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RESEARCH

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Measurement properties of device-based physical activity instruments in ambulatory adults with physical disabilities and/or chronic diseases: a scoping review

Pim Brandenburg^{1,2*}, Femke Hoekstra^{1,2,3}, Ioulia Barakou¹, Bregje L. Seves^{1,2}, Florentina J. Hettinga⁴, Trynke Hoekstra^{2,5}, Lucas H. V van der Woude^{1,2}, Rienk Dekker² and Leonie A. Kroops²

Abstract

Background People with physical disabilities and/or chronic diseases tend to have an inactive lifestyle. Monitoring physical activity levels is important to provide insight on how much and what types of activities people with physical disabilities and/or chronic diseases engage in. This information can be used as input for interventions to promote a physically active lifestyle. Therefore, valid and reliable physical activity measurement instruments are needed. This scoping review aims 1) to provide a critical mapping of the existing literature and 2) directions for future research on measurement properties of device-based instruments assessing physical activity behavior in ambulant adults with physical disabilities and/or chronic diseases.

Methods Four databases (MEDLINE, CINAHL, Web of Science, Embase) were systematically searched from 2015 to April 16th 2023 for articles investigating measurement properties of device-based instruments assessing physical activity in ambulatory adults with physical disabilities and/or chronic diseases. For the majority, screening and selection of eligible studies were done in duplicate. Extracted data were publication data, study data, study population, device, studied measurement properties and study outcome. Data were synthesized per device.

Results One hundred three of 21566 Studies were included. 55 Consumer-grade and 23 research-grade devices were studied on measurement properties, using 14 different physical activity outcomes, in 23 different physical disabilities and/or chronic diseases. ActiGraph ($n=28$) and Fitbit ($n=39$) devices were most frequently studied. Steps ($n=68$) was the most common used physical activity outcome. 97 studies determined validity, 11 studies reliability and 6 studies responsiveness.

Conclusion This scoping review shows a large variability in research on measurement properties of device-based instruments in ambulatory adults with physical disabilities and/or chronic diseases. The variability highlights a need for standardization of and consensus on research in this field. The review provides directions for future research.

Keywords Physical activity, Device-based instruments, Accelerometry, Measurement properties, Validity, Reliability, Responsiveness, Physical disability, Chronic disease, Scoping review

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Background

Physical activity (PA), defined as “any bodily movement produced by skeletal muscles that result in energy expenditure” [1], is a multidimensional construct with dimensions as setting (e.g. PA during leisure time, work), mode (e.g. walking, bicycling), frequency (e.g. times per week), duration (e.g. in hours) and intensity (e.g. light, moderate or vigorous) [2, 3]. PA has many health benefits across the lifespan, especially for people with physical disabilities and/or chronic diseases [4, 5]. Still, people with physical disabilities and/or chronic diseases tend to have an inactive lifestyle [6, 7]. Monitoring PA in this population is important, as it will provide insight in how much and what types of PA they engage in. Information on the amount and types of PA can help tailor PA promotion activities to individuals and uncover opportunities for improving PA for people with physical disabilities and/or chronic diseases. Furthermore, self-monitoring is one of the most effective behavior change techniques for improving PA, further stressing the importance of accurately measuring PA [8]. The need to measure and quantify PA in this varied population has also been emphasized by various research groups [9, 10], including the developers of the new World Health Organization’s PA guidelines [11].

A variety of instruments exist to measure PA in people with physical disabilities and/or chronic diseases. Instruments for PA measurement can be classified into two main categories: device-based instruments (e.g. accelerometers and pedometers; later also mentioned as devices) and self-report instruments (e.g. questionnaires and diaries). Both types of instruments have advantages and disadvantages [12] and are believed to measure different aspects of the PA construct [13]. Self-report instruments are assumed to capture the perceived PA behavior, whereas device-based instruments aim to capture the continuous acceleration of the body above a certain threshold [13]. The consensus is currently that both types of instruments have their own value and should be used complementarily to one another, depending on the research questions or clinical and/or practical goals [14].

Device-based instruments collect raw movement data (e.g. acceleration) from a variety of locations on the human body. These data are converted into different PA outcomes (e.g. energy expenditure, steps) often using dedicated algorithms [15]. These algorithms are commonly developed for a general (non-disabled) population [9]. People with physical disabilities and/or chronic diseases such as those with stroke, Parkinson’s disease, and chronic obstructive pulmonary disorder, might have a different pattern of locomotion (e.g. slower and/or asymmetrical) [16–18]. Also, people with physical disabilities and/or chronic diseases could have a different

energy expenditure during PA compared to people without physical disabilities and/or chronic diseases, due to a lower efficiency of walking or other motor actions in general [19–21] or due to an increased energy cost of daily activities [22]. This could be of influence on the validity of the algorithms used in device-based PA instruments when applied to people with physical disabilities and/or chronic diseases. Research already showed that slower walking speeds limit the validity of measuring steps using certain devices [23, 24]. Furthermore, energy expenditure estimations of devices had poor correlations with estimations of indirect calorimetry in people with stroke [25]. These findings warrant a critical mapping of the measurement properties of device-based instruments used to assess PA in people with physical disabilities and/or chronic diseases.

There have been reviews in the past on the measurement properties of device-based instruments in people with physical disabilities and/or chronic diseases. However, these are mostly either diagnosis- or PA-outcome specific [25–29]. Also, manual wheeled mobility involves a completely different class of bodily activities and their energetic consequences as opposed to individuals who walk. A recent systematic review gave an extensive overview of the measurement properties of device-based and self-reported instruments assessing PA in people using a wheelchair [30]. Therefore, the current review focused on the ambulatory population of adults with physical disabilities and/or chronic diseases.

This scoping review aims to provide a critical mapping of the existing literature on the measurement properties of device-based instruments assessing physical activity behavior in ambulant adults with various physical disabilities and/or chronic diseases. Using this critical mapping, we provide future directions to study the measurement properties of device-based instruments assessing PA in ambulatory adults with physical disabilities and/or chronic diseases.

Methods

Study design

This scoping review was guided by the methodological framework for scoping reviews [31, 32] and the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guideline [33]. A scoping review was chosen as it can be used to summarize research findings and potentially identify research gaps in the literature, which matches our aim. The study protocol is available at <https://osf.io/c27xv/>. During the review process, we deviated from the published protocol. In Supplementary file 1 we report the reason and the nature of these deviations. In short, we deviated from the protocol in three main ways: 1) because

of the large amount of research, we changed the scope of the review from all literature on both device-based and self-reported instruments into only device-based instruments in a set time period; 2) we therefore changed the review question accordingly; and 3) we changed the method from a systematic into a scoping review.

Following the aim and scope of the original protocol, we defined the following PICO criteria: (*P*) Adults (≥ 18 years old) with physical disabilities and/or chronic diseases. *Physical disability* was defined as a congenital disease, acquired illness, or trauma that causes an impairment, activity limitation and participation restriction that lasts at least 1 year [34, 35]. *Chronic disease* was defined broadly as conditions that last 1 year or more and require ongoing medical attention or limit activities of daily living or both [36]. (*I*) Physical activity measurement instrument. *Physical activity measurement instrument* was defined as a device-based or self-report instrument that assesses any bodily movement produced by the muscles that results in increased energy expenditure [1] in the activity domain of the International Classification of Function, Disability and Health (ICF) model [35]. (*C*) We did not use a comparison group, since this is not relevant for studies on measurement properties. (*O*) Measurement properties (e.g. reliability, validity, responsiveness). Operationalization of *Measurement properties* followed the definitions of COSMIN [37].

Search strategy and information sources

Together with an information specialist (KS), we combined the three different concepts of our PICO to create our search terms: physical activity measurement instrument, physical disability and/or chronic disease and measurement properties. We used a combination of both MeSH-terms and free text words for each concept, linked with Boolean operators. Literature was initially searched up to June 26th 2019, with a first update of the search up to November 20th 2020, and a second update of the search up to April 16th 2023 in four databases: Medline, Cinahl, Web of Science and Embase. We adapted the search strategy for each database using the same keywords and, where possible, MeSH-terms. The full search strategies for each of the four databases can be found in Supplementary file 2.

Eligibility criteria

Articles were eligible for inclusion in the scoping review when 1) included participants were 18 years or older and had a physical disability or chronic disease, with having the physical disability or chronic disease a primary reason for rehabilitation treatment; 2) PA was measured as an amount or energy cost using a self-reported or device-based instrument; 3) measurement properties were a

(primary or secondary) outcome measure of the studies; 4) articles were published in peer-reviewed journals and involved primary research. Articles were excluded when 1) studies were not in humans; 2) participants had an intellectual-, sensory-, cognitive- or mental disability; 3) all included participants were wheelchair users; 4) PA was measured as a functional or a performance outcome; 5) articles were not in English or Dutch. We excluded literature studying participants with intellectual-, sensory-, cognitive- or mental disabilities, as these studies may require different approaches and interpretations compared to studies involving people with physical disabilities and/or chronic diseases. As the authors are knowledgeable in Dutch and English, we excluded all non-English/Dutch articles.

Selection of sources of evidence

Before screening, duplicates were removed using Bramer et al.'s method [38] in EndNote. Two researchers independently screened titles (PB & LAK) and subsequently abstracts (PB & IB) on eligibility using custom Excel spreadsheets. Disagreement was resolved by including those articles to the next phase. For the title and abstract phase, pilot tested checklists with specific instructions for in- and exclusion were used. During the abstract screening phase, regular meetings were held to ensure equal interpretation of the abstracts between both researchers and to discuss uncertainties. Before full text screening, articles were removed that used self-reported PA instruments or were published before 2015. We did this due to the change of focus (on device-based instruments only) of the review after the abstract phase (see Supplementary file 1).

Eligibility of full texts was screened by two researchers independently (PB & IB), using a checklist for full text eligibility and a custom Excel spreadsheet. Disagreements were discussed, and if necessary, a third assessor (LAK) was consulted. Cohen's Kappa statistics were calculated to assess the agreement between the two screeners for the title, abstract and full text phase [39]. For feasibility reasons, the second update was performed by one researcher (PB) only. A second researcher (LAK) was consulted in case of questions and doubt with respect to the interpretation of the study. The PICO, in- and exclusion criteria and complete checklists per phase can be found in Supplementary file 3. The used custom Excel spreadsheets can be found on Open Science Framework (<https://osf.io/c27xv/>).

Data charting process

The first author (PB) extracted data using an extraction form in Excel (available at Open Science Framework: <https://osf.io/c27xv/>). The data extraction form included

the following information: 1) publication data (author, year of publication, land of origin); 2) study data (design, setting, sample size, and protocol tasks); 3) study population (diagnosis group(s), age, gender, and walking speed); 4) device (name, type, placement, unit of measurement, epoch length, sampling rate, and algorithm used); 5) studied measurement properties (validity, reliability, or responsiveness) and criterion measure (name, type, unit of measurement, algorithm used); and 6) study outcomes.

Synthesis of results

We synthesized the data based on device. For each device, the available measurement properties were presented using the following ordering: 1) PA outcome; 2) diagnosis group; 3) study; 4) device placement; and 5) algorithm. We separated research-grade devices from consumer-grade devices.

Results

Figure 1 shows a flowchart of the screening and review process. A total of 21566 records were identified through the search. After removing duplicates and publications categorized as non-primary research, 13219 records were screened on title. Based on title, we excluded 10752 records. We screened the remaining records on abstract, and excluded 1725 records. A further 403 records were excluded, as they were published before 2015 or used self-report measurement instruments for physical activity. The remaining 287 records were read in full. Of these, we excluded 184 records that did not meet the eligibility criteria, which resulted in a total of 103 studies included in this review. Agreement of the initial search and first update for title, abstract and full text screening was moderate (title phase: Cohen’s Kappa=0.68, agreement = 78%; abstract phase: Cohen’s Kappa=0.55, agreement = 82%; full text phase: Cohen’s Kappa = 0.57, agreement = 78%).

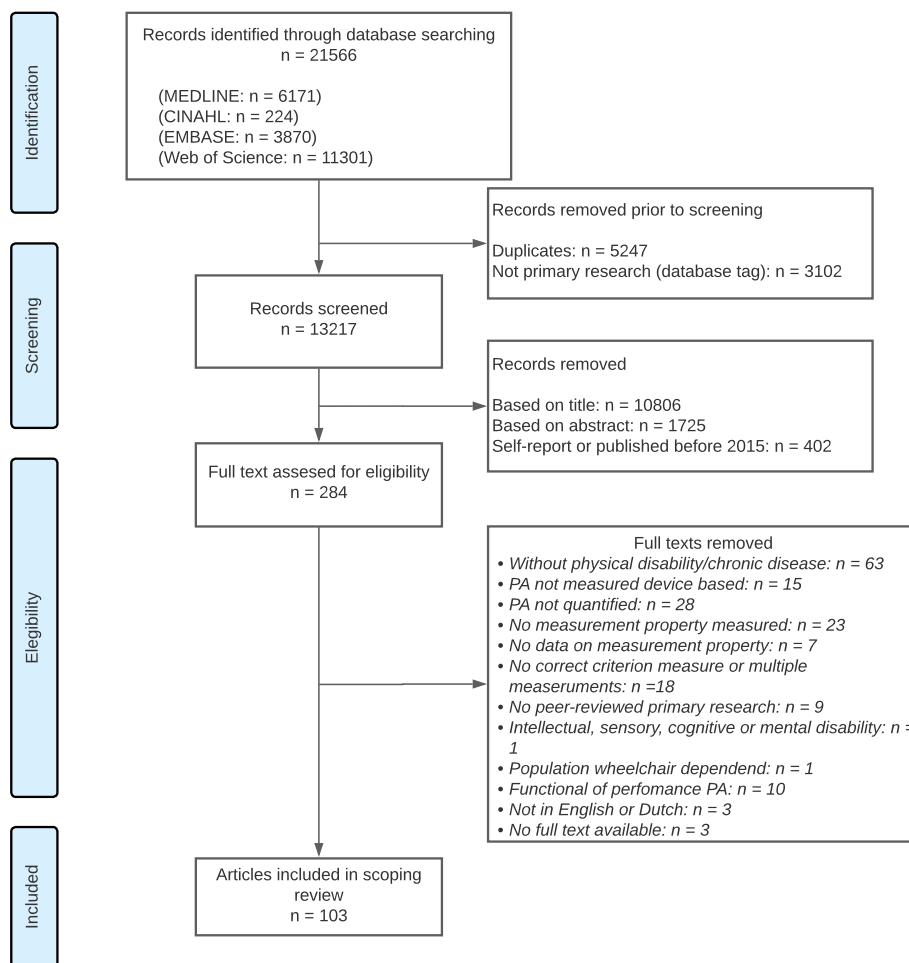


Fig. 1 Flowchart of screening and review process of included studies on device-based instruments assessing physical activity. *n* = number of studies

Characteristics of the included studies are shown in Table 1. In total, 23 different physical disabilities and/or chronic diseases were included in the studies. Most studies included people with stroke ($n=27$) [40–66], chronic obstructive pulmonary disease ($n=11$) [67–77] and multiple sclerosis ($n=10$) [78–87]. Six studies included a mixed population of people with different physical disabilities and/or chronic diseases [23, 75, 77, 88–90]. Sample sizes ranged from 4 to 176, with a median of 28. The majority of studies were performed in Northern America (USA, $n=28$ [51, 64, 69, 70, 72, 74, 76, 83–85, 91–107]; Canada, $n=10$ [40, 47, 50, 52, 53, 89, 108–111]) and Western Europe (UK, $n=11$ [78, 80, 82, 86, 112–118]; France, $n=8$ [42–45, 55, 119]; the Netherlands, $n=6$ [48, 75, 77, 120–122]; Germany, $n=4$ [68, 87, 123, 124]; Switzerland, $n=4$ [66, 81, 125, 126]; Denmark, $n=3$ [127–129]; Belgium, $n=2$ [67, 88]; Italy, $n=2$ [56, 130]; Sweden, $n=2$ [71, 79]; Ireland, $n=1$ [131]; Portugal, $n=1$ [132]). Only 14 studies were performed in other countries (Brazil, $n=6$ [46, 49, 57, 62, 63, 133]; Japan, $n=4$ [59, 73, 134, 135]; Australia, $n=3$ [60, 90, 136]; Czech Republic, $n=1$ [65]). Of the 103 included studies, 65 were performed in a laboratory setting with protocolled activities [23, 40–46, 49, 51–59, 61–66, 70, 72, 75, 78–80, 83, 86, 88–90, 92, 93, 95–97, 101, 103, 104, 107, 109, 111–115, 119, 120, 122, 123, 125, 126, 128–133, 137–139], 28 during free-living (activities of own choice) [50, 60, 67, 68, 71, 73, 76, 82, 87, 91, 94, 98–100, 102, 105, 106, 108, 110, 117, 121, 124, 127, 134–136, 140, 141], nine in a combined laboratory and free-living setting [47, 48, 69, 77, 81, 84, 85, 116, 118], and one in the home setting in which participants had to perform a set of protocolled activities [74]. Walking speed of the participants was on average slow, with speeds predominantly below 1.0 m/s. Supplementary file 4 provides an extended version of Table 1. This table provides extra information on important in- and exclusion criteria, the tasks performed, and criterion for valid measurement days and cases (for studies performed in a free-living setting).

In total, 78 different PA devices from 43 different companies were studied on their measurement properties. In 39 studies multiple devices were used and compared [23, 43, 44, 46, 49, 51, 54, 55, 57, 58, 63, 64, 67, 70, 75, 79–81, 83, 84, 89, 92–97, 101, 103, 107, 112, 115, 116, 118, 122, 132, 133, 137, 141]. Twenty-three devices were research-grade and 55 were consumer-grade. The most frequently studied research-grade devices were from the companies ActiGraph ($n=28$ studies) [23, 40, 43–45, 49, 51, 55, 61, 64, 76, 79, 81, 84, 89, 93–96, 104, 105, 107, 108, 112, 114–116] and PAL technology ($n=8$ studies) [23, 54, 86, 91, 95, 116, 131, 138]. The most frequently studied consumer-grade devices were from the companies Fitbit ($n=39$ studies) [23, 41, 46, 47, 50, 52, 53, 58,

60, 64, 65, 67, 74, 75, 80, 81, 83–85, 90, 92, 94, 97–99, 101–103, 106, 109, 112, 118, 122, 127, 133, 136, 137, 140, 141] and Garmin ($n=10$ studies) [23, 58, 66, 80, 97, 101, 107, 130, 137, 141].

With respect to measurement properties, 97 studies determined validity [23, 40–90, 92–110, 112, 114–129, 131–134, 136–138, 140, 141], 11 studies determined reliability [46, 54, 58, 66, 91, 105, 106, 111, 113, 118, 135] and six study determined responsiveness [82, 100, 105, 106, 118, 136]. The measurement properties of 14 different PA outcomes were studied. Step count was the most frequently studied PA outcome ($n=68$) [23, 40, 41, 46, 47, 50, 52–54, 56–58, 63–69, 74, 75, 79–86, 89–98, 101–109, 111, 112, 116–118, 121, 123, 124, 126–133, 136, 137, 140, 141], followed by energy expenditure ($n=19$) [42, 43, 45, 49, 51, 55, 61, 62, 70, 71, 82, 88, 96, 114, 115, 119, 122, 125, 134] and activity time ($n=15$) [48, 54, 68, 80–82, 86, 91, 95, 100, 116, 117, 120, 131, 138]. In the majority of studies ($n=60$), PA was measured by means of only walking tasks or by using walking-related PA outcomes (e.g. steps, walked distance) [23, 40, 41, 43, 44, 46, 47, 49, 52–54, 56–58, 61, 62, 64–67, 69, 72, 74, 75, 77, 78, 83–85, 89, 90, 92, 93, 97, 98, 101, 103, 104, 107–109, 112, 113, 115, 119, 121, 123, 126–130, 132, 133, 136–139, 141].

The proprietary algorithm of the instrument was most frequently used, or the algorithm used was not reported at all. A population-specific custom algorithm was used in three research-grade and three consumer-grade devices. Devices were positioned at 15 different body positions, with the positions at the ankle, thigh, waist and wrist as most common. One device (Medtronic ICD/CRT device) was a type of pacemaker, and was surgically implanted in patients with heart failure. Validity was measured using 21 different statistical methods, reliability with three different methods, and responsiveness with five methods.

Table 2 provides an overview of the measurement properties of the research-grade devices, per PA outcome, study population, device properties (placement of the device, used algorithms) and outcome (used statistical test, result). Table 3 provides the same overview for the consumer-grade devices. Supplementary files 5 and 6 contain a more in-depth version of both tables, with extra information such as epoch length, sampling rate and results per condition.

Research-grade devices

ActiGraph

Measurement properties of a type of ActiGraph were determined in 28 studies, with 24 studies evaluating type GT3 [23, 40, 43–45, 49, 51, 55, 61, 64, 81, 84, 89, 94–96, 104, 105, 108, 112, 114–116, 139] and four studies evaluating type GT9 [76, 79, 93, 107] (Table 2). Only validity

Table 1 Descriptives of the 103 included studies

Author	Year	Country	Study design	Population	N	Study setting	% Male	Age (years)	Task	Walking speed (m/s)
Albaum et al. [108]	2019	Canada	Cross	iSCI	17	FL	76.5	62.0 (41.5–78.5)	Physical therapy & self-directed tasks	NR
Alexander et al. [78]	2022	UK	Cross	MS	100	Lab	30.0	53.5 (47.8–58.0)	Circuit outdoors	Comfortable
Alharbi et al. [140]	2016	Australia	Cross	Coronary heart disease	28	FL	71.4	NR	Free-living 4 days	NR
Alothman et al. [91]	2020	USA	Long	DM2	30	FL	36.7	64.87 ± 5.99	Free-living 7 days (2x)	NR
Anens et al. [79]	2023	Sweden	Cross	MS	30	Lab	30.0	49.2 ± 14.0	Circuit + sedentary activities	0.76 IQR 0.31 – 1.30 IQR 0.39
Arch et al. [92]	2018	USA	Cross	Amputation ^a	50	Lab	64–76	55.4 ± 10.1 – 58.6 ± 11.7	Circuit	0.95 ± 0.21 – 1.01 ± 0.19
Ata et al. [93]	2018	USA	Cross	Peripheral Arterial Disease	114	Lab	77.2	69.5 ± 13.1	6MWT	NR
Balto et al. [83]	2016	USA	Cross	MS	45	Lab	NR	46.7 ± 10.0	treadmill 500 steps	1.21 ± 0.27
Bianchini et al. [130]	2022	Italy	Cross	Parkinsons disease	47	Lab	67.0	66.3 ± 8.2	6MWT	Self-selected
Block et al. [84]	2017	USA	Cross	MS	82	Both	29.3	51.0 ± 13.7	2MWT and free-living 7 days	NR
Block et al. [85]	2019	USA	Cohort	MS	61	Lab	28.0	50.0 ± 14.4	2 MWT	NR
Blondeel et al. [67]	2020	Belgium	Cross	COPD	31	FL	41.9	53.4 ± 11.7	Free-living 7 days	NR
Boeselt et al. [68]	2016	Germany	Cross	COPD	30	FL	61.0	66 ± 8	Free-living 14 days	NR
Campos et al. [40]	2018	Canada	Cross	Stroke	20	FL	85.0	66.4 ± 7.4	Free-living 3 days	NR
Caron et al. [119]	2019	France	Cross	DM2	33	Lab	69.7	64.9 ± 14.7	7 h on a single day	0.82 ± 0.27
Cederberg et al. [104]	2021	USA	Cross	Parkinsons disease	29	lab	62.0	64.2 ± 6.4	Treadmill	0.50, 0.75, 1.00, 1.25 & 1.50
Chandrasekar et al. [112]	2018	UK	Cross	Polymyalgia rheumatica	27	Lab	11.0	69.2 ± 8.8	6MWT + treadmill	1.03 ± 0.18
Claridge et al. [120]	2019	Netherlands	Cross	Cerebral palsy	14	Lab	60.0	35.4 ± 13.1	2 MWT & stairs test	1.19 (IQR 0.95–1.31)
Clay et al. [41]	2019	New Zealand	Cross	Stroke	19	Lab	42.0	65.6 ± 8.2	Circuit	Self-selected (0.97 ± 0.22)
Collins et al. [94]	2019	USA	Cross	Osteoarthritis (knee)	15	FL	33.0	68 ± 8	6MWT	NR
Compagnat et al. [45]	2018	France	Cross	Stroke	35	Lab	NR	64.6 ± 14.4	Free-living waking hours 28 days	0.6 ± 0.3
Compagnat et al. [44]	2019a	France	Cross	Stroke	35	Lab	NR	64.6 ± 14.8	Circuit	Comfortable (0.56 ± 0.30)
Compagnat et al. [42]	2019b	France	Cross	Stroke	38	Lab	52.6	65.7 ± 13.5	6MWT	0.52 ± 0.28
Compagnat et al. [43]	2020	France	Cross	Stroke	26	Lab	NR	64.6 (55.5–77.0)	Circuit	0.56 ± 0.3
Compagnat et al. [61]	2022	France	Cross	Stroke	26	Lab	61.5	63.5 (55.3–77.5)	6MWT	0.53 ± 0.30
Costa et al. [46]	2020	Brazil	Cross	Stroke	55	Lab	54.5	62.5 ± 14.9	2 MWT	0.7 ± 0.3
Coulter et al. [86]	2017	UK	Cross	MS	20	Lab	45.0	53.7 ± 7.4	Circuit	83.9 ± 25.1 steps/min
Daligadu et al. [109]	2018	Canada	Cross	Cardio-thorax surgery patients ^b	20	Lab	90.0	61.3 ± 10.2	6 MWT	0.7 ± 0.2

Table 1 (continued)

Author	Year	Country	Study design	Population	N	Study setting	% Male	Age (years)	Task	Walking speed (m/s)
Daniel et al. [62]	2022	Brazil	Cross	Stroke	24	Lab	54.0	46.2±12.0	Treadmill walking	0.22–0.89
Danilack et al. [69]	2015	USA	Cross	COPD	176	Both	99.0	72±8	Circuit & free-living 14 days	0.97±0.22
de Carvalho Lana et al. [133]	2021	Brazil	Cross	Parkinsons disease	34	Lab	76.5	66.8±7.1	2MWT	Self-selected
Dhillon et al. [70]	2018	USA	Cross	Lung disease ^c	8	Lab	NR	42.1±17.1	Circuit	NR
Douma et al. [121]	2018	Netherlands	Cross	Cancer	72	FL	63.0	63±11.5	Free-living 14 days	NR
Duclos et al. [47]	2019	Canada	Cross	Stroke	20	Both	65.0	53.9±10.8	6MWT and Circuit at mall	1.02±0.41 (6MWT) 0.86±0.29 (Circuit)
Falter et al. [88]	2019	Belgium	Cross	Heart disease ^d , DM 1&2	40	Lab	80.0	61.9±15.2	Cardiopulmonary exercise test, cycling ergometer	NR
Fanchamps et al. [48]	2018	Netherlands	Cross	Stroke	25	Both	84.0	56±12	Circuit	NR
Faria et al. [49]	2019	Brazil	Cross	Stroke	30	Lab	70.0	62±12	Circuit	Maximum speed 1.3±1.0
Farmer et al. [90]	2022	Australia	Cross	Orthopedic, neurological and other	88	Lab	49.0	73±11	Circuit: indoors and outdoors	0.81 & 0.78 (in, outdoor)
Farooqi et al. [71]	2015	Sweden	Cross	COPD	19	FL	0.0	69.2±6.0	Free-living 14 days	NR
Femiano et al. [126]	2022	Switzerland	Cross	Cardiac rehabilitation patients ^e	22	Lab	NR	56.6±9.0	Physical therapy	NR
Ferreira et al. [132]	2020	Portugal	Cross	Chronic pain	50	Lab	36.0	72.30±6.76	Circuit	Self-selected & maximum walking speed
Garcia Oliveira et al. [63]	2021	Brazil	Cross	Stroke	50	Lab	64.0	62 (57–70)	10 mWT +TUG	0.88 (0.50–1.13)
Gustafsson et al. [128]	2022	Denmark	Cross	Lumbar spinal stenosis	30	Lab	63.0	76.2±7.8	Circuit	Comfortable
Hei Chow et al. [60]	2023	Australia	Cross	Stroke	23	FL	65.0	74.8±9.8	Free-living 7 days	NR
Henderson et al. [64]	2021	USA	Cross	Stroke	21	Lab	48.0	64.0±13.5	Physical therapy	0.33 (0.00–1.21)
Herkert et al. [122]	2019	Netherlands	Cross	Coronary artery disease	7	Lab	71.0	65.5±8.3	Exercise training walking	0.49 (0.16–1.08)
Holubova et al. [65]	2022	Czech Republic	Cross	Heart failure	19	Lab	74.0	61.4±6.9	Circuit and treadmill	NR
Huber et al. [66]	2022	Switzerland	Cross	Stroke	24	Lab	89.0	65.1±6.6	Circuit and treadmill	NR
Hui et al. [50]	2018	Canada	RCT	Stroke	20	Lab	62.5	58.95±12.25	Circuit	NR
Jao et al. [95]	2017	USA	Cross	Stroke	12	FL	65.0	63.1±12.4	Circuit, outdoor	1.34 (0.77–1.47)
					31	Lab	58.0	62.6±9.3	Free-living 3 days (fri-sun)	0.73±0.27
				DM (half with foot amputation)			NR	56±7.5	Circuit	Self-selected, 60 & 100 steps/min

Table 1 (continued)

Author	Year	Country	Study design	Population	N	Study setting	% Male	Age (years)	Task	Walking speed (m/s)
Jayaraman et al. [96]	2016	USA	Cross	iSCI	8	Lab	87.5	48.5±3.7	Circuit	NR
Jayaraman et al. [51]	2018	USA	Cross	Stroke	8	Lab	60.0	55.6±9.4	Circuit	NR
Jimenez-Moreno et al. [113]	2019	UK	Cross	DM1	30	Lab	66.7	48.5±10.4	Circuit	NR
	2019	UK	Cross	DM1	30	Lab	66.7	48 (25–72)	Circuit	NR
Juen et al. [72]	2015	USA	Cross	pulmonary diseases ^f	28	Lab	42.8	NR	6MWT	NR
Klassen et al. [52]	2016	Canada	Cross	Stroke	43	Lab	70.0	65.0±10.7	Circuit	Self-selected & 0.3–0.9 with increases of 0.1
Klassen et al. [53]	2017	Canada	Cross	Stroke	21	Lab	NR	55±10	Physical therapy	0.41±0.27
Ladlow et al. [114]	2017	UK	Cross	Amputation ^g	20	Lab	NR	32±5 (unilateral) 29±4 (bilateral)	Treadmill	0.48, 0.67, 0.89, 1.12, 1.34
Ladlow et al. [115]	2019	UK	Cross	Amputation ^g	19	Lab	100.0	30.4±4.6	Treadmill	0.48, 0.67, 0.89, 1.12, 1.34
Lai et al. [97]	2020	USA	Cross	Parkinsons disease	31	Lab	NR	64.3±6.3	Circuit & treadmill	1.05±0.16
Lamont et al. [137]	2018	Australia	Cross	Parkinsons disease	33	Lab	64.0	68.8±8	Circuit	Self-selected & 60, 80, 100, 120, 140 steps/min
Larkin et al. [131]	2016	Ireland	Cross	Rheumatoid arthritis	20	Lab	15.0	55±14	Circuit & treadmill	Self-selected pace
Lavelle et al. [80]	2021	UK	Cross	MS	19	Lab	31.6	52.1±11.9	Circuit	NR
Mahendran et al. [54]	2016	Australia	Cross	Stroke	15	Lab	53.3	63.4±8.3	6MWT, circuit & treadmill	Slow (0.31±0.11), comfortable (0.42±0.17) & fast (0.54±0.25)
Mandigout et al. [55]	2017	France	Cross	Stroke	24	Lab	62.5	68.2±13.9	Circuit	NR
McGinley et al. [110]	2015	Canada	Cross	DM2	35	FL	60.0	62.8±7.8	Free-living 14 days	NR
Miyamoto et al. [73]	2018	Japan	Cross	COPD	11	FL	91.6	76.6±6.9	Free-living 7 days	NR
Negrini et al. [56]	2020	Italy	Cross	Stroke	43	Lab	62.8	61.3±14.95	Circuit	0.75±0.32
Nishida et al. [134]	2020	Japan	Cross	DM2	51	FL	45.1	70±5	Free-living 12–16 days	NR
O'Brien et al. [116]	2020	UK	Cross	Rheumatoid arthritis	22	Lab	14.0	53.7±12.5	Circuit	NR
O'Neill et al. [117]	2017	UK	Cross	Rheumatoid arthritis	100	FL	29.0	58.5±12.1	Free-living 7 days	NR
Pham et al. [123]	2017	Germany	Long	Bronchiectasis	55	FL	40.0	60±10	Free-living 7 days	NR
Pollese et al. [57]	2019	Brazil	Cross	Parkinsons disease	20	Lab	52.4	66.4±9.0	Circuit	NR
	2019	Brazil	Cross	Stroke	37	Lab	75.7	62±11	Circuit	0.9±0.3 Comfortable 1.3±0.6 Fast
Polhemus et al. [81]	2023	Switzerland	Cross	MS	45	Both	35.6	46 (QR 40–51)	Circuit+Free-living 14 days	109 (61–146) steps/min
Popp et al. [125]	2019	Switzerland	Cross	iSCI	30	Lab	70.0	54.1±11.9	Circuit	NR
Prieto-Centurion et al. [74]	2016	USA	Cross	COPD	4	Home	100.0	69±10	6MWT	NR

Table 1 (continued)

Author	Year	Country	Study design	Population	N	Study setting	% Male	Age (years)	Task	Walking speed (m/s)
Roberts-Lewis et al. [118]	2022	UK	Long	Progressive muscle diseases	20	Lab	N.R.	N.R.	Circuit	N.R.
Rockette-Wagner et al. [105]	2021	USA	Long	Inflammatory myopathy	56	FL	44.6	44.7 ± 15.1	Free-living 7 days	N.R.
Rossi et al. [98]	2018	USA	Cross	Endometrial cancer	25	FL	0.0	62 ± 9	Free-living 30 days	N.R.
Salih et al. [138]	2016	Australia	Cross	Amputation ^h	21	Lab	71.4	59.4 ± 11.5	Circuit	N.R.
Saygin et al. [106]	2022	USA	Long	Myositis	24	FL	29.2	46.2 ± 14.4	Free-living 7 days	N.R.
Schaffer et al. [58]	2017	USA	Cross	Stroke	24	Lab	58.3	54 ± 13.4	Circuit	0.72 ± 0.40
Semanik et al. [99]	2020	USA	RCT	Chronic knee symptoms	35	FL	31.0	52 ± N.R.	Free-living 7 days	N.R.
Shimizu et al. [59]	2018	Japan	Cross	Stroke	10	Lab	50.0	57.5 ± 16.2	circuit	0.98 ± 0.36
Shoemaker et al. [100]	2017	USA	Cohort	Heart failure	16	FL	56.3	64.9 ± 11.3	Free-living 7 days	N.R.
Smith et al. [101]	2019	USA	Cross	Amputation ^g	32	Lab	66.0	49.7 ± 14.0	Self-selected	
Smith & Guerra [107]	2021	USA	Cross	Amputation ^g	35	Lab	54.3	48.5 ± 14.8	2MWT	1.23 ± 0.22
Stuart et al. [82]	2020	UK	Long	MS	56	FL	52.0	53.6 ± 8.0	Free-living 2–7 days	N.R.
Takasaki [135]	2017	Japan	Cross	Lower back pain	15	FL	40.0	22.1 ± 4.3	Free-living 14 days	N.R.
Taoum et al. [139]	2020	France	Cross	Peripheral artery disease	23	Lab	N.R.	60.0 ± 10.0	Circuit	Self-selected
Thorup et al. [127]	2017	Denmark	Cross	Heart disease ⁱ	24	FL	91.6	67.0 ± 10.0	Day at hospital and day at home	N.R.
Treacy et al. [23]	2017	Australia	Cross	Diverse motor disabilities ^j	166	Lab	55.0	80 ± 11	6MWT	0.42 ± 0.22
Ummels et al. [75]	2018	Netherlands	Cross	CVD, cancer, COPD, osteoarthritis, chronic pain	130	Lab	43.6	61.5 ± 11.1	Circuit	1.3 ± 0.3
Van Blarigan et al. [102]	2017	USA	Cross	prostate cancer	22	FL	100.0	66 (56–83)	Free-living 7 days	N.R.
Van der Weegen et al. [77]	2015	Netherlands	Cross	COPD & DM2	9	Lab	N.R.	60.9 ± 7.1 (Lab)	Treadmill	0.56 + 0.14 every 3 min
Van Laerhoven et al. [124]	2022	Germany	Cross	DM	28	FL	65.0	74.8 ± 9.8	Free-living 6–7 consecutive days	N.R.
Vetrovsky et al. [141]	2019	Australia	Cross	Heart failure	15	FL	60.0	65.5 ± 12.6	Free-living 3 days	N.R.
Wagner et al. [105]	2022	Denmark	Cross	RA	30	Lab	17.0	61 (50–74)	Treadmill	0.69 – 1.39, increments of 0.14
Webber & John [89]	2016	Canada	Cross	Geriatric rehabilitation ^k	38	Lab	10.5	83.2 ± 7.1	Hallway walk	0.4 ± 0.2

Table 1 (continued)

Author	Year	Country	Study design	Population	N	Study setting	% Male	Age (years)	Task	Walking speed (m/s)
Webster et al. [76]	2021	USA	Cross	COPD	59	FL	52.5	69.4±7.8	Free-living 7 days	N.R
Wendel et al. [103]	2018	USA	Cross	Parkinsons disease	33	Lab	58.0	65.5±9.4	Circuit	Comfortable and fast pace
Zbogar et al. [111]	2016	Canada	Cohort	SCI	35	Lab	70.0	48.9±18.3	1 day of rehab	0.75±0.39
Zhai et al. [87]	2020	Germany	Cross	MS	67	FL	37.3	42.9±10.9	Free-living 7 days	N.R
Yu et al. [136]	2022	Australia	Long	OA	65	FL	54.0	61.3±5.99	Free-living 7 days	N.R

^a Lower limb, below knee, unilateral

^b Post-coronary artery bypass graft surgery, aortic valve repair, mitral valve replacement

^c COPD, interstitial lung disease, cystic fibrosis

^d Ischemic heart disease, valvular heart disease

^e coronary infarction, hypertensive cardiomyopathy, valvular cardiopathy, type-a aortic dissection

^f COPD, congestive heart failure, other pulmonary diseases requiring pulmonary function test

^g Lower limb, below and above knee, unilateral and bilateral

^h Lower limb, below and above knee, unilateral

ⁱ Acute coronary syndrome, heart failure, coronary artery bypass grafting or valve surgery

^j Fractured hip, pelvis, lower limb orthopedic surgery, stroke, TIA, neurological event, decreased mobility post medical or non-orthopedic surgical event, post fall with no lower limb fracture, other

^k respiratory/infection, orthopedic, falls/decreased mobility, neurological, gastrointestinal, cancer, endocrine

Cross Cross sectional, Long Longitudinal, RCT Randomized controlled trial, CAD Coronary artery disease, COPD Chronic obstructive pulmonary disease, CVD Cardiovascular disease, DM1 Diabetes mellitus type 1, DM2 Diabetes mellitus type 2, DM Diabetes mellitus (further details unknown), SCI Incomplete spinal cord injury, MS Multiple sclerosis, PAD Pulmonary artery disease, SCJ Spinal cord injury, Both Both free-living and laboratory with protocolled activities, FL Free-living, Home Home situation with protocolled activities, Lab Laboratory setting with protocolled activities, MWT Minutes walking test, mWT Meter walking test, TUG Timed up and go-test, N.R. Not reported

Table 2 Overview of research grade devices evaluated on their measurement properties in the 52 studies

Type	PA outcome	Population	Study	Measurement property	Criterion	Placement	Algorithm	Result		
								Test	Outcome	
ActiGraph GT3	EE	Amputation	Ladlow [114]	CV	IC	Waist (SRL)	Cust	Pearson's r	r: 0.86—0.94	
			Ladlow [115]	CV	IC	Waist (SRL)	Cust	Pearson's r	r: 0.92 – 0.96	
		iSCI	Jayaraman [96]	CV	IC	Ankle	Prop (Freedson)	ANOVA	Sed; $p < .05$; low & high; $p > .05$	
	Stroke			Jayaraman [51]	CV	IC	U-arm	Prop (Freedson)	ANOVA	Sed & low; $p < .05$; high; $p > .05$
							Waist	Prop (Freedson)	ANOVA	Sed & low; $p < .05$; high; $p > .05$
							Ankle	Prop (Freedson)	Kruskal wallis	Lying, sitting & standing; $p < 0.5$
							U-arm	Prop (Freedson)	Kruskal wallis	Lying, sitting, standing & 50SWT; $p < .05$
							Waist	Prop (Freedson)	Kruskal wallis	All $p < .05$
							Ankle (ua)	N.R	Pearson's r	$r = 0.41$
							Waist	N.R	Pearson's r	$r = 0.15$
							Wrist (ua)	N.R	Pearson's r	$r = 0.12$
							Waist	Prop	Pearson's r	$r = 0.19$
							Ankle	Cust	Pearson's r	$r = 0.44$
				Compagnat [61]	CV	IC	Ankle	Cust (multiple)	LoA	-69.1 [-148.7; 10.5] -8.3 [-1.1; 17.8]
							Ankle (a)	Prop (work-energy theorem)	Pearson's r	$r = 0.04$
								Prop (Freedson)	Pearson's r	$r = 0.04$
								Prop (combined)	Pearson's r	$r = 0.37$
							Ankle (a)	Prop (Freedson)	Kruskal wallis	Lying, sitting, standing & STS; $p < 0.5$
							Ankle (ua)	Prop (Freedson)	Kruskal wallis	Lying, sitting, standing & STS; $p < 0.5$
							U-arm (a)	Prop (Freedson)	Kruskal wallis	Lying, sitting & standing; $p < 0.5$
			Jayaraman [51]	CV	IC	U-arm (ua)	Prop (Freedson)	Kruskal wallis	Lying, sitting & standing; $p < 0.5$	
						Waist (a)	Prop (Freedson)	Kruskal wallis	Lying, sitting & standing; $p < 0.5$	
						Waist (ua)	Prop (Freedson)	Kruskal wallis	Lying, sitting & standing; $p < 0.5$	

Table 2 (continued)

Type	PA outcome	Population	Study	Measurement property	Criterion	Placement	Algorithm	Result	
								Test	Outcome
Steps		Inflammatory myopathy	Mandigout [55]	CV	IC	Ankle (ua)	N.R	Spearman's rho	rho = 0.19
						Ankle (a)	N.R	Spearman's rho	rho = 0.21
						Waist	N.R	Spearman's rho	rho = 0.04
						Wrist (ua)	N.R	Spearman's rho	rho = 0.20
						Wrist (a)	N.R	Spearman's rho	rho = 0.08
						Waist	Prop	Accuracy (%)	43.0—81.4%
						Waist	Prop	Pearson's r	r: -0.42—0.66
						Waist	Prop	ICC	ICC = 0.92 (CI 0.86 – 0.96)
						Waist	Prop	Pearson's r	r = 0.47 (CI 0.12—0.71)
						Ankle (la)	Prop	ICC	ICC: 0.15 – 0.99
MS		iSCI	Albaum [108] Jayaraman [96]	CV	DO	Ankle	Prop (Freedson)	ANOVA	p > .05
						U-arm	Prop (Freedson)	ANOVA	p < .05
						Waist	Prop (Freedson)	ANOVA	p < .05
						Waist	Prop	ICC	ICC = 0.76 (CI 0.63–0.85)
						Waist	Prop	CCC	CCC = 0.68 (CI 0.37—0.82)
						Waist	Prop (+ LFE filter)	CCC	CCC = 0.73 (0.13—0.84)
						Waist	Prop	ICC	ICC = 0.123 (CI -0.071–0.355)
						Ankle	Prop	ICC	ICC = 0.682 (CI -0.211–0.895)
						Waist	Prop (+ LFE filter)	ICC	ICC = 0.938 (CI 0.870–0.969)
						Waist	Prop	ICC	ICC = -0.051 (CI -0.191–0.153)
PD	Osteoarthritis	Collins [94] Cederberg [104]	CV	DO	Acc	Wrist	Prop (+ LFE filter)	ICC	ICC = 0.829 (CI 0.329–0.936)
						Wrist (ua)	Prop	ICC	ICC = 0.602
						Wrist (a)	Prop	Mean difference	62—76 steps
						Wrist (a)	Prop	Mean difference	32—66 steps

Table 2 (continued)

Type	PA outcome	Population	Study	Measurement property	Criterion	Placement	Algorithm	Result	
								Test	Outcome
		Polymyalgia rheumatica	Chandrasekar [112]	CV	DO	Waist	Prop	LoA	Walking: 141 + (0.5*mean count) [110 + (0.5*mean count)]
							Prop (+LFE filter)	LoA	Walking: 20 [-40; 81]
							Prop	LoA	Stairs: 4 [-4; 12]
		RA	O'Brien [116]	CV	DO	Thigh	Prop (+LFE filter)	LoA	Stairs: 0 [-5; 5]
		Stroke	Campos [40]	CV	Acc	Ankle	Prop	LoA	-30 [-116; 57]
							Prop	ICC	ICC = 0.80 (CI 0.63–0.90)
							Prop (+LFE filter)	ICC	ICC = 0.76 (CI 0.56–0.87)
						Waist	Prop	ICC	ICC = 0.70 (CI 0.47–0.84)
							Prop (+LFE filter)	ICC	ICC = 0.82 (CI 0.66–0.90)
			Henderson [64]	CV	DO	Ankle (a)	Prop	ICC	ICC: 0.57–0.81
							Prop (+LFE filter)	ICC	ICC: 0.84–0.96
						Ankle (ua)	Prop	ICC	ICC: 0.84–0.86
							Prop (+LFE filter)	ICC	ICC: 0.77–0.97
	Intensity time	Osteoarthritis	Collins [94]	CV	Acc	Wrist	Cut off: counts < 200	% bias	Sedi: 66%
							Cut off: 1924 counts/min, bouts of 10 min	Difference	MVPA: + 281 min
	Activity time	DM	Jao [95]	CV	DO	Waist	Prop	Accuracy (%)	41.8 – 100%
		RA	O'Brien [116]	CV	DO	Thigh	Prop	LoA	-0.3 [-1.2; 0.6] min—0.2 [-0.7; 1.1] min
	Distance walked	Stroke	Compagnat [44]	CV	DO	Ankle (ua)	Prop	Pearson's r	r = 0.95
						Ankle (a)	Prop	Pearson's r	r = 0.93
						Waist	Prop	Pearson's r	r = 0.86
						Wrist (ua)	Prop	Pearson's r	r = 0.79
		Peripheral artery disease	Taoum [139]	CV	GPS	Wrist (a)	Prop	Pearson's r	r = 0.81
						Hip	Cust	MAPE	11.9—18.8

Table 2 (continued)

Type	PA outcome	Population	Study	Measurement property	Criterion	Placement	Algorithm	Result	
								Test	Outcome
GTX9	Counts	Amputation	Ladlow [114]	CV	IC	Waist (SRL)	Prop	Pearson's r	r: 0.82–0.92
						Waist (LRL)	Prop	Pearson's r	r: 0.76 – 0.80
	MET	Stroke	Jayaraman [51]	CV	IC	Waist (Sp)	Prop	Pearson's r	r: 0.68 – 0.80
						Ankle (a)	Prop (Freedson)	Kruskal wallis	STS: $p < .05$
						Ankle (ua)	Prop (Freedson)	Kruskal wallis	50SWT, 6MWT & STS: $p < .05$
						U-arm (a)	Prop (Freedson)	Kruskal wallis	All $p > .05$
						U-arm (ua)	Prop (Freedson)	Kruskal wallis	All $p > 0.5$
						Waist (a)	Prop (Freedson)	Kruskal wallis	All $p > .05$
	Vector magnitude	iSCI	Jayaraman [51]	CV	IC	Waist (ua)	Prop (Freedson)	Kruskal wallis	All $p > .05$
						Ankle	Prop (Freedson)	Kruskal wallis	Lying & STS $p < .05$
GTX9	Steps	Inflammatory myopathy	Rockette-Wagner [105]	Con V	F Tests & F SR	U-arm	Prop (Freedson)	Kruskal wallis	50SWT $p < .05$
						Waist	Prop (Freedson)	Kruskal wallis	50SWT, 6MWT & STS $p < .05$
	Steps	Amputation	Smith & Guerra [107]	CV	DO	Waist	Prop	Pearson's r	r: -0.35—0.60
						Waist	Prop	ICC	ICC=0.80 (CI 0.62 – 0.89)
						Waist	Prop	Pearson's r	$r = 0.53$ (CI 0.20—0.75)
						Ankle	N.R	ICC	ICC=0.111 (CI -0.202—0.418)
						Wrist	N.R	ICC	ICC=0.005 (CI -0.256—0.299)
						Waist	Prop	Spearman's rho	rho: 0.74—0.79
						Waist	Prop (+ LFE filter)	Spearman's rho	rho: 0.85—0.93
						Waist	Prop	% error	-3.1 ± 10.3%
Pal Technologies	Steps	Multi	CV	DO	Waist	Prop (multiple)	CCC	CCC: 0.614–0.838	
					Waist	Prop	Spearman's rho	rho: 0.18—0.39	
					Waist	Prop (+ LFE filter)	Spearman's rho	rho: 0.16—0.38	
					Thigh	Prop	ICC	ICC=0.91	
					Thigh	Prop	Accuracy (%)	90.7 – 98.5%	
					Thigh	Prop	ICC	ICC=0.781 [CI 0.231; 0.911]	

Table 2 (continued)

Type	PA outcome	Population	Study	Measurement property	Criterion	Placement	Algorithm	Result	
								Test	Outcome
	Activity time	RA	Larkin [131]	CV	DO	Thigh	Prop	Pearson's r	r = 0.94 [CI 0.86; 0.98]
		Stroke	Mahendran [54]	CV	DO	Thigh	Prop	ICC	ICC: 0.72 – 0.99
	Amputation	DM	Salih [138]	TRT R		Thigh	Prop	ICC	ICC: 0.66 – 0.98
				CV	DO	Thigh (a)	N.R	LoA	Walking: 0.11 [-0.43; 0.66] sec (ue)
	MET	Stroke	Alothman [91]	TRT R		Thigh (ua)	N.R	LoA	Walking: 0.004 [-0.09; 0.10] sec (ue)
				CV	DO	Thigh	Prop	ICC	ICC: 0.74 – 0.90
	Steps	MS	Larkin [131]	CV	DO	Thigh	Prop	Accuracy (%)	96.6 – 100%
				CV	DO	Thigh	Prop	Pearson's r	r: 0.74 – 0.93
	Activity time	Stroke	Mahendran [54]	CV	DO	Thigh	Prop	ICC	ICC = 0.99
				TRT R		Thigh	Prop	APE	0.3 – 3.2%
ActivPAL3	Stroke	Mahendran [54]	TRT R		Thigh	Prop	ICC	ICC: 0.66 – 0.98	
			CV	DO	Thigh	Prop	APE	3.3 – 6.5%	
StepWatch 3	Amputation	Multiple	TRT R		Thigh	Prop	ICC	ICC: 0.65 – 0.99	
			CV	DO	Thigh	Prop	LoA	-4.7 [-22.88; 13.47] (ue)	
Modus Health	Steps	Multiple	CV	DO	Thigh	Prop	LoA	-30 [-116; 57] (ue)	
			CV	DO	Thigh	Prop	LoA	-4.6 [-26.1; 17.0] – 1.1 [-1.12; 3.34] sec	
StepWatch 4	Amputation	Peripheral artery disease	CV	DO	Thigh	Prop	LoA	-0.3 [-1.2; 0.6] – 0.2 [-0.7; 1.1] min	
			CV	DO	Ankle (a)	N.R	ICC	ICC: 0.90 – 0.99	
Distance walked	Amputation	Peripheral artery disease	CV	DO	Ankle	Prop	ICC	ICC = 0.982 [CI 0.975; 0.986]	
			CV	DO	Ankle	Prop	ICC	ICC = 0.960 [CI 0.924; 0.979]	
Steps	Amputation	Peripheral artery disease	CV	DO	Ankle (la)	Prop	Spearman's rho	rho: 0.963 – 0.994	
			CV	DO	Ankle (a)	Prop	ICC	ICC: 0.92 – 0.96	
Steps	Amputation	Peripheral artery disease	CV	GPS	Ankle (ua)	Prop	ICC	ICC: 0.97 – 0.97	
			CV	DO	Ankle	Cust	MAPE	16.7 ± 10.7	
Steps	Amputation	Peripheral artery disease	CV	DO	Ankle	N.R	ICC	ICC = 0.967 (CI 0.929 – 0.984)	
			CV	DO	Ankle	N.R	ICC	ICC = 0.967 (CI 0.929 – 0.984)	

Table 2 (continued)

Type	PA outcome	Population	Study	Measurement property	Criterion	Placement	Algorithm	Result	
								Test	Outcome
Body Media Sensewear armband	EE	Chronic lung disease	Dhillon [70]	CV	IC	U-arm	Prop	LoA	-1.26 [-4.71; 2.19] – 0.56 [-1.68–2.80]
		MS	Stuart [82]	Con V	F Tests & F SR	Arm	Prop	Spearman's rho	rho: -0.412—0.365
		Stroke	Compagnat [42]	Resp	F Tests & F SR	Arm	Prop	Spearman's rho	rho: -0.196—0.168
			Mandigout [55]	CV	IC	U-arm (ua)	Prop	Pearson's r	r: 0.48 – 0.81
						U-arm (a)	N/R	Spearman's rho	rho=0.61
						U-arm (ua)	N/R	Spearman's rho	rho=0.45
	Steps	MS	Stuart [82]	Con V	F Tests & F SR	Arm	Prop	Spearman's rho	rho: -0.325—0.305
				Resp	F Tests & F SR	Arm	Prop	Spearman's rho	rho: -0.170—0.250
	Activity time	MS	Stuart [82]	Con V	F Tests & F SR	Arm	Prop	Spearman's rho	rho: -0.640—0.493
				Resp	F Tests & F SR	Arm	Prop	Spearman's rho	rho: -0.128—0.272
	Distance walked	Stroke	Compagnat [44]	CV	DO	U-arm (a)	Prop	Pearson's r	r=0.72
	MET	MS	Stuart [82]	Con V	F Tests & F SR	U-arm (ua)	Prop	Pearson's r	r=0.68
PA composite score	MS	Stuart [82]	Resp	F Tests & F SR	Arm	Prop	Spearman's rho	rho: -0.343—0.316	
			Con V	F Tests & F SR	Arm	Prop	Spearman's rho	rho: -0.191—0.295	
				F Tests & F SR	Arm	Prop	Spearman's rho	rho: -0.444—0.376	
Sensewear Pro2	Steps	Stroke	Mahendran [54]	Resp	F Tests & F SR	Arm	Prop	Spearman's rho	rho: -0.110—0.356
				CV	DO	U-arm (a)	N/R	APE	21.9 – 66.8%
	MET	Stroke	Mahendran [54]	TRT R		U-arm (a)	N/R	APE	2.2 – 38.5%
						U-arm (a)	N/R	APE	17.8 – 26.8%
	Activity time	CP	Claridge [120]	CV	DO	Thigh (frontal) (la)	N/R	Spearman's rho	rho: -0.04 – 0.86
						Thigh (lateral 2 cm) (la)	N/R	Spearman's rho	rho: 0.49 – 0.99
Activ8		Stroke	Fanchamps [48]	CV	DO	Pocket	N/R	Spearman's rho	rho: 0.14 – 0.79
						Thigh (frontal)	N/R	% time difference	-3.8 – 6.5%
	Steps	Multi	Urmels [75]	CV	DO	Pocket	N/R	Pearson's r	r=0.24

Table 2 (continued)

Type	PA outcome	Population	Study	Measurement property	Criterion	Placement	Algorithm	Result	
								Test	Outcome
Philips									
Actual	EE	Chronic lung disease	Dhillon [70]	CV	IC	Wrist	Prop	LoA	-3.4 [-6.4;-0.4]—0.8 [-1.6; 0.0]
		Stroke	Mandigout [55]	CV	IC	Ankle (a)	N.R	Spearman's rho	rho = 0.30
						Ankle (ua)	N.R	Spearman's rho	rho = 0.20
						Waist	N.R	Spearman's rho	rho = -0.01
						Wrist (a)	N.R	Spearman's rho	rho = -0.19
						Wrist (ua)	N.R	Spearman's rho	rho = -0.27
	Activity kilo-counts	SCI	Zbogar [111]	TRT R		Wrist	N.R	Pearson's r	r = -0.74 [CI 0.54; 0.86]
	Steps	SCI	Zbogar [111]	TRT R		Waist	N.R	Pearson's r	r = -0.84 [CI 0.70; 0.92]
Activity									
AX3/AX6	Steps	Cardiac rehab	Femiano [126]	CV	DO	Wrist	Cust	MAPE	4.1—143.0%
		Lumbar spinal stenosis	Gustafsson [128]	CV	DO	Lower back	Prop	ICC	ICC: -0.04—1.00
						Thigh	Prop	ICC	ICC: -0.16—1.00
						Waist	Prop	ICC	ICC: -0.10—1.00
						Wrist	Prop	ICC	ICC: -0.10—0.99
McRoberts									
Dynaport	EE	Stroke	Daniel [62]	CV	IC	Lower back	Prop	ICC	ICC: 0.77—0.94
Dynaport Hybrid	Steps	PD	Pham [123]	CV	DO	Lower back	Cust	Kappa	k: 0.70—0.71

Table 2 (continued)

Type	PA outcome	Population	Study	Measurement property	Criterion	Placement	Algorithm	Result	
								Test	Outcome
Vandrico Inc									
Metrica-IH1	EE	iSCI	Jayaraman [96]	CV	IC	U-arm	Prop	ANOVA	All $p > .05$
		Stroke	Jayaraman [51]	CV	IC	U-arm	Prop	Kruskal wallis	All $p > .05$
			Jayaraman [51]	CV	IC	U-arm (a)	Prop	Kruskal wallis	All $p > .05$
						U-arm (ua)	Prop	Kruskal wallis	STS; $p < .05$
	Steps	iSCI	Jayaraman [96]	CV	DO	U-arm	Prop	ANOVA	$p < 0.05$
	MET	iSCI	Jayaraman [51]	CV	IC	U-arm	Prop	Kruskal wallis	All $p > .05$
		Stroke	Jayaraman [51]	CV	IC	U-arm (a)	Prop	Kruskal wallis	50SWT & STS; $p < .05$
						U-arm (ua)	Prop	Kruskal wallis	STS; $p < .05$
Activinsight									
GENEactive	Raw acceleration (ENMO—mg)	Myotonic dystrophy type 1	Jimenez-Moreno et al. [113]	TRT R		Wrist & Ankle	N.A	ICC	0.86 [95%CI 0.74; 0.93] to 0.97 [95% CI 0.95; 0.99]
CamNtech									
Actiheart	EE	Amputation	Ladlow [115]	CV	IC	Chest	Branched-Model equation	Pearson's r	$r 0.81 - 0.86$
Espruino									
Banglejs	Steps	DM	Van Laerhoven [124]	CV	Acc	Wrist	Custom (open source)	LoA	-566.7 [-4111.5—2978.0]—17.48 [-211.5—246.5]
Garcia Oliveira et al									
AMoR	Steps	Stroke	Garcia Oliveira [63]	CV	DO	Thigh	NR	ICC	ICC: 0.999—0.999
		Stroke	Garcia Oliveira [63]	CV	Acc	Thigh	NR	ICC	ICC: 0.981—0.985
	Sedentary time	Stroke	Garcia Oliveira [63]	CV	DO	Thigh	NR	ICC	ICC=0.960 (CI 0.929—0.977)

Table 2 (continued)

Type	PA outcome	Population	Study	Measurement property	Criterion	Placement	Algorithm	Test	Result	Outcome
Maastricht Instruments BV										
MOX (1.01)	Counts	Multi	Van der Weegen [77]	CV	Acc	Lower back		Pearson's r	$r = 0.98$ (range 0.95—1.00)	
	Intensity time	Multi	Van der Weegen [77]	CV	Acc	Lower back		Spearman's rho	$\rho = 0.82$ (range 0.60—0.94)	
	Activity time	Heart failure	Shoemaker [100]	CV	Acc	Chest (internal)	Prop	LoA	-0.77 [-2.71; 1.17] hours/day (ue)	
Medtronic										
ICD/CRT device	Activity time	Heart failure	Shoemaker [100]	CV	Acc	Chest (internal)	Prop	LoA	0.19 [-0.79; 1.17] hours/day (oe)	
StepsCounts										
PiezoRX	Steps	MS	Anens [79]	CV	DO	N.R	N.R	Spearman's rho	$\rho = 0.82$ —0.99	
Xsens										
MTw	EE	DM	Caron [119]	CV	IC	Lower back	Bouten's equation	LoA	-1.17 [-6.45; 4.14]W/kg (oe)	
ZurichMOVE										
JUMP	EE	iSCI	Popp [125]	CV	IC	Multiple	Cust	Pearson's r	$r = 0.92$	

Ordering on number of studies evaluating manufacturer. This is a condensed version of the more detailed table in Supplementary file 5

EE Energy expenditure, MET Metabolic equivalent, PAL Physical activity level, CAD Coronary artery disease, COPD Chronic obstructive pulmonary disease, DM Diabetes mellitus, iSCI incomplete spinal cord injury, MS Multiple sclerosis, PAD Pulmonary artery disease, PD Parkinson's disease, RA Rheumatoid arthritis, SCI Spinal cord injury, CV Criterion validity, Con V Construct validity, Resp Responsiveness, TRT R Test-retest reliability, Acc Accelerometer, DLW Doubly labelled water, DO Direct observation, F Tests Functional tests, F SR Functional Self-report, IC Indirect calorimetry, SR Self-report, Q questionnaire, (a) Affected side, (b) both affected and unaffected side, (lo) Less affected side, (LRL) Longest residual limb, (SRL) shortest residual limb, (ue) unaffected side, Cust Custom algorithm, LFE Low frequency effect, N.R. Not reported, Prop Proprietary algorithm, TEE Total energy expenditure, APE Absolute percentage error, CCC Concordance correlation coefficients, ICC Intraclass correlation coefficient, LoA = limits of agreement, MAPE = mean absolute percentage error, IMPE Mean percentage error, [CI] 95% confidence intervals, (oe) Over estimation, (ue) Under estimation, MVPA Moderate to vigorous physical activity, MWT Minutes walking test, Sed Sedentary, STS Sit-to-stand test, SWT Steps walk test

Table 3 Overview of consumer grade devices evaluated on their measurement properties in the 67 studies

Type	PA outcome	Population	Study	Measurement property	Criterion	Placement	Algorithm	Result Test	Outcome
Fitbit									
Alta	Steps	Cancer	Rossi [98]	Con V	SR	N.R	N.R	CCC	CCC = 0.00005 [CI -0.22—0.22]
		COPD	Blondeel [67]	CV	Acc	Wrist	Prop	LoA	306 [-2068; 2680] (oe)
		MS	Lavelle [80]	CV	DO	Wrist	N.R	LoA	-302.8 [-1036.8; 431.1] (oe)
		Stroke	Holubova [65]	CV	DO	Upper limb (b)	Prop	MARD	3.05—85.67%
	Lower limb (b)					Prop	MARD	1.33—11.08%	
Waist	Prop	MARD	0.47—3.66%						
Activity time	MS	Lavelle [80]	CV	Acc	Wrist	N.R	% error	100% [range -38.7—100]	
Charge	Steps	Amputation	Smith [101]	CV	DO	Wrist	N.R	ICC	ICC = 0.86
		Multi	Treacy [23]	CV	DO	Wrist	N.R	ICC	ICC = 0.399 [CI -0.026- 0.654]
Charge 2	EE	PDs	Lamont [137]	CV	Acc	Wrist	N.R	ICC	ICC: 0.18 – 0.94
		CAD	Herkert [122]	CV	IC	Wrist	Prop	ICC	ICC = 0.10
		Heart failure	Herkert [122]	CV	IC	Wrist	Prop	ICC	ICC = 0.42
	Steps	Heart failure	Vetrovsky [141]	CV	Acc	Wrist	N.R	CCC	CCC = 0.48 [CI 0.20—0.69]
		Osteoarthritis	Collins [94]	CV	Acc	Wrist	Prop	ICC	ICC = 0.602
		PD	Lai [97]	CV	DO	Wrist	N.R	ICC	ICC: 0.27 – 0.47
Progressive muscle diseases	Roberts-Lewis et al. [118]	CV	DO	Wrist	N.R	Spearman's rho	rho = 0.97 [CI 0.96—0.98]		
Flex	Intensity time	Osteoarthritis	Collins [94]	CV	Acc	Wrist	Cust	% bias	-5 – 37%
	Steps	Amputation	Smith [101]	CV	DO	Wrist	N.R	ICC	ICC = 0.843
		CAD	Alharbi [140]	CV	Acc	N.R	Prop	Pearson's r	r = 0.947
		Post heart operation	Daligadu [109]	CV	DO	Wrist	N.R	CCC	CCC = 0.43
	MS	Balto [83]	CV	DO	Wrist	N.R	MPE	12.4 – 13.8%	
					Wrist	N.R	ICC	2MWT DO: ICC = 0.69 2MWT ACC: ICC = 0.59	
		Block [85]	CV	ACC	Wrist	N.R	ICC	ICC = 0.74	
					Wrist	N.R	ICC	ICC = 0.69 [CI 0.53—0.80]	
	Intensity time	Multi	Ummels [75]	CV	DO	Wrist	N.R	Pearson's r	r = 0.31
						Wrist	Prop	Spearman's rho	rho: 0.25 – 0.73
Wrist						Prop	Pearson's r	r: 0.04 – 0.72	
Chronic knee symptoms		Semanik [99]	CV	Acc	N.R	Prop	ICC	ICC: -0.236—0.884	
					Wrist	Prop	ICC	ICC = 0.98 [CI 0.97—0.99]	
					Wrist	Prop	ICC	ICC = 0.98 [CI 0.97—0.99]	
Stroke	Hei Chow [60]	CV	Acc	Wrist	Prop	ICC	ICC = 0.98 [CI 0.97—0.99]		
				Wrist	Prop	ICC	ICC = 0.98 [CI 0.97—0.99]		
Flex 2	Distance walked	Post heart operation	Daligadu [109]	CV	DO	Wrist	N.R	CCC	CCC = 0.37
	Steps	MS	Block [84]	CV	Acc	Wrist	N.R	ICC	ICC = 0.98 [CI 0.97—0.99]
		Osteoarthritis	Yu [136]	CV	SR	Wrist	N.R	Correlation	0.20—0.28
Inc	Steps	PD	de Carvalho Lana [133]	CV	DO	Waist	N.R	Pearson's r	r = 0.82
				Resp	SR & tests	Wrist	N.R	Correlation	-0.28—0.28

Table 3 (continued)

Type	PA outcome	Population	Study	Measurement property	Criterion	Placement	Algorithm	Result Test	Outcome
Inspire HR	Steps	MS	Polhemus [81]	CV	DO	Wrist	N.R	CCC	CCC=0.66 (CI 0.14–0.80)
				CV	Acc	Wrist	N.R	CCC	CCC: 0.33–0.65
		Progressive muscle diseases	Roberts-Lewis [118]	CV	Acc	Wrist	N.R	Spearman's rho	rho=0.76 (CI 0.60–0.87)
				TRT R	Acc	Wrist	N.R	ICC	ICC=0.96 (CI 0.92–0.98)
	Activity time	MS	Polhemus [81]	CV	Acc	Wrist	N.R	AUC	AUC=0.86 (CI 0.75–0.97)
				Resp	Acc	Wrist	N.R	CCC	CCC: 0.18–0.52
	Intensity time	MS	Polhemus [81]	CV	Acc	Wrist	N.R	CCC	CCC: 0.41–0.80
				CV	Acc	Wrist	N.R	Spearman's rho	rho=0.51 (CI 0.29–0.69)
		Progressive muscle diseases	Roberts-Lewis et al. [118]	TRT R		Wrist	N.R	ICC	ICC=0.78 (CI 0.63–0.87)
				Resp	Acc	Wrist	N.R	AUC	AUC=0.72 (CI 0.56–0.88)
	MET	Progressive muscle diseases	Roberts-Lewis et al. [118]	CV	Acc	Wrist	N.R	Spearman's rho	rho=0.63 (CI 0.47–0.74)
				TRT R		Wrist	N.R	ICC	ICC=0.94 (CI 0.89–0.97)
Resp				Acc	Wrist	N.R	AUC	AUC=0.90 (CI 0.81–0.98)	
One	Steps	Amputation	Arch [92]	CV	DO	Ankle (a)	N.R	ICC	ICC: 0.88 – 0.97
		Cancer	Van Blarigan [102]	CV	Acc	Waist	N.R	Pearson's r	r=0.94
				CV	Acc	Waist	N.R	Pearson's r	r=0.67
		MS	Balto [83]	CV	DO	Waist	N.R	MPE	1.9%–1.9%
		Multi	Unmeis (2018)	CV	DO	Waist	N.R	Pearson's r	r=-0.15
				CV	DO	Ankle	N.R	ICC	ICC=0.919 [CI 0.772–0.961]
		Myositis	Saygin [106]	CV	Acc	Waist	Prop	ICC	ICC=0.397 [CI -0.087–0.689]
				TRT R		Waist	Prop	ICC	ICC=0.96 (CI 0.92–0.98)
				Resp	SR	Waist	Prop	Spearman's rho	rho=0.63
		PDs	Lai [97]	CV	DO	Waist	N.R	ICC	ICC: 0.98 – 0.98
		Stroke	Duclos [47]	CV	DO	Ankle	Prop	% error	0.50 – 2.67%
				CV	DO	Ankle (a)	Prop	ICC	ICC: 0.71–0.92
Henderson [64]			Ankle (ua)	Prop	ICC	ICC: 0.78–0.92			
Hui [50]	CV	Acc	Ankle (ua)	Prop	Regression r	r: 0.97 – 0.99			

Table 3 (continued)

Type	PA outcome	Population	Study	Measurement property	Criterion	Placement	Algorithm	Result Test	Outcome								
Surge Ultra Zip	Intensity time	Cancer	Klassen [52]	CV	DO	Ankle (ua)	Prop	MPE	4.0 – 15.8%								
						Waist	Prop	MPE	7.7 – 84.6%								
						Ankle (ua)	Prop	LoA	156.1 [-239.6; 551.9] (u)								
	Steps	Myositis	Van Blarigan [102]	CV	Acc	Waist	Prop	Prop	Pearson's r	r: 0.65 – 0.85							
									Steps	Stroke	Hui [50]	CV	Acc	Waist	Prop	ICC	ICC: 0.59–0.96
																PD	Wendel [103]
	Steps	Stroke	Costa [46]	CV	DO	Wrist (b)	N.R	Prop	ICC	ICC: -0.003 – 0.41							
									Steps	COPD	Blondeel [67]	CV	Acc	Waist	Prop	Prop	Pearson's r
	Steps	MS	Lavelle [80]	CV	DO	Waist	N.R	Prop									LoA
									Steps	Cardiac diseases	Thorup [127]	CV	Acc	Waist	Prop	Prop	LoA
	Steps	Multi	Farmer [90]	CV	DO	Foot	Prop	Prop									ICC
									Steps	PD	Wendel [103]	CV	DO	Waist	Prop	Prop	ICC
	Steps	Polymyalgia rheumatica	Chandrasekar [112]	CV	DO	Waist	N.R	Prop									LoA
									Steps	Stroke	Clay [41]	CV	DO	Waist	N.R	Prop	LoA
	Steps	Stroke	Schaffer [58]	TRT R	DO	Waist	N.R	Prop									Kendall Tau-b
Steps									Stroke	Schaffer [58]	TRT R	DO	Waist	N.R	Prop	MAPE	-88.2 – 4.2%
	Steps	Stroke	Schaffer [58]	TRT R	DO	Waist	N.R	Prop								ICC	ICC = 0.974
Steps									Stroke	Huber [66]	CV	Acc	Wrist (ua)	N.R	Prop	LoA	-1.6 [-86.9; 83.5]—5.0 [-63.7; 2689.5]
	Steps	Stroke	Huber [66]	CV	Acc	Wrist (ua)	N.R	Prop								ICC	ICC: 0.989—0.996
Steps									Amputation	Smith [101]	CV	DO	Wrist (b)	N.R	Prop	ICC	ICC = 0.86
	Steps	Heart failure	Vetrovsky [141]	CV	Acc	Wrist	N.R	Prop								CCC	CCC = 0.89 [CI 0.75; 0.96]
Steps									Multi	Treacy [23]	CV	DO	Wrist	N.R	Prop	ICC	ICC = 0.259 [CI -0.071; 0.556]
	Steps	PD	Lamont [137]	CV	Acc	Wrist	N.R	Prop								ICC	ICC: 0.36 – 0.97
Steps									Stroke	Schaffer [58]	CV	Acc	Wrist (ua)	N.R	Prop	MAPE	-90.1 – -16.0%
	Steps	Stroke	Schaffer [58]	CV	Acc	Wrist (a)	N.R	Prop								MAPE	-68.2 – -4.0%
Steps									Stroke	Schaffer [58]	TRT R	DO	Wrist (ua)	N.R	Prop	ICC	ICC = 0.964 [CI 0.916; 0.984]
	Steps	Stroke	Schaffer [58]	TRT R	DO	Wrist (a)	N.R	Prop								ICC	ICC = 0.858 [CI 0.672; 0.939]
Steps									Amputation	Smith & Guerra [107]	CV	DO	Ankle	N.R	Prop	ICC	ICC = 0.122 [CI -0.141—0.398]
	Steps	Amputation	Smith & Guerra [107]	CV	DO	Ankle	N.R	Prop								ICC	ICC = 0.895 (CI 0.802—0.945)
Steps									Heart failure	Vetrovsky [141]	CV	Acc	Wrist	N.R	Prop	CCC	CCC = 0.92 [CI 0.78; 0.97]

Table 3 (continued)

Type	PA outcome	Population	Study	Measurement property	Criterion	Placement	Algorithm	Result Test	Outcome
Vivifit 4	Steps	MS	Lavelle [80]	CV	DO	Wrist	N.R	LoA	-251.05 [-717.4; 253.6] (oe)
	Activity time	MS	Lavelle [80]	CV	DO	Wrist	N.R	% error	100% [range 100–100]
Vivosmart 3	Steps	PD	Lai [97]	CV	DO	Wrist (la)	N.R	ICC	ICC: 0.67 – 0.97
Vivosmart 4	Steps	PD	Bianchini [130]	CV	DO	Wrist (b)	Prop	ICC	ICC = 0.66 (CI 0.31–0.83)
Omron									
Active Style Pro HJA-350	MET	Stroke	Shimizu [59]	CV	MET com	Waist	Prop	T-test (1-sample)	$P < .05$
Active Style Pro HJA-750c	EE	DM	Nishida [134]	CV	DLW	Waist	TEE = BMR (Ganpule's equation) * PAL	Pearson's r	TEE: $r = 0.87$
	PAL	DM	Nishida [134]	CV	DLW	Waist	PAL = ((BMR (Ganpule's equation) + AEE (prop)) * 10/9) * BMR	Pearson's r	$r = 0.71$
	Intensity time	COPD	Miyamoto [73]		Acc	Waist	Cust	Pearson's r	$r: 0.38 - 0.81$
					Acc	Waist	Cust	Pearson's r	$r: -0.05 - 0.83$
HJ-113	Steps	Amputation	Smith [101]	CV	DO	Waist	N.R	ICC	ICC = 0.928
HJ-322U-E	Steps	Heart failure	Vetrovsky [141]	CV	Acc	Waist	N.R	CCC	CCC = 0.82 [CI 0.56; 0.93]
HJ-720ITC	Steps	COPD	Danilack [69]	CV	DO	Waist	N.R	LoA	34 [-186; 253]
Walking Style x	Steps	Multi	Ummels [75]	CV	DO	Waist	N.R	Pearson's r	$r = 0.25$
Yamax									
Digiwalker CW-700	Steps	Bronchiectasis	O'Neill [117]	CV	Acc	Waist	N.R	LoA	-167 [-3078; 2745] (oe)
		Multi	Ummels [75]	CV	DO	Wrist	N.R	Pearson's r	$r = -0.33$
	Activity time	Bronchiectasis	O'Neill [117]	CV	Acc	Waist	N.R	LoA	Daily activity time: 165 [62; 269] min
Digiwalker SW-200	Steps	MS	Anens [79]	CV	DO	N.R	N.R	Spearman's rho	$\rho: 0.64 - 0.97$
			Balto [83]	CV	DO	Waist	N.R	MPE	8.5 – 9.7%
			Lavelle [80]	CV	DO	Waist	N.R	LoA	119.4 [-498.0; 736.8] (ue)
	EE	COPD	Farooqi [71]	CV	DLW	Waist	Harris-Benedict	ICC	ICC = 0.70 [CI 0.23; 0.89]
							Schofield	ICC	ICC = 0.71 [CI 0.21; 0.89]
							WHO	ICC	ICC = 0.74 [CI 0.33; 0.90]
							Moore	ICC	ICC = 0.69 [CI 0.21; 0.88]
						Nordic Nutrition Recommendation	ICC	ICC = 0.70 [CI 0.17; 0.89]	
						Nordenson	ICC	ICC = 0.40 [CI -0.16; 0.77]	
PAL	COPD	Farooqi [71]	CV	DLW + IC	Waist	Cust	ICC	ICC = 0.34	

Table 3 (continued)

Type	PA outcome	Population	Study	Measurement property	Criterion	Placement	Algorithm	Result Test	Outcome
Google									
Fit	Steps	PD	de Carvalho Lana [133]	CV	DO	Waist	N.R	Pearson's r	$r=0.92$
		Stroke	Costa [46]	CV	DO	Waist	N.R	Pearson's r	$r=0.66$
			Polese [57]	TRT R CV	DO	Waist	N.R	ICC	ICC = 0.76
	EE	Stroke	Faria [49]	CV	IC	Front pocket (a)	N.R	ICC	ICC = 0.93 [CI 0.86; 0.96]
Android stepcounter	Steps	RA	Wagner [129]	CV	DO	Front pocket (a)	N.R	Pearson's r	$r=0.30$
	Steps	RA	Wagner [129]	CV	DO	Waist	Prop	MAPE	1.0—19.3%
Apple									
Watch Sport Health	EE	Multi	Falter [88]	CV	IC	Wrist	Prop	ICC	ICC = 0.797
	Steps	MS	Balto [83]	CV	DO	Front pocket	N.R	MPE	2.7 – 2.9%
Iphone CMPedometer	Steps	PAD	Ata [93]	CV	DO	Hand/front pocket	N.R	% error	$-7.2 \pm 13.8\%$
Iphone SE	Steps	Cancer	Douma [121]	CV	Acc	Waist	N.R	ICC	ICC = 0.97 [CI 0.95; 0.98]
	Distance walked	Cancer	Douma [121]	CV	Acc	Waist	N.R	ICC	ICC = 0.47 [CI 0.21; 0.67]
Geonaute									
Onstep 400	EE	Stroke	Compagnat [43]	CV	IC	Waist	Prop	Pearson's r	TEE: $r=0.66$
			Mandigout [55]	CV	IC	Neck	N.R	Pearson's r	TEE: $r=0.87$
				CV	IC	Waist	N.R	Spearman's rho	$\rho=-0.16$
	Distance walked	Stroke	Compagnat [44]	CV	DO	Neck	Prop	Spearman's rho	$\rho=-0.07$
					DO	Waist	Prop	Pearson's r	$r=0.91$
					DO	Waist	Prop	Pearson's r	$r=0.98$
JawBone									
Up2	Steps	MS	Balto [83]	CV	DO	Wrist	N.R	MPE	1.9 – 3.9%
		PD	Wendel [103]	CV	DO	Wrist	Prop	ICC	ICC: -0.02 – 0.17
Up24	Steps	Multi	Ummels [75]	CV	DO	Wrist	N.R	Pearson's r	$r=0.09$
Up Move	Steps	MS	Balto [83]	CV	DO	Waist	N.R	MPE	8.4 – 8.9%
		PD	Wendel [103]	CV	DO	Waist	Prop	ICC	ICC: -0.03 – 0.85
Polar									
A300	Steps	COPD	Boeselt [68]	CV	Acc	Wrist	Prop	ICC	ICC = 0.986
	Activity time	COPD	Boeselt [68]	CV	Acc	Wrist	Prop	ICC	Daily activity: ICC = 0.335
	MET	COPD	Boeselt [68]	CV	Acc	Wrist	Prop	ICC	ICC = 0.066
	Calories	COPD	Boeselt [68]	CV	Acc	Wrist	Prop	ICC	ICC = 0.829
Loop	Steps	Amputation	Smith [101]	CV	DO	Wrist	N.R	ICC	ICC = 0.723
T131	EE	Chronic lung disease	Dhillon [70]	CV	IC	N.R	Flex Heart Rate Method	LoA	-0.5 [-1.6; 0.7] – 0.4 [-0.3; 1.1]
Samsung									
Galaxy S4 mini	Mean vector magnitude	MS	Zhai [87]	CV	Acc	Habitual phone pos	N.R	Spearman's rho	$\rho: 0.06 – 0.33$
	Variance vector magnitude	MS	Zhai [87]	CV	Acc	Habitual phone pos	N.R	Spearman's rho	$\rho: -0.13 – 0.29$

Table 3 (continued)

Type	PA outcome	Population	Study	Measurement property	Criterion	Placement	Algorithm	Result Test	Outcome
Health	Steps	PD	de Carvalho Lana [133]	CV	DO	Waist	N.R	Pearson's r	$r=0.54$
		Stroke	Costa [46]	CV TRT R	DO	Waist Waist	N.R N.R	Pearson's r ICC	$r: 0.18 - 0.19$ ICC: $-0.70 - 0.10$
Lumo									
Lumoback	Steps	Multi	Ummels [75]	CV	DO	Lower back	N.R	Pearson's r	$r=0.19$
	Intensity time	Lower back pain	Takasaki [135]	TRT R		Lower back	Prop	ICC	Sed: ICC=0.75 [CI 0.26; 0.91]
Pacer Health									
Pacer Pedometer	Steps	PD	de Carvalho Lana [133]	CV	DO	Waist	N.R	Pearson's r	$r=0.77$
		Stroke	Costa [46]	CV TRT R	DO	Waist Waist	N.R N.R	Pearson's r ICC	$r: 0.68 - 0.80$ $r: 0.68 - 0.80$
Withings									
Go	Steps	Heart failure	Vetrovsky [141]	CV	Acc	Wrist	N.R	CCC	CCC=0.90 [CI 0.77–0.96]
Health Mate	Steps	MS	Balto [83]	CV	DO	Front pocket	N.R	MPE	1.5 – 3.5%
Alexander et al									
mSteps	Distance walked	MS	Alexander [78]	CV	DO	Arm	N.R	LoA	0.262 [-1.496; 2.020] m (oe)
Corussen LLC									
Accupedo	Steps	Multi	Ummels [75]	CV	DO	Waist	N.R	Pearson's r	$r=0.32$
DHS group									
MOVEBAND	Steps	Amputation	Smith [101]	CV	DO	Wrist (b)	N.R	ICC	ICC=0.897
Juen									
MoveSense	Distance walked	Pulmonary disease	Juen [72]	CV	DO	Lower back	Cust	LoA	-7.7 [CI -33.0; 17.6] meter (oe)
Leap Fitness Group									
Pedometro	Steps	Chronic pain	Ferreira [132]	CV	DO	Arm & waist	N.R	Pearson's r	For all tasks and placements: $p \geq 0.99$
Letscom									
Letscom smartwatch	Steps	MS	Lavelle [80]	CV	DO	Wrist	N.R	LoA	-390.0 [-1006.7; 226.7] (oe)
	Activity time	MS	Lavelle [80]	CV	Acc	Wrist	N.R	% error	52.9% [range 5.6–65.1]
Mario Herzberg									
EasyFit pedometer	Steps	Chronic pain	Ferreira [132]	CV	DO	Arm & waist	N.R	Pearson's r	For all tasks and placements: p between -0.32 and 0.24
Mio									
Slice	EE	CAD	Herkert [122]	CV	IC	Wrist	Prop	ICC	ICC=0.12
		Heart failure	Herkert [122]	CV	IC	Wrist	Prop	ICC	ICC=0.11
Nakosite									
3D walking	Steps	Stroke	Negrini [56]	CV	DO	Ankle (a)	Prop	ICC	ICC: $-0.20 - 0.70$
						Ankle (ua)	Prop	ICC	ICC: $-0.28 - 0.69$
						Waist	Prop	ICC	ICC: $-0.42 - 0.57$
						Wrist (a)	Prop	ICC	ICC: $-0.50 - 0.45$
						Wrist (ua)	Prop	ICC	ICC: $-0.41 - 0.45$

Table 3 (continued)

Type	PA outcome	Population	Study	Measurement property	Criterion	Placement	Algorithm	Result Test	Outcome
Pedometer Australia									
G-Sensor 2026	Steps	Multi	Treacy [23]	CV	DO	Waist	N.R	ICC	ICC = 0.308 [CI -0.094; 0.604]
ProtoGeo Oy									
Moves	Steps	MS	Balto [83]	CV	DO	Front pocket	N.R	MPE	12.5 – 14.2%
Technogym									
MyWellnes Key	Intensity time	DM	McGinley [110]	CV	SR	Waist	Prop	Spearman's rho	rho = 0.81 [CI 0.76; 0.85]

Ordering on number of studies evaluating manufacturer. This is a condensed version of the more detailed table in Supplementary file 6

EE Energy expenditure, MET Metabolic equivalent, PAL Physical activity level, CAD Coronary artery disease, COPD Chronic obstructive pulmonary disease, DM Diabetes mellitus, iSCI incomplete spinal cord injury, MS Multiple sclerosis, PAD Pulmonary artery disease, PD Parkinson's disease, RA Rheumatoid arthritis, SCI Spinal cord injury, CV Criterion validity, Con V Construct validity, Resp Responsiveness, TRT R Test–retest reliability, Acc Accelerometer, DLW Doubly labelled water, DO Direct observation, IC Indirect calorimetry, SR Self-report, (a) Affected side, (b) Both affected and unaffected side, (la) Less affected side, (LRL) Longest residual limb, (SRL) Shortest residual limb, (ua) Unaffected side, Cust Custom algorithm, LFE Low frequency effect, N.R. Not reported, Prop Proprietary algorithm, TEE Total energy expenditure, APE Absolute percentage error, CCC Concordance correlation coefficients, ICC Intraclass correlation coefficient, LoA Limits of agreement, MAPE Mean absolute percentage error, MARD Mean absolute relative difference, MPE Mean percentage error, [CI] 95% confidence intervals, (oe) Over estimation, (ue) Under estimation, MVPA Moderate to vigorous physical activity, MWT Minutes walking test, Sed Sedentary, STS Sit-to-stand test, SWT Steps walk test

was measured in these 28 studies, with 27 determining criterion validity, and 1 construct validity [105]. For the GT3, the criterion validity of energy expenditure, steps, time spent in intensity zones, time in activities, distance walked, metabolic equivalent (MET) and activity counts and construct validity for steps and vector magnitude was measured in 12 unique diagnosis groups and one mixed group with variable diagnoses. Four studies applied custom-created algorithms [61, 114, 115, 139], two studies applied both a custom and a proprietary algorithm [43, 61], two studies did not report on used algorithms [45, 55] and the other studies used proprietary algorithms ($n=21$), with Freedson [142] the most commonly reported. The GT3 was placed at five different body regions (ankle, upper arm, thigh, waist and wrist), at both the affected and unaffected side (for diagnosis groups that may suffer from unilateral impairment, e.g. stroke, unilateral amputation). The GT9 was studied on criterion validity of steps and sedentary time in 5 different diagnosis groups, placed on the ankle, waist or wrist. Three studies used one or more proprietary algorithms [76, 79, 93], and one study did not report on the used algorithm [107]. The used epoch length of the instruments ranged from 0.033 s to 60 s, or it was not reported. Sampling rate was set at 10 Hz (1 study [45]), 30 Hz (14 studies (40, 44, 49, 51, 64, 76, 81, 84, 113, 115, 116, 117{Compagnat, 2022 #154, 140}), 50 Hz (1 study [107]), 90 Hz (1 study [79]), 100 Hz (2 studies [93, 104]), or it was not reported (9 studies [23, 43, 55, 89, 94–96, 105, 108])). The criterion validity was measured with 13 different statistical tests (among others: Pearson's r, Spearman's rho, intraclass correlation coefficient (ICC), Bland–Altman level of agreement, %

accuracy). The results had a wide range of variation, with correlations between 0.004 to 0.97 and accuracy between 43.0% to 81.4%. This large variability was found among different PA outcomes, but also within PA outcomes.

PAL technologies

The devices of PAL technologies were evaluated in eight studies, six studies evaluating the ActivPAL [23, 54, 91, 95, 131, 138] and two studies evaluating the ActivPAL3 [86, 116] (Table 2). Criterion validity for steps, time spent in different activities or MET were measured in seven studies [23, 54, 86, 95, 116, 131, 138] in five unique diagnosis groups and one mixed group with variable diagnoses. Test–retest reliability was measured for steps, time spent in different activities and MET in two studies [54, 91] in two unique diagnosis groups. One study did not report the used algorithm [138], the other seven used proprietary algorithms. All studies placed the device on the thigh. The used epoch lengths were 0.1 s [91], 1 s [95] and 15 s [54, 131, 138]. Three studies did not report the epoch length [23, 86, 116]. Sampling rate was set at 10 [54, 91] or 20 Hz [86], or was not reported [23, 95, 116, 131, 138]. Test–retest reliability was measured as ICC, ranging from 0.654 to 0.997 and as absolute percentage error, ranging from 3.3% to 6.5%, depending on the PA outcome, diagnosis group and task. Criterion validity was measured as Pearson's r, ICC, Bland–Altman level of agreement, percentage accuracy and percentage error, and varied with correlations between 0.65 and 0.99, accuracy between 90.7–100% and error between 0.3–3.1%, all depending on the PA outcome, diagnosis group and task.

Consumer-grade devices

Fitbit

Eleven different types of Fitbits were evaluated: Alta ($n=4$ studies) [65, 67, 80, 98], Charge ($n=3$ studies) [23, 101, 137], Charge 2 ($n=5$ studies) [94, 97, 118, 122, 141], Flex ($n=9$ studies) [60, 75, 83–85, 99, 101, 109, 140], Flex 2 ($n=2$ studies) [84, 136], Inc ($n=1$ study) [133], One ($n=12$ studies) [23, 47, 50, 52, 53, 64, 75, 83, 92, 97, 102, 106], Surge ($n=1$ study) [103], Ultra ($n=1$ study) [46] and Zip ($n=9$ studies) [41, 58, 67, 74, 80, 90, 103, 112, 127] (Table 3). Criterion validity was measured for steps, energy expenditure, MET, time spent in different intensity zones, time spent in different activities and distance walked by 38 studies in 15 unique diagnosis groups, and three mixed groups with variable diagnoses. Convergence validity of the Alta was measured in one study for steps in cancer patients [98]. Test–retest reliability of the Inspire ($n=1$ study) [118], One ($n=1$ study) [106] and the Zip ($n=1$ study) [58], for steps, MET and time spent in different intensity zones in patients with stroke, myositis or progressive muscle diseases. Responsiveness was measured for the Flex 2 ($n=1$ study), Inspire ($n=1$ study) and One ($n=1$ study) for steps, MET and time spent in different intensity zones in patients with osteoarthritis, myositis or progressive muscle diseases. The Charge, Charge 2, Flex, Flex 2, Surge and Ultra were positioned at the wrist or it was not reported, the Alta at the lower limb, waist or wrist, the One at the ankle or waist, and the Zip at the foot, the waist or the midline of a shirt. Devices were placed at both the affected and unaffected side (for diagnosis groups that may suffer from unilateral impairment). One study used a custom algorithm [94], the other studies either used proprietary algorithms or did not report the used algorithm. Criterion validity of the Fitbits was measured with 13 different statistical tests, with correlations ranging from -0.236 to 0.99 and mean percentage errors ranging from 1.9 to 84.9%. Convergence validity, measured with concordance correlation coefficient, was smaller than 0.001 compared with a questionnaire. Test–retest reliability, measured with ICC, was 0.78–0.97. Responsiveness was measured with area under the curve (0.72 – 0.90) or correlation (-0.28 – 0.63).

Garmin

Six different types of Garmin devices were evaluated: Forerunner 35 ($n=1$ study) [66], Vivofit ($n=5$ studies) [23, 58, 101, 137, 141], Vivofit 3 ($n=2$ studies) [107, 141], Vivofit 4 ($n=1$ study) [80], Vivosmart 3 ($n=1$ study) [97] and Vivosmart 4 ($n=1$ study) [130] (Table 3). Studies measured criterion validity for steps and time spent in different activities in five unique diagnosis groups and one mixed group with variable diagnoses. Test–retest reliability of the Forerunner 35 and Vivofit was measured

for steps in a stroke population. All devices were worn on the wrist, with the Vivofit 3 also worn on the ankle in one study [107]. One study used the proprietary algorithm [130], the other studies did not report on the used algorithm. Sampling rate and epoch length were not reported for the devices. Criterion validity was measured using 5 different statistical tests (ICC, concordance correlation coefficient, Bland–Altman level of agreement, percentage error and mean absolute percentage error). Correlations ranged from 0.12 to 0.97, depending on the device, PA outcome and task. Test–retest reliability was measured using ICC, ranging from 0.86 to 0.99.

Discussion

This scoping review provides a critical mapping of the research on measurement properties (validity, reliability and responsiveness) of device-based instruments assessing PA in ambulatory adults with disabilities and/or chronic diseases. The results show a large variability in research on the measurement properties of device-based instruments assessing PA in adults with physical disabilities and/or chronic diseases. Predominantly, different forms of validity are assessed in a total of 78 different research- and consumer-grade devices using 14 different PA outcomes in 23 different diagnosis groups. There is large variability in measurement properties within and between instruments and studies. The ActiGraph devices are the most frequently studied research-grade devices, and the Fitbit devices are the most frequently studied consumer-grade devices.

PA outcomes

PA behavior is assessed with a variety of different PA outcomes. The most commonly used PA outcome is step count, comparable to previous reviews on the use of device-based PA instruments [143–145]. However, step count informs only about walking and walking-related tasks and does not give information on the intensity and duration of PA behavior from a broader perspective. Even when step count is not used as the PA outcome, we have found that studies mostly use walking-related tasks to study the measurement properties. This results in device-based PA instruments only applicable for valid and reliable measurement of walking, and thereby excluding valid and reliable measurement of other modes of PA behavior such as cycling and swimming.

The importance of frequency, intensity and duration of PA is stressed by the guidelines for PA, which typically include statements on the frequency and duration in certain intensities needed for achieving optimal health benefits [146, 147]. Energy expenditure and intensity time are PA outcomes that take two of these dimensions into account (i.e. intensity and duration).

However, the trend visible in this scoping review is that incorporating intensity in the PA outcome results in lower validity outcomes. As intensity depends on the used cut-off points and algorithms [148], given the fact that these are mostly developed for a general population [9], this finding is not surprising. Custom-made disease-specific algorithms could be a solution to increase validity outcomes. In the eight studies using custom algorithms in five different instruments, generally moderate to good values of validity are found [43, 61, 73, 94, 114, 115, 125, 134]. However, just two of these studies compare a custom disease-specific algorithm with a proprietary algorithm, reporting increased validity for the custom algorithm [43, 61]. More research needs to compare custom disease-specific algorithms with proprietary algorithms.

When using intensity time and energy expenditure as PA outcomes only, information on how and where PA is being performed is not acquired. This information can be of importance for rehabilitation specialists and policymakers to identify possibilities to improve PA behavior in people with physical disabilities and/or chronic diseases. The how (or mode) of PA can be measured using activity time. This outcome is used by 15 studies, with a variety of outcomes on measurement properties [48, 54, 68, 80–82, 86, 91, 95, 100, 116, 117, 120, 131, 138]. As device-based PA instruments only capture movement or acceleration of the body, the where (or context) of PA cannot be measured with these instruments [15]. Self-report instruments can fill this gap, hence the consensus that both self-report and device-based PA instruments should be used in complement to each other [12, 14]. In conclusion, we can say that different PA outcomes have different advantages and disadvantages, but none of the device-based PA outcomes is able to capture the complete construct of PA (i.e. setting, mode, intensity, duration, frequency). This requires future research consideration.

Population

Most of the studies on measurement properties of device-based PA instruments are conducted in diagnosis-specific populations, and only six studies concerned a mixed population including people with different physical disabilities and/or chronic diseases [23, 75, 77, 88–90]. People with different diagnoses may suffer from different walking-related complications [19–22], which could have an effect on measurement properties of device-based PA instruments (e.g. frequency spectrum of accelerations, energetic cost and efficiency of movement/activities). Thus, a diagnosis-specific approach in these studies seems logical. However, this

diagnosis-specific focus does have the drawback that it lacks generalizability to other types of physical disabilities and/or chronic diseases. It might be of interest to conduct studies using a functioning-specific focus, in line with the ICF model [35]. Functional limitations may differ between individuals within diagnosis groups, and different diagnoses might share problems with functioning, such as slower and asymmetrical gait [16–18], which can influence the measurement properties of PA devices [24]. Studies using this functioning-specific approach can give insight in PA devices with good measurement properties for multiple physical disabilities and/or chronic diseases. This is of relevance as monitoring and measuring PA is important for all physical disabilities and/or chronic diseases. As self-monitoring is an important behavior change technique [8], a PA device that is valid and reliable for a variety of people with physical disabilities and/or chronic diseases might increase feasibility of PA promoting interventions for people with physical disabilities and/or chronic diseases. The same can be suggested for the rehabilitation setting, in which a variety of patient groups are treated. Correct measurement and monitoring of PA in the rehabilitation setting can lead to a more tailored approach to improve PA behavior, which ultimately may improve health and functioning [149].

Measurement properties and statistics

The criterion validity of the device-based PA instruments is the most common studied measurement property. Besides criterion validity, only 11 studies on (test–retest) reliability [46, 54, 58, 66, 91, 105, 106, 111, 113, 118, 135] and six studies on responsiveness are included [82, 100, 105, 106, 118, 136]. Good reliability of a device-based PA instrument is needed for suitable clinical application to ensure that a change in PA behavior over time is related to an actual change instead of measurement error. Good responsiveness is needed as a prerequisite for measuring effectiveness of PA promotion in clinical care. During our search, we found studies that investigated the number of days needed for reliable measurement of PA using devices in free-living settings [150–153]. Although this is important information, it is not considered a measurement property since it does not provide information on the measurement error and the extent to which repeated measurement outcomes are the same for people who have not changed [37].

There is a large variety of statistical methods used to study the measurement properties of the different devices, which makes it difficult to compare the different studies. Most studies included in this review assessed criterion validity and test–retest reliability, for which methods of correlational nature are recommended [154]. The

use of techniques comparing means (e.g. t-test and analysis of variance) is irrelevant in studies on measurement properties, since these pretend to measure a difference (from a criterion measure or between two measurements), instead of an agreement [37]. Still, a number of included studies did not use the appropriate statistical methods according to the international standards of the COSMIN group.

Technical decisions

Using device-based PA instruments in research or clinical practice, numerous choices about data collection and data processing need to be made. All these choices could influence the measurement properties. First, one needs to think about the placement of the device on the body. Multiple studies showed the influence of placement of the device on measurement properties [23, 40, 44, 45, 51, 53, 55, 56, 58, 65, 89, 96, 107, 112, 114, 120, 128], with no clear advantage to a single location. Algorithms and cut-off points are developed with a certain placement in mind, and are not interchangeable between placements [149, 155], explaining at least part of the influence of placement on measurement properties. Secondly, epoch length and sampling rate should be considered when using PA measurement devices. Previous studies have shown that different epoch lengths result in differences in PA outcomes [15, 156]. However, none of the reviewed studies have looked at the influence of epoch length on measurement properties. Furthermore, in a large number of studies ($n=25$ in research-grade devices, $n=59$ in consumer-grade devices) the used epoch length is not reported. The same is found for sampling rate, which is also not always reported. Therefore, we cannot make recommendations on the optimal epoch length and sampling rate. However, for the use of device-based instruments in practice, one needs to critically assess considerations such as accuracy versus storage capacity. Thirdly, another important choice is the algorithm used to convert the measured accelerations of movement into interpretable PA outcomes. Applying different general algorithms could lead to differences in measurement properties, which is shown by the three studies that compared multiple algorithms [49, 71, 76]. And as mentioned previously, custom-made disease-specific algorithms could influence the measurement properties when using intensity-based PA outcomes [43]. For research and clinical use, we suggest applying an algorithm that is evaluated for the specific population and activity level. However, based on our findings we cannot recommend certain algorithms, as this is beyond the scope of this review. Considering the effect of these technical choices

on PA outcomes and the measurement properties of the device-based instruments, Burchartz et al. already stated in their state of science paper on device-based PA instruments that all important technical decisions (such as placement on the body, the used epoch length, sampling rate and algorithm) should be reported in studies on measurement properties [15]. As it is apparent from this review that reporting the technical decisions is not common practice in studies on measurement properties, we wholeheartedly support this recommendation.

Strengths and limitations

The main strength of this scoping review is the detailed and extensive mapping of studies using a broad range of methodological approaches and in a diverse group of ambulatory people with physical disabilities and/or chronic diseases. Furthermore, we used a systematic process in this scoping review, with the screening and selection process for the majority done in duplicate using information from four major databases. Another strength is the transparency and openness of the current scoping review. We provided additional information on the screening and analysis processes in the supplements and on Open Science Framework, which greatly improves the reproducibility of our scoping review. Lastly, we provided detailed information on decisions made in the included studies, which has not been reported in such detail in previous reviews on this topic. The [Supplementary files](#) add an extra layer of information for the interested reader, and provide extra emphasis on the large variability of the studies (e.g. the variety in what is considered a valid day/case among the studies).

However, some limitations of this scoping review should be acknowledged. One of the limitations is related to the search strategy. Although we carefully developed our search strategy, together with an information specialist, it is possible that we missed important search terms (e.g. specific wearables, specific disease groups), which could have resulted in missed relevant studies. Also, the inclusion of some search terms could have led to a relative overrepresentation of certain studies or devices used in the studies. As an example, 'ActiGraph' was included as a search term in our search strategy, which we found as the most used research-grade device in the literature. However, a previous review of device-based PA instruments in cardiovascular patients also found the ActiGraph as most frequently used instrument [145]. We did not apply the search filter for measurement properties developed by the COSMIN group [157], as this increased our search results exponentially.

Another limitation is our Dutch view on the rehabilitation setting. One of our inclusion criteria was that the physical disability or chronic disease of the participants

must be a primary reason for rehabilitation. However, rehabilitation might not be organized the same across countries. This may have resulted in us excluding certain diagnosis groups that would be included by researchers of other countries, and vice versa, using the same in- and exclusion criteria.

In the current scoping review, we did not differentiate the overview of the measurement properties to the used setting (i.e. laboratory setting vs free-living setting) of the studies, which can be considered a limitation. The difference in setting might influence the measurement properties, and thus entail different concepts. We reported the used setting of the studies in the description table (Table 1) so that readers who are interested in these concepts can find this information in the current scoping review. However, future reviews could put more in-depth focus on the differences in setting and their effect on measurement properties.

A limitation inherent to research on device-based PA instruments is the rapidly changing field with regard to the technology. The technology of these devices develops rapidly, leading to newer models to hit the market before previous models have been properly studied. This is especially true for the consumer-grade instruments, which illustrates a commercially-driven approach to the development of new technology, not necessarily leading to a quality-driven market. For research purposes, there is more need for valid and reliable instruments.

Future directions

Considering the importance of PA in people with physical disabilities and/or chronic diseases, and the need to measure and quantify PA in this population as stated by different research agenda's [9–11], instruments with good measurement properties are vital. Due to the large variability in measurement devices and the methods used to evaluate these, we were unfortunately unable to make concrete recommendations for specific devices and settings based on this review. However, this review provides an overview of detailed information per measurement device, which we use to provide directions for research on measurement properties of device-based instruments assessing PA in people with physical disabilities and/or chronic diseases.

- The focus of research on measurement properties of device-based PA instruments in people with physical disabilities and/or chronic diseases needs to be less on step count as a PA outcome, as it provides a very narrow view of PA behavior. Energy expenditure and intensity time seem important, but the validity of these outcomes needs to be improved. More research is needed on the measurement properties when using

activity time since this can be important information for rehabilitation purposes. To better measure the multidimensionality of PA, the use of device-based PA instruments can be supplemented by the simultaneous application of self-report instruments.

- Studies on measurement properties of device-based instruments should inform readers of important technical decisions made for data collection and data processing. Especially the placement of the device on the body, the epoch length, sampling rate, and the used algorithm in full detail should be reported, as these are known to influence PA measurement. This information will help with data comparison between studies, but will also inform in detail in which situation a device-based instrument should or could be used.
- Future research should investigate the influence of disease-specific versus general algorithms on the measurement properties (in this case mainly validity) of device-based PA instruments. Intensity is an important aspect of PA, as evidenced by the focus of PA guidelines on moderate to vigorous PA [146, 147]. The use of custom disease-specific algorithms could improve the ability of device-based instruments to capture intensity.
- More research on the measurement properties of device-based PA instruments should be conducted in populations consisting of people with different physical disabilities and/or chronic diseases, for example by using a functioning-specific approach. It would be beneficial to have a single device-based PA instrument with good measurement properties available for different diagnosis groups. This will improve the ease of use in a rehabilitation setting where different diagnosis groups are treated.
- Raw data from device-based instruments should be used, instead of using PA outcomes processed by proprietary algorithms. In this way, the measurement properties of the device-based instruments when using raw data can be studied in a diverse population, and this raw data can subsequently be processed into PA outcomes using disease-specific or even individualized algorithms. Important to note, is that these algorithms should also be validated. The use of raw data has also been recommended by previous studies [15, 149].
- Reliability and responsiveness of device-based instruments should be studied more often. These measurement properties are especially important when device-based PA instruments are used to study changes in PA behavior over time. And although there has been an increase in studies on these measurement properties (especially responsiveness) in

the last two to three years, they are still underrepresented in the literature of this scoping review.

- The methodologically correct statistical methods should be used while studying measurement properties of device-based instruments. This will help with comparing different studies and will result in better informed researchers and health professionals when selecting device-based instruments.

Conclusion

There is a large variability in research on the measurement properties of device-based instruments assessing PA in ambulatory adults with physical disabilities and/or chronic diseases. This variability shows a need for more standardization of and consensus on research in this field. Based on this scoping review, the results could provide researchers and health professionals with some directions for selecting a device-based PA instrument that suits their need. Finally, to improve research and bridge knowledge gaps, we provide future directions for researchers interested in studying the measurement properties of device-based instruments assessing PA in ambulatory adults with physical disabilities and/or chronic diseases.

Abbreviations

PA	Physical activity
MET	Metabolic equivalent
ICC	Intraclass correlation coefficient

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s13102-023-00717-0>.

Additional file 1: Supplementary file 1. Protocol deviations. A file containing details of the deviations we made to the protocol.

Additional file 2: Supplementary file 2. Full search strategy for each database. A file containing the search strategy used for each database.

Additional file 3: Supplementary file 3. PICO, Selection criteria and Checklists. A file containing the PICO and the selection criteria used for the scoping review. Als contains the checklist that were used during the screening process.

Additional file 4: Supplementary file 4. Expanded description of the 103 studies included in the scoping review. A file containing the description of the included studies in more detail. Extra information on in- and exclusion criteria, the used task in the study and criteria for valid days and cases.

Additional file 5: Supplementary file 5. Expanded overview of research-grade devices evaluated on their measurement properties in 52 studies. An expanded overview of the research-grade devices evaluated on their measurement properties. Extra information on epoch length, sampling rate and results per condition.

Additional file 6: Supplementary file 6. Expanded overview of consumer-grade devices evaluated on their measurement properties in 74 studies. An expanded overview of the consumer-grade devices evaluated on their measurement properties. Extra information on epoch length, sampling rate and results per condition.

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Authors' contributions

PB, FH, LHVdW, RD and LAK conceptualized the scoping review. PB, LAK and IB performed selection of the eligible studies. PB extracted data, synthesized the data, prepared tables and figures, and drafted the manuscript. All authors contributed significantly in interpretation of results. All authors critically reviewed the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

Additional information can be found on Open Science Framework (<https://osf.io/c27xv/>). This includes information on the original protocol, the complete list of search results, an overview of the screening process (number of search results, duplications removed per deduplication step according to the method of Bramer et al., included and excluded per phase), the used checklists for the screening, the filled-in checklists by the screeners with results, and the data extracting tool (both the filled in version and a clean version).

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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