1) [0.9 to 7.3] 80 m/min: 0.2 (0.8) [–0.2 to 0.63] 107 m/min: 0.3 (1.9 [–0.3 to 0.9] There was a statistically significant and large main effect for speed [$F(2, 92)$ 59.13, $p < 0.0001$, $\eta^2 = 0.17$]
Mudge and Stott [44]	40 participants with chronic stroke (23 male, 17 female, age: 69.2±12.6 years) Home environment	A StepWatch activity monitor was attached to the lateral side of the ankle of the non-paretic leg with a strap or cuff	To assess the test-retest reliability of the StepWatch activity monitor in individuals with chronic stroke The participants were instructed to wear the monitor for 3 days and for the same 3 days the following week, removing it for sleeping and showering	Step count Number of steps at high, medium, and low stepping rates	Total step count: ICC 0.989; CV 10.7%; ±95% LOA 37.8% Number of steps at medium stepping rate: ICC 0.964; CV 17.8%; ±95% LOA 87.1% Number of steps at high stepping rate: ICC 0.926; CV 37.6%; ±95% LOA 153% Number of steps at low stepping rate: ICC 0.953; CV 11.1%; ±95% LOA 63.6%

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Table 2 (continued)

	Population and setting	Device	Aim and methods	Endpoints	Findings
Nightingale et al. [50]	17 male manual wheelchair users (age: 36±10 years) Community gym	An ActiGraph GT3X and a GENEActiv accelerometer were worn on the right wrist and upper arm	To assess the validity of two commonly used accelerometer devices, at two different anatomical locations, for the prediction of physical activity EE in manual wheelchair users in a controlled laboratory environment The participants completed 10 activities: resting, folding clothes, propulsion on a 1% gradient (3–6 and 7 km/h), and propulsion at 4 km/h (with an additional 8% body mass, 2 and 3% gradient) on a motorised wheelchair treadmill. IC was used as a criterion measurement of physical activity EE	EE Activity count	*MAPE* ActiGraph upper arm: 35.3±30.8% ActiGraph wrist: 33.0±39.5% GENEActiv upper arm: 20.4±14.3% GENEActiv wrist: 21.0±15.1% *Overall percent error of estimate (±95% LOA)* ActiGraph upper arm: 15±87% ActiGraph wrist: 14±97% GENEActiv upper arm: 3±49% GENEActiv wrist: 4±50% *Pearson CC* ActiGraph upper arm: 0.68 ActiGraph wrist: 0.82 GENEActiv upper arm: 0.87 GENEActiv wrist: 0.88
Rand et al. [45]	40 adult community-dwelling participants with stroke (13 male, age: 66.5±9.6 years, BMI: 24.63±3.6) Home environment	Two Actical monitors were positioned over the anterior-superior iliac spine on the paretic and the non-paretic side	To assess the reliability of the Actical accelerometer for the paretic and the non-paretic side in people with stroke The participants wore the Actical monitors continuously for 3 days and were instructed to go about their normal lives	EE Activity count	*Paretic hip* Activity count: ICC 0.95 (95% CI 0.92 to 0.97); SEM 18,324; MDC 50,792 EE: ICC 0.95 (95% CI 0.92 to 0.97); SEM 31.38; MDC 86.98 *Non-paretic hip* Activity count: ICC 0.94 (95% CI 0.91 to 0.97); SEM 17,690; MDC 49,035 EE: ICC 0.95 (95% CI 0.90 to 0.96); SEM 32.26; MDC 89.42 *Paretic vs. non-paretic hip* Activity count: ICC 0.98 (95% CI 0.97 to 0.99); SEM 9,755; MDC 27,039 EE: ICC 0.96 (95% CI 0.93 to 0.98); SEM 27.63; MDC 76.58

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Table 2 (continued)

	Population and setting	Device	Aim and methods	Endpoints	Findings
Ryan et al. [52]	18 adults (10 male, age: 31.9±9.5 years, BMI: 25.3±4.8) with CP[a] Clinical setting	An RT3 was worn on the right hip in the mid-axillary line An SWA was positioned over the triceps muscle of the right arm IDEEA sensors were worn on the chest, thighs, and soles of the feet	To evaluate the validity of the SWA, the IDEEA, and the RT3 at estimating EE in adults and children with CP EE data were collected using each monitor during rest and a number of walking activities. IC was used as the criterion measure of EE	EE	*MAPE* RT3: 17.2% (range 0.4 to 37.9) SWA: 35.5% (range 8.2 to 74.9) IDEEA: 16.3% (range 8.4 to 24.5) *LOA* RT3: –2.47 to 3.18 kcal/min SWA: –5.38 to 3.35 kcal/min IDEEA: –2.41 to 3.78 kcal/min
Sandroff et al. [39]	63 participants with MS (15 male, age: 50.7±9.2 years) Research laboratory	A StepWatch activity monitor was worn on an elastic strap around the ankle above the right lateral malleolus An ActiGraph GT3X+ was worn on an elastic belt around the waist and above the right hip	To examine the accuracy of the StepWatch and ActiGraph in capturing steps taken at various speeds during over-ground ambulation in people with MS The participants completed three 6MWT: at CWS, at FWS (+0.5 mph of CWS), and at SWS (–0.5 mph of CWS). The actual number of steps taken was counted through direct observation using hand-held tally counters	Step count	ActiGraph step count accuracy: CWS 97.4%; FWS 95.6%; SWS 95.5% StepWatch step count accuracy: CWS 99.8%; FWS 99.9%; SWS 99.9%
Sandroff and Motl [40]	41 participants with MS (5 male, 36 female, age: 47.7±8.8 years) and 41 age-matched healthy controls (5 male, age: 47.7±9.1 years) Research laboratory and home environment	An ActiGraph 7164 and a GT3X accelerometer were worn on an elastic belt around the waist on the non-dominant hip	To compare the activity count outputs from the 7164 and GT3X models of the ActiGraph in persons with MS and healthy controls under free-living and laboratory conditions The participants concurrently wore the accelerometers for 6 days during waking hours, except while swimming, bathing, or showering. They also undertook up to 5 bouts of walking that were each 6 min in duration on a treadmill The 5 possible walking speeds were 54, 67, 80, 94, and 107 m/min	Activity count	*Free-living – difference between units* 12,487 (SD 27,199), $p < 0.01$, ICC 0.983 (95% CI 0.967 to 0.991) *Treadmill walking – difference between units* 54 m/min: 178 (SD 226), $p < 0.01$, ICC 0.869 (95% CI 0.651 to 0.937) 67 m/min: 73 (SD 390), $p = 0.09$, ICC 0.891 (95% CI 0.831 to 0.930) 80 m/min: –30 (SD 484), $p = 0.61$, ICC 0.9 (95% CI 0.837 to 0.939) 94 m/min: 42 (SD 664), $p = 0.64$, ICC (95% CI 0.834 to 0.943) 107 m/min: 70 (SD 893), $p = 0.61$, ICC (95% CI 0.701 to 0.901)

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Table 2 (continued)

	Population and setting	Device	Aim and methods	Endpoints	Findings
Schmidt et al. [41]	20 participants diagnosed with PD (*n* = 11) and MS (*n* = 9) Clinical setting	A StepWatch activity monitor was worn on an elastic strap around the ankle above the lateral malleolus	To explore the validity of the StepWatch Step Activity Monitor (SAM) in assessing stride counts in persons with PD or MS The participants walked 15 m over a GaitMat II while wearing the StepWatch activity monitor. The strides counted by the GM were compared with the strides counted by the StepWatch activity monitor	Number of strides	Pearson CC for MS: 0.99 Pearson CC for PD: 1.0 StepWatch mean strides (95% CI): 15.55 (13.43 to 17.67) GaitMat II mean strides (95% CI): 15.85 (13.59 to 18.11)
Speelman et al. [48]	Part a: 28 participants with PD (age: 65.5±6.6 years) Part b: 23 participants with PD (age: 63.8±9.4 years) Community setting	A DynaPort activity monitor was placed in a belt, positioned on the lower back between the posterior superior iliac spines	To evaluate the ability of the DynaPort activity monitor to estimate walking distances in PD Part a: the participants walked at their preferred speed along a marked linear distance in a hallway (ranging between 21 and 27 m) Part b: the participants walked along a much longer (max. distance 1,097 m) and more complex "real life" walking trajectory (walking in the hospital corridors, with curves and path deviations). The actually measured walking distance was taken as the gold standard	Walking distance Step length	Difference between DynaPort and gold standard: <16% In case of a longer walking distance, the LOA were –43 and +41%. The difference between the results and the gold standard did exceed more than 40%

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Table 2 (continued)

	Population and setting	Device	Aim and methods	Endpoints	Findings
Vanroy et al. [46]	15 stroke patients (9 male, age: 60.4±10.26 years)[a] Clinical setting	A Yamax Digi-Walker (SW-200) was worn on the anterior side of the hip (on the belt) and the anterolateral side of the knee (patella support strap) on the non-hemiplegic side in stroke patients A SenseWear Armband (Pro2) was worn on both upper arms and positioned on the triceps muscle halfway between the acromion and the olecranon	To examine the validity and reliability of the SWA and the Digi-Walker in measuring the number of steps and EE in stroke patients and healthy individuals Different activities were performed: treadmill walking, walking up/down a step, cycling, and walking on an even surface. Validity was examined by comparing the number of steps registered by the SWA and the Digi-Walker with that counted with a hand-held tally counter. EE was measured with the SWA and compared to IC. To determine the reliability of the two devices, repeated measurements on the treadmill and bike were compared for the number of steps and EE	Step count EE	**Step count** *Validity (Spearman CC)* Treadmill walking: SWA right –0.37 to 0.60; SWA left –0.52 to 0.46; Digi-Walker hip –0.41 to 0.90; Digi-Walker knee 0.30 to 0.69 Normal walking: SWA right –0.13; SWA left –0.23; Digi-Walker hip 0.33; Digi-Walker knee 0.95 Brisk walking: SWA right –0.04; SWA left 0.46; Digi-Walker hip 0.46; Digi-Walker knee 0.98 *Test-retest reliability (ICC)* Treadmill walking 1.5 km/h: SWA right 0.98; SWA left 0.89; Digi-Walker hip 0.88; Digi-Walker knee 0.73 Treadmill walking 3 km/h: SWA right 0.93; SWA left 0.92; Digi-Walker hip 0.96; Digi-Walker knee 0.95

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Table 2 (continued)

Population and setting	Device	Aim and methods	Endpoints	Findings
				EE *Validity (Spearman CC)* Lying: SWA right 0.56; SWA left 0.49 Standing: SWA right 0.79; SWA left 0.81 Sitting: SWA right 0.78; SWA left 0.85 Treadmill walking: SWA right 0.01 to 0.75; SWA left 0.50 to 0.82 Stepping: SWA right 0.29 to 0.59; SWA left 0.48 to 0.71 Cycling: SWA right 0.54 to 0.71; SWA left 0.00 to 0.52 *Test-retest reliability (ICC)* Treadmill walking 1.5 km/h: SWA right 0.85; SWA left 0.76 Treadmill walking 3 km/h: SWA right 0.63; SWA left 0.97 Cycling 30 W: SWA right 0.90; SWA left 0.84 Cycling 50 W: SWA right 0.95; SWA left: 0.98

2MWT, 2-min walk test; 6MWT, 6-min walk test; BMI, body mass index; CC, correlation coefficient; CI, confidence interval; CV, coefficient of variation; CP, cerebral palsy; CWS, comfortable walking speed; EE, energy expenditure; FWS, fast walking speed; IC, indirect calorimetry; ICC, intra-class correlation coefficients; LOA, limits of agreement; MAPE, mean absolute percentage error; MD, mean *difference;* MDC, minimal detectable change; MS, multiple sclerosis; MVPA, moderate-to-vigorous-intensity physical activity; PD, Parkinson disease; RPE, rate of perceived exertion; SCI, spinal cord injury; SEM, standard error of measurement; SWS, slow walking speed; TBI, traumatic brain injury. [a] The study included young healthy participants as well; however, the results are presented only for the population of interest.

A detailed description of each study included in this review is presented in Table 2. The methodological quality of each validation study is presented in Appendix 2. Overall the methodological quality of the studies examined was high, with each scoring ≥7. Of the assessed studies, 10 included participants with multiple sclerosis [32–41], 7 included participants after stroke [32, 33, 42–46], 4 included participants with PD [27, 33, 47, 48], 3 included participants with a spinal cord injury [32, 49, 50], 2 included participants with cerebral palsy [51, 52], 2 included participants with a traumatic brain injury [32, 42], and participants with Rett syndrome [53] and muscular dystrophy [32] were included in 1 study each. The most frequently used monitors included the StepWatch activity monitor (a biaxial accelerometer) [39, 41, 42, 44, 53], the ActiGraph GT3X (a triaxial accelerometer) [35, 39, 40, 50], the SWA (a multisensor device) [46, 49, 52], and the Digi-Walker pedometer [27, 32, 34, 42]. Table 3 outlines the monitors that were used in the included studies, the outcome measures produced, and the findings reported regarding the validity and reliability of the measurements produced.

Discussion

This review identified 23 studies examining the validity and reliability of 16 different monitors (9 triaxial accelerometer-type monitors, 1 biaxial accelerometer-type monitor, 2 uniaxial accelerometer-type monitors, 3 multisensor devices, and 1 spring-mounted lever arm pedometer-type monitor) in individuals with neurological disorders. The studies included in this review were highly heterogeneous in terms of their study design, the participants included, the activity monitors used, the placement of the monitor on the body, the outcomes measured, and the algorithms used to calculate the measurement outcome. Therefore it was difficult to directly compare the findings. Nevertheless an attempt was made to summarise the key findings of the papers.

Step counts are the most frequently reported outcome measure of physical activity in individuals with neurological disorders, and the evidence suggests that ankle-worn biaxial or triaxial accelerometer-type devices provide the most accurate measurement. There is conflicting evidence regarding the validity and reliability of wearable activity monitors in measuring activity counts, while accelerometer-type devices appear to be more appropriate in estimating energy expenditure than multisensor devices, which are more frequently used. The sections below describe these findings in greater detail.

Ankle-Worn Devices Provide the Most Accurate Measurement of Step Counts

Step counts are the most frequently reported outcome measure of physical activity in individuals with neurological disorders. The evidence suggests that for accurate and reliable measurements of step counts, a number of factors need to be considered. Firstly the validity and reliability of wearable activity monitors in measuring step counts appears to be dependent on the type of device that is used. Spring-mounted lever arm pedometers appear to underestimate step counts in participants with a range of neurological disorders, particularly at slower walking speeds, and are also less accurate for short walking trajectories [27, 32, 42]. Similarly uniaxial accelerometers appear to underestimate steps in slower walking conditions [38, 51]. Using multiaxial accelerometers appears to be a less speed-dependent method of counting steps, producing more accurate measurements [27, 35, 39, 42, 44, 53]. The validity and reliability of wearable activity monitors in measuring step counts also appears to be dependent upon the position on the body in which the device is placed. Activity monitors positioned on the ankle appear to be more accurate than wrist-mounted and waist-mounted devices in counting steps, particularly during slow walking conditions [39, 42, 43]. This may be because larger accelerations occur at the ankle during walking due to the distance from

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Table 3. Devices studied and results

Device	Manufacturer	Device form factor	Reported findings			
			population	setting	endpoints	validity/reliability/accuracy
Triaxial accelerometers						
actibelt 	Trium	Waistband	MS (37)	Laboratory	Walking speed	Overestimates walking speed significantly in those with moderate (by –0.12±0.17 m/s) and severe (by –0.26±0.12 m/s) disability
Actical 	Philips Respironics	Clip-on or custom waistband or wristband 1.14 × 1.45 × 0.43 in (16 g without band)	MS (34)	Laboratory	Activity count	Test-retest reliability poor for sedentary and free-living activities, but better for more vigorous or rhythmic activities; validity not established, high variability for all activities
			Stroke (45)	Home	Activity count EE	Excellent reliability for activity count and EE with Actical worn on both the paretic and the non-paretic hip
ActiGraph GT3X/+ 	ActiGraph Corp.	Wristband or waistband 4.6 × 3.3 × 1.5 cm (19 g)	MS (35)	Home	Activity count Step count	Both measures highly reliable across 6 months
			MS (39)	Laboratory	Step count	ActiGraph worn on the waist is highly accurate (95.6–97.4%) in measuring steps taken under comfortable and fast walking speed; less accurate in measuring steps under slow walking conditions (95.5%), particularly in those with severe disability (87.3%)
			MS (40)	Laboratory and home	Activity count	Activity counts from the ActiGraph 7164 and the GT3X are significantly different under free-living conditions; difference in output due to slow walking speeds
			Manual wheelchair users (50)	Community	EE Activity count	ActiGraph worn on the wrist and upper arm and compared with the GENEActiv device worn on the wrist and upper arm; both ActiGraphs overestimate EE, with the wrist-worn device (percent estimation error: 14%) providing more valid results than that worn on the upper arm (15%)
DynaPort Activity Monitor 	McRoberts	Waistband 6.2 × 6.2 × 1.3 cm (55 g)	PD (27)	Laboratory	Step count Gait duration	The DynaPort overestimated gait duration (11.1%) and underestimated the number of steps (6.9%); step count accuracy decreased significantly as the walking distance decreased (10 m, 5.7%; 5 m, 9.6%; 3 m, 18.4%); the DynaPort was less speed dependent and proved to be more appropriate for the PD patients than pedometer methods for walking trajectories of 5 m or more
			PD (48)	Community	Walking distance Step length	The precision in estimating short walking distances was good (percent error: 16%); however, the precision in estimating long walking distances (percent error: <40%) was less appropriate; the overall moderate precision limits the use of this activity monitor for clinical purposes

Table 3 (continued)

Device	Manufacturer	Device form factor	Reported findings			
			population	setting	endpoints	validity/reliability/accuracy
Fitbit Ultra 	Fitbit Inc.	Clip 5.5 × 1.9 × 1.4 cm (11.34 g)	Stroke and TBI (42)	Laboratory	Step count	The Fitbit Ultra underestimated steps (percent error: 5%); however, it had an acceptable accuracy; it was generally accurate in participants who took more steps, and it may be a less costly alternative to research-based activity monitors for identifying steps taken
Fitbit One 	Fitbit Inc.	Clip/wristband 1.9 × 1 × 4.8 mm (80 g)	Stroke (43)	Laboratory	Step count	It is more accurate as the walking speed increases and is more accurate when placed at the ankle (percent error range: 4.9–15.8%) versus the waist (7.7–84.6%)
GENEActiv 	Activinsights	Wristband 4.3 × 4 × 1.3 cm (16 g)	Manual wheelchair users (50)	Community	EE Activity count	The GENEActiv device worn on either the upper arm (percent error: 3%) or the wrist (4%) provided the most valid prediction of EE
Nike FuelBand 	Nike	Wristband	Stroke and TBI (42)	Laboratory	Step count	The Nike FuelBand is not accurate in estimating steps, grossly underestimating steps (33.9%) in this study

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Table 3 (continued)

Device	Manufacturer	Device form factor	Reported findings			
			population	setting	endpoints	validity/reliability/accuracy
RT3 accelerometer 	Stayhealthy Inc.	Waistband 7.1 × 5.6 × 2.8 cm (65.2 g)	MS, PD, stroke (33)	Home	Activity count	Good test-retest reliability in measuring free-living activity; the daily data collected in the first 3 days were significantly different from those collected over 7 days; a 7-day monitoring period provides the most reliable measurement of physical activity
			SCI (49)	Laboratory	EE	Overestimated EE (percent estimation error range: 22–52.8%); however, EE estimations with the RT3 were closer to the criterion EE than those with the SWA
			CP (52)	Clinic	EE	The LOA revealed that the RT3 provided the best agreement with the indirect calorimeter in estimating EE compared to the SWA and IDEEA; however, the RT3 could significantly overestimate or underestimate individual estimates of EE (LOA –67.2 to 86.3% of the mean EE), with smaller errors for over-ground walking compared to treadmill walking
Biaxial accelerometers						
StepWatch Activity Monitor 	Modus Health	Ankle band 7 × 5 × 2 cm (38 g)	MS (39)	Laboratory	Step count	Accurately measures step counts at slow (99%), comfortable (99.8%), and fast (99.6%) walking speeds
			PD and MS (43)	Clinic	Number of strides	Accurately counts the number of strides in both MS (Pearson CC 0.99) and PD (Pearson CC 1.0) patients
			Stroke and TBI (42)	Laboratory	Step count	Accurately counts steps, with only marginal overestimation (percent error: 2.4%) in this population
			Stroke (44)	Home	Step count	The total step count has excellent test-retest reliability when used for 3 days in individuals with stroke; monitoring for less than a 3-day period is not recommended due to high variability
			Rett syndrome (27)	Home	Step count	Accurately counts steps (mean difference: 0 steps/min); agreement did not differ with the level of general or complex gross motor skills

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Table 3 (continued)

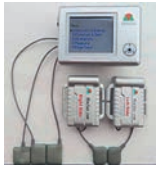
Device	Manufacturer	Device form factor	Reported findings			
			population	setting	endpoints	validity/reliability/accuracy
Uniaxial accelerometers						
ActiGraph 7164 	ActiGraph Corp.	Clip-on or waist/wristband 5.1 × 4.1 × 1.5 cm (45.5 g)	MS (36)	Home	Activity count Minutes of MVPA	Highly reliable over a 6-month period in an MS population
			MS (38)	Home	Step count	Accurately measures steps during moderate (percent error: 0.2%) and fast (0.3%) walking in persons with MS; however, there is a small degree of underestimation of step counts during slower walking (4.1%)
			MS (40)	Laboratory and home	Activity count	Activity counts from the ActiGraph 7164 and the GT3X are significantly different under free-living conditions; difference in output due to slow walking speeds
ActivPAL 	PAL Technologies Ltd.	Adheres directly to skin using PALStickies (hydrogel/ waterproof attachment pad) 3.5 × 5.3 × 7 cm (15 g)	CP (51)	Clinic	Time spent standing Time spent sitting Time spent lying Step counts	Validity was high (r^2 ≥0.96); the limits of group agreement were relatively narrow, but the LOA for individuals were narrow only for the number of steps (>5.5%); the relative reliability was high for the number of steps and moderate for the time spent sitting and lying and the time spent standing; the ActivPAL is sufficiently accurate and reliable to be used for research purposes, but less so for measuring physical activity and sedentary behaviour in an individual
Multisensors						
SWA 	BodyMedia, Inc.	Biaxial accelerometer, heat flux sensor, skin temperature sensor, near-body ambient temperature sensor, and galvanic skin response sensor; armband around the right upper arm 8.5 × 5.3 × 2 cm (79 g including armband)	Stroke (46)	Clinic	Step count EE	There was a poor validity of the SWA in measuring steps and EE during a range of activities and walking tasks; there was good-to-excellent test-retest reliability in measuring steps and EE
			SCI (49)	Laboratory	EE	Significantly overestimated EE (percent error estimation range: 24.4–125.8%) in this population
			CP (52)	Clinicl	EE	Overestimated EE in adults with CP, with smaller errors for over-ground walking compared to treadmill walking
IDEEA 	MiniSun, LLC	Intelligent Device for Energy Expenditure and Activity (IDEEA) 5 biaxial accelerometers collect data and transmit it through thin, flexible wires to a recorder; the accelerometer is placed on the chest, thighs, and soles of the feet Recorder: 7 × 5.4 × 1.7 cm (59 g) Sensor: 1.8 × 1.5 × 0.3 cm (2 g)	CP (52)	Clinic	EE	The mean absolute percentage error was smallest for the IDEEA (range: 8.4–24.5%) when compared to the RT3 and the SWA

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Table 3 (continued)

Device	Manufacturer	Device form factor	Reported findings			
			population	setting	endpoints	validity/reliability/accuracy
Vitaport Activity Monitor	TEMEC Instruments Inc.	Five accelerometers attached to the body connected to a portable battery-powered activity monitor (Vitaport) by cables which run under the clothes; the Vitaport is attached to a belt worn around the waist, with 1 accelerometer on each and 3 placed on the lower third of the sternum 9 × 4.5 × 1.5 cm (1,360 g)	PD (47)	Laboratory	Gait speed Step length Step frequency	Excellent validity (ICC(2, 2) = 0.92–0.99, $p < 0.0001$) for the use of the Vitaport Activity Monitor to measure spatiotemporal gait characteristics during a functional walking test for PD
Spring-mounted lever arm pedometer						
Digi-Walker SW-701/ SW-200 	Yamax Corporation	Clip to waistband or belt 5 × 3.8 × 1.4 cm (21 g)	Stroke and TBI (42)	Laboratory	Step count	Moderate accuracy, tending to underestimate steps in this study (percent error: 14.7%)
			Stroke, MS, SCI, ABI, muscular dystrophy (32)	Clinic	Step count	Undercounts steps (percent error: 24–35%) in a neurological population; however, this is not strongly related to walking speed
			Stroke (46)	Clinic	Step count	Reliably counts steps; wearing it on the knee is a valid option for measuring steps, except during high-intensity walking; the device is more valid as walking speed increases
			PD (34)	Laboratory	Step count	Underestimates step counts (percent error: left, 11.1%; right, 16.3%) and is less accurate for short trajectories and as the walking pace decreases

ABI, acquired brain injury; CC, correlation coefficient; CP, cerebral palsy; EE, energy expenditure; ICC, intra-class correlation coefficient; LOA, limits of agreement; MS, multiple sclerosis; MVPA, moderate-to-vigorous-intensity physical activity; PD, Parkinson disease; SCI, spinal cord injury; TBI, traumatic brain injury.

the pivot point of the hip. Many device manufacturers recommend that monitoring devices are best positioned at the waist for usability reasons. However, wearing a device around the waist in the centre of the back is considered uncomfortable by many, especially when sitting and driving [33], making long-term adherence in the home environment a challenge to achieve. Therefore, for accurate step count measurements in individuals with neurological disorders, it is recommended, based on the evidence, to use biaxial or triaxial accelerometer-type devices, positioning the device around the ankle.

Validity and Reliability of Accelerometer Activity Counts

A number of studies have reported accelerometer activity counts as a measure of physical activity [33–36, 40, 45, 50]; however, the evidence is conflicting regarding the validity and reliability of this measure in patients with neurological disorders. Some authors report good reliability in measuring activity counts during free-living activities from an activity monitor positioned at the waist [33, 36, 45]. However, others found that an accelerometer positioned around the waist was not reliable at measuring activity counts during sedentary and free-living activities [34]. Two studies reported on the validity of activity count outputs from accelerometers, and conflicting findings were also reported [34, 50].

Multisensor Devices Are Inaccurate in Estimating Energy Expenditure

Four studies included in this review reported on the accuracy of using a wearable device in estimating energy expenditure in this population. Multisensor devices such as the SWA are most frequently used to estimate energy expenditure, but this device was shown to be inaccurate in estimating energy expenditure in this population [27, 49, 52]. Similarly, the multisensor Intelligent Device for Energy Expenditure and Activity (IDEEA) was shown to be inaccurate in estimating energy expenditure [52]. Accelerometer devices may be more appropriate for estimating energy expenditure. The Actical triaxial accelerometer was shown to have excellent day-to-day reliability in estimating energy expenditure during free-living physical activities in individuals with stroke living in the community [45].

Limitations

There are a number of limitations to this review that need to be considered. The majority of the studies identified in this review include a small sample of participants. In addition the majority of the studies were conducted in a controlled laboratory or clinical setting, and much more work is required to establish the accuracy of measurements in free-living environments. Despite the best efforts of the authors, it is possible that some studies were not identified in the literature search, or were excluded given the study selection criteria and the electronic databases that were searched to retrieve studies. However, given the systematic approach that was adopted, this review can be accepted as an accurate reflection of the existing evidence exploring activity monitoring in individuals with neurological disorders. Nonetheless this is a rapidly expanding and evolving field of research; therefore the findings of this review should be substantiated as new evidence emerges and new studies are published.

Recommendations for Clinical Use

Activity monitors selected for clinical use should be confined to those for which there is a body of evidence outlining the validity and the reliability of the measurements produced. In addition the psychometric properties of the monitor selected should be established in the clinical cohort of interest, as the validity and reliability of a monitor in one cohort does not

necessarily infer the same in another. Furthermore consideration should be given to the stage and severity of a disorder to ensure the monitor selection is appropriate.

Besides the validity and the reliability of the measurements produced, other factors need to be considered when selecting a device. One should also consider the cost of obtaining the device (hardware and software) and its attachments (e.g., belts or adhesives). Other factors which also warrant attention include the aesthetic appearance of the device, the comfort and wearability of the device, the user experience, the obtrusiveness of the device, the device's durability, and the privacy and discretion afforded with its use. Taking these human factors into consideration when selecting a device will help minimise the impact of potential user acceptance issues that may arise.

Further work is required in this field before wearable activity monitoring can be more widely implemented. Standardised activity monitoring protocols need to be developed for implementing these devices in clinical trials and clinical practice, and consensus is required as to the reporting and interpretation of derived variables.

Conclusions

Recent technological advances have led to the development of a wide range of devices capable of measuring physical activity and mobility. Wearable sensors have immense potential in clinical trials and clinical practice; however, as yet they have not been widely adopted. This review of the literature attempted to summarise the evidence exploring the validity and reliability of body-worn monitors that measure physical activity and mobility in patients with neurological disorders. The variety of methods used in the included studies limits the ability to draw definitive conclusions. Nonetheless, the evidence appears to suggest that multiaxial accelerometer devices – in particular the StepWatch activity monitor and the ActiGraph GT3X – positioned around the ankle most accurately measure step counts in patients with neurological disorders, and are acceptable in slow walking conditions. The findings regarding the reliability and validity of activity counts and energy expenditure are largely inconclusive in this population.

Appendix 1

Search Terms

Free-text and MeSH terms used in the PubMed database:

accelerometry [MeSH] OR *accelerometer* OR *accelerometer and gyroscope* OR *pedometer* OR *physical activity trackers* OR *activity trackers* OR *activity monitor* OR *activity tracker* OR *fitness tracker* OR *physical activity tracker* OR *physical activity monitor* OR *step counter* OR *wearable technology* OR *wearable sensor* OR *wearable device* OR *wearable* OR *sensor* OR *inertial sensor* OR *inertial measurement unit* OR *IMU*

AND

physical fitness [MeSH] OR *motion* [MeSH] OR *energy metabolism* [MeSH] OR *motor activity* [MeSH] OR *steps*

AND

validity OR *validation* OR *validation study* OR *reliability* OR *reliability study* OR *accuracy* OR *comparison* OR *comparison study*

Appendix 2

Quality Assessment of Method Comparison Validation Studies

The following criteria were used for assessing the methodologic quality of method comparison studies as either "yes," "no," or "unclear":

		Yes (✓)	No (✗)	Unable to Determine (?)
		(1)	(0)	(0)
1	Was the spectrum of participants representative of patients who will receive the test in practice?			
2	Were selection criteria clearly described?			
3	Is the reference measurement an acceptable measure of physical activity of the patient?			
4	Is the index test device and reference standard device measurement collected on the same patient at the same time (i.e., both measurements are carried out concurrently)?			
5	Did all of the patients receive the same reference device measurement?			
6	Were the index test and reference standard device measurements performed independently (blind) of each other?			
7	Were the same clinical data available when index test results were interpreted as would be available when the tests are used in practice?			
8	Was the execution of the index test described in sufficient detail to permit replication of the test?			
9	Was the execution of the reference standard described in sufficient detail to permit its replication?			
10	Was the study free of commercial funding from the manufacturers of the device(s) being validated in the study (i.e., is there any indication in the article that funding was received)?			

Study	1	2	3	4	5	6	7	8	9	10
Bania [51]	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓
Dijkstra et al. [27]	✓	✓	✓	✗	✓	?	✓	✓	✓	✓
Downs et al. [53]	✓	✓	✓	✗	✓	?	✓	✓	✓	✓
Elsworth et al. [32]	✓	✓	✓	✓	✓	?	✓	✓	✓	✓
Fulk et al. [42]	✓	✓	✓	✓	✓	?	✓	✓	✓	✓
Hiremath and Ding [49]	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓
Kayes et al. [34]	✓	✓	✓	✓	✓	?	✓	✓	✓	✓
Klassen et al. [43]	✓	✓	✓	✗	✓	?	✓	✓	✓	✓
Lord et al. [47]	✓	✓	✓	✓	✓	?	✓	✓	✓	✓
Motl et al. [37]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗
Motl et al. [38]	✓	✓	✓	✓	✓	?	✓	✓	✓	✓
Nightingale et al. [50]	✓	✗	✓	✓	✓	?	✓	✓	✓	✓
Ryan et al. [52]	✓	✓	✓	✓	✓	?	✓	✓	✓	✓
Sandroff et al. [39]	✓	✓	✓	✓	✓	?	✓	✓	✓	✓
Schmidt et al. [41]	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓
Speelman et al. [48]	✓	✗	✓	?	✓	?	✓	✓	✓	✓
Vanroy et al. [46]	✓	✓	✓	✓	✓	?	✓	✓	✓	✓

Ethics Statement

The authors have no ethical conflicts to disclose.

Conflict of Interest Statement

I.C. and L.W. work for Novartis. O.M.G. is on secondment with Novartis.

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