Published in final edited form as:

Expert Rev Med Devices. 2017 November ; 14(11): 891–900. doi:10.1080/17434440.2017.1386550.

MOTION SENSORS IN MULTIPLE SCLEROSIS: NARRATIVE REVIEW AND UPDATE OF APPLICATIONS

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Abstract

Introduction: The use of motion sensors for measuring physical activity in multiple sclerosis (MS) has evolved with increasing research particularly during the past decade.

Areas covered: This manuscript reviews the literature regarding the application of motion sensors for measuring physical activity in MS. We first describe ‘what is known’ about their use in MS by examining the evidence generated between 1997 and 2012, including the psychometric properties of motion sensors in MS and the development of MS-specific accelerometer cut-points. We then evaluate ‘what is new’ based on research conducted between 2013 and 2017. This includes newer research on psychometric properties of motion sensors in MS, development of new MS-specific accelerometer and step-rate cut-points, sedentary behavior assessment, and research on fitness trackers and multisensors in MS. The final part presents a picture of “what is next” for the applications of motion sensors in MS, especially pertaining new opportunities for testing and using fitness trackers in MS, and tracking disease and disability progression based on motion sensor output.

Expert commentary: The use of motion sensors in MS has grown substantially over the years; however, a lot more can be done to explore the full potential and utility of these devices in MS.

Keywords

Physical activity; sedentary behavior; wearable technology; assessment; multiple sclerosis

1. INTRODUCTION

There is a well-established body of evidence on the application of motion sensors for measuring physical activity behavior in the general population of adults [1]. By comparison, there is a substantially smaller, yet steadily increasing body of literature in this area that

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Declaration of interest

The authors have no relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript apart from those disclosed

involves persons with mobility disability such as multiple sclerosis (MS) [2]. This might be explained by the only recent shift in paradigm wherein physical activity is now recognized as yielding beneficial effects on symptoms and function in this population rather than being potentially harmful for MS [3]. Such a change in paradigmatic view requires that research and clinical practice involving physical activity in MS capitalize on the objective measurement of this behavior that can be provided by motion sensors [4].

The objective measurement of human movement began over 500 years ago [5], but the first study on motion sensors for measuring physical activity in MS was published only 20 years ago [6]. Since then, the application of accelerometers and pedometers for measuring physical activity in MS has increased considerably [2]. Importantly, accelerometers provide measures of raw acceleration (g force) and/or activity counts (proprietary measures) based on the intensity of displacement of the body during physical activity. Pedometers, alternatively, record the number of steps taken as a binary event based on movement of the body during physical activity. Researchers typically use those metrics provided by accelerometers and pedometers for assessment and characterization of physical activity behavior in MS [4,5].

Of note, there has been a substantial proliferation of research on motions sensors for measuring physical activity in MS over the past 5 years; this was perhaps spurred on by the publication of a new set of MS-specific accelerometer cut-points for moderate-to-vigorous physical activity (MVPA) in 2012 [7]. This time point further corresponds with the last comprehensive review paper on the application of motion sensors in persons with MS [8]. The burgeoning research examining the application of motion sensors in this population has resulted in the generation of important considerations and directions for future research involving physical activity measurement in persons with MS.

The present manuscript provides a narrative review and update on the application of motion sensors for measuring physical activity in MS. The first section provides a brief synopsis of research on the psychometric properties, more specifically the validity and reliability, of motion sensors for measuring physical activity up through 2012. We then provide an updated summary of research involving motion sensors for physical activity measurement in MS based on research between 2013 and 2017. The last section of this paper provides important considerations and directions for future research in this area (i.e., 5-year projection). We do not provide information on the application of motion sensors for other purposes (e.g., quantifying mobility or gait kinematics) in persons with MS, as this falls outside the scope of the current review.

2. RESEARCH FROM 1997–2012: WHAT IS KNOWN?

The study by Ng and Kent-Braun in 1997 [6] was the cornerstone application of motion sensors for measuring physical activity in MS. The study was important because it indicated that, while estimates of self-report physical activity-related energy expenditure were statistically similar for persons with MS and sedentary controls (35.9 ± 3.0 vs. 36.2 ± 4.1 kcal·kg⁻¹·day⁻¹), physical activity measured objectively with the TriTrac-R3D accelerometer differed significantly among the two groups ($121,027 \pm 59,336$ vs. $185,892 \pm 60,566$

arbitrary units/day) [6]. Since its publication, a substantial body of literature has emerged on the use of motion sensors in MS. The early studies primarily focused on examining the psychometric properties of motion sensors in MS, including the validity and reliability of scores. Such psychometric research eventually resulted in the publication of MS-specific accelerometer cut-points in 2012; the provision of cut-points provided a springboard for newer directions of research on physical activity motion sensors in MS beyond the evaluation of psychometric properties. We provide a brief overview of the literature from 1997 to 2012 based on three categories of studies: (1) validity of scores from motion sensors (both pedometers and accelerometers) in MS; (2) reliability of scores from motion sensors in MS; (3) and MS-specific accelerometer cut-points for MVPA.

2.1 Validity of Scores from Motion Sensors in MS

2.1.1 Pedometers.—Some of the early psychometric research on motion sensors in MS focused on the validation of pedometers as objective physical activity measures. The studies tested the validity of pedometers in MS based on accurately counting steps taken while walking at different speeds on a treadmill and/or over-ground; both paradigms were performed under controlled laboratory conditions [9,10]. Results from an early study indicated that the Yamax SW-200 and SW-401 were accurate (up to 4.4% error) in recording steps at comfortable and fast walking speeds on a treadmill (i.e., 67, 80, and 94 m/min), but not at slower speeds (i.e., 41 and 54 m/min; up to 31.6% error) [9]. This systematic inaccuracy was especially concerning for the application of those spring-loaded pedometers in persons with MS-related mobility impairment, because this group of persons with MS walk substantially slower than fully ambulatory individuals [11]. The results from a subsequent study raised further concerns on the accuracy of pedometers in persons with MS [10]. That study reported a measurement error of 24% in pedometer-measured steps taken during self-selected speeds of over-ground walking for persons with MS; there was only 3% measurement error in steps taken for healthy controls. The substantial proportion of the measurement error in MS was probably caused by the low sensitivity of spring-levered pedometers during slow walking (i.e., the displacement of the center of mass during walking was not large enough for triggering the spring-loaded lever arm mechanism and closing the circuit for counting a step). Interestingly, some studies in the general population [12] and in persons with MS [12,13] indicated smaller measurement errors (~4–7% underestimation) for piezoelectric pedometers (i.e., accelerometer mechanism) compared with larger errors for spring-levered pedometers during slow walking speeds (e.g., 54 m/min). Based on this evidence, it became apparent that the use of piezoelectric pedometers was desirable for application in persons with MS, particularly in situations requiring accurate assessment of steps per unit time.

2.1.2 Accelerometers.—Regarding the validity of scores from accelerometers in MS, early studies examined correlations between accelerometer output (i.e., activity counts) and other measures of physical activity (i.e., objective and self-report measures). Some studies reported statistically significant correlations of activity counts/day over a 7-day period from a waist-worn ActiGraph 7164 accelerometer with pedometer-derived steps/day ($r = 0.77 - 0.93$) [14,15] and moderate-to-strong correlations with scores from self-reported physical activity questionnaires in persons with MS, including the Godin Leisure-Time Exercise

Questionnaire ($r = 0.36 - 0.60$) [15–18], the International Physical Activity Questionnaire ($r = 0.34 - 0.56$) [15,16,18], and 7-day Physical Activity Recall ($r = 0.75$) [17]. Nevertheless, results from some studies suggested that accelerometer activity counts might reflect walking mobility in MS. Indeed, significant correlations were observed between a waist-worn ActiGraph 7164 accelerometer with self-report and objective measures of mobility, such as the Multiple Sclerosis Walking Scale-12 ($r = -0.38$) [16], Patient Determined Disease Steps ($r = -0.40$) [16], 6-minute walk test ($\rho = 0.78$) [19], and Timed Up and Go test ($\rho = -0.68$) [19]. Activity counts from a waist-worn ActiGraph 7164 accelerometer further demonstrated a strong correlation with walking speed ($r = 0.82$) during over-ground walking at comfortable, slower and faster walking speeds [20]. Collectively, such initial evidence supported the validity of accelerometers for capturing physical activity and possibly mobility.

Nevertheless, most of the evidence on the validity of accelerometers in MS evolved around the use of the ActiGraph 7164 activity monitor. Less was known about the psychometric properties of other accelerometer models for measuring physical activity in this population, such as the Tritrac RT3, the Actical, and the ActiBelt. The existing research with these other devices focused on distinguishing mobility disability based on accelerometer output. For example, the waist-worn Tritrac RT3 distinguished between mobility disability levels in persons with MS in two studies [21,22]. Conversely, another study indicated that the waist-worn Actical was associated with performance on the 6-minute walk test and the 30-second chair stand test [23]. The validity of the ActiBelt®, a waist-worn accelerometer that is intended to accurately capture walking speed for those who walk especially slowly, was tested in 51 persons with MS during a 6-minute walk test [24]. The ActiBelt overestimated walking speed in MS ($+0.12 \pm 0.17$ m/s), particularly in those persons who had moderate ($+0.10 \pm 0.16$ m/s) and severe ($+0.26 \pm 0.12$ m/s) MS-related ambulatory disability [24]. Collectively, the results of these studies suggested that accelerometer output could be an indicator of mobility level and physical function in MS, and that mobility disability could affect the accuracy of accelerometer output.

Overall, the evidence generated from 1997 to 2012 suggested that data from spring-loaded pedometers are valid for accurately measuring steps during normal and fast walking speeds (e.g., >54 m/min), but not during slow walking speeds (e.g., <54 m/min) in persons with MS. By comparison, piezoelectric pedometers presented higher accuracy than spring-levered pedometers across all speeds. The evidence from early research on motion sensors in MS indicated that accelerometers, particularly the ActiGraph 7164, are valid for measuring physical activity and notably mobility in this cohort. The association with mobility prompted later interest in developing MS-specific approaches for processing accelerometer data that account for levels of mobility disability and the effect on energy expenditure during walking.

2.2 Reliability of Scores from Motion Sensors in MS

The reliable measurement of habitual physical activity as well as its changes with an intervention or clinical manifestation is important when using motion sensors in MS. This is only possible when these devices produce consistent estimates over time with scores that are stable in the absence of intervention. Studies have examined the reliability of output from

pedometers and accelerometers in MS. One early study reported an intraclass correlation coefficient (ICC) of 0.93 for steps/day from the Yamax SW-200 pedometer and the ActiGraph 7164 accelerometer (measured over a 7-day monitoring period) in persons with minimal MS-related ambulatory disability; this indicates strong reliability of outcome from both units as measures of physical activity in MS [14]. The Tritrac RT3 accelerometer demonstrated an ICC of 0.83 for test-retest reliability of free-living physical activity estimates in MS, based on two measurement periods separated by eight weeks [22]. One study examined reliability of the Actical accelerometer in 31 individuals with MS presenting with different levels of disability [23]. Participants performed six different activities ranging between sedentary and moderate intensity physical activity (i.e., newspaper reading, washing, vacuuming, stair climb, 30-second chair stand, and 6-minute walking test) on two separate occasions, seven days apart. Reliability was low for sedentary and low-intensity activities (ICC = 0.00 and 0.38), respectively, but high for moderate intensity activities (ICC = 0.75 – 0.90) [23]. Such results suggest that the Actical could be problematic for assessing habitual physical activity in persons with MS, especially those with mobility disability who walk slowly and engage in sedentary or light-intensity activities.

One accelerometer model that gained interest in persons with conditions that present with mobility disability was the Vitaport. The Vitaport may differentiate between static activity (i.e., sitting, standing, lying) and dynamic movement (e.g., sit-to-stand transition, stand-to-sit transition, walking). One study reported adequate reliability of this accelerometer in a sample of 43 persons with MS [25]. Across a period of 24-hours of continuous monitoring, the ICC for output from the Vitaport accelerometer was 0.72 for dynamic activity and 0.71 for static activity, respectively, in persons with mild MS ambulatory disability, based on a median Expanded Disability Status Scale (EDDS) score of 3.5 (interquartile range: 2.5) [25]. Another device of high interest in neurological conditions that present with mobility disability is the StepWatch; this device is worn on the ankle and has better sensitivity for capturing steps during slow walking than most pedometers [26]. One study by Busse et al. [27] indicated that the ICC for two 7-day periods of monitoring using the StepWatch in persons with neurological conditions (i.e., MS, Parkinson's disease, and primary muscular disorder) was 0.86; this denoted a high degree of reliability [27].

Based solely on the evidence published through 2012, it is difficult to reach definitive conclusions regarding the extent of reliability of output from accelerometers and pedometers for assessing physical activity among persons with MS. There were few studies that examined the same pedometer and accelerometer models in persons with similar MS disability status (e.g., fully ambulatory, ambulatory with assistive device). Although most results indicated that these motion sensors were reliable for physical activity assessment in fully ambulatory persons with MS, there was a clear need for further examining how disability level and motion sensor type influenced the reliability of physical activity measures in MS. Data on stability over time were lacking in any MS sample.

2.3 MS-Specific Accelerometer Cut-Points for MVPA

The US Department of Health and Human Services published physical activity recommendations for the US population in 2008 [28]. These guidelines indicated that adults

should engage in at least 150 minutes per week of MVPA for general health benefits [28]. The objective quantification of physical activity within the context of such a recommendation in the general population was facilitated by published accelerometer cut-points that were developed in the late 1990s' and early 2000s'. However, the same was not true for persons with MS, as efforts for generating condition-specific accelerometer cut-points among this population had not begun until 2009. The generation of cut-points involves calibrating the relationship between accelerometer output (i.e., counts/minute) and energy expenditure (i.e., metabolic equivalents [METs]), thereby determining the number of activity counts per minute that correspond with different intensities of physical activity (i.e., moderate intensity = 3 METs; vigorous intensity = 6 METs) [29,30].

Importantly, altered gait parameters (e.g., walking velocity, cadence, step length) result in increased energy expenditure during ambulation among persons with MS compared with the general population [31]. Accordingly, higher MET values per a given number of activity counts per minute are observed in persons with MS compared to healthy matched controls, justifying the need for developing MS-specific accelerometer cut-points [32]. To address this issue, the studies by Motl et al. [32] and Sandroff et al. [7] developed cut-points that were specific for classification of accelerometer output based on physical activity intensity in fully ambulatory individuals with MS. The initial effort by Motl et al. [32] established preliminary cut-points based on uniaxial accelerometer data from the ActiGraph 7164 (light < 591 counts/min; moderate = 591–6460 counts/min; vigorous > 6460 counts/min). Another laboratory-based study by Sandroff et al. [7] proposed a new set of cut-points for processing both uniaxial data from the ActiGraph 7164 (MVPA=1723 counts/min) and triaxial data from the ActiGraph GT3X (MVPA = 1584 counts/min). Those latter cut-points have been applied in observational and experimental studies measuring physical activity in persons with MS [18,33–35] and have allowed for significant advancement in the understanding of associations between physical activity with different health outcomes [36].

3. RESEARCH FROM 2013–2017: WHAT IS NEW?

There has been a particularly noticeable increase in research on the application of motion sensors for measuring physical activity in persons with MS during the time period of 2013–2017, perhaps associated with the publication of the first MS-specific accelerometer cut-points for MVPA [7,32]. This increase has primarily involved: (1) newer research on the psychometric properties of motion sensors; (2) updated cut-points and the first step-rates for MVPA; (3) the application of motion sensors for measuring sedentary behavior; and (4) examination of new, commercially available fitness trackers and applications (e.g., FitBit™) in persons with MS.

3.1 Newer Research on Psychometric Properties of Motion Sensors in MS

With the increasing use and application of different types and models of motion sensors in MS, interest emerged on the comparability of outputs across devices in controlled and free-living conditions. To that end, one study involved a comparison of the outputs from the 7164 and GT3X models of ActiGraph accelerometers under free-living conditions (i.e., 6-day monitoring) and during five different speeds of treadmill walking (54, 67, 80, 94, and 107 m/

min) [37]. Under free-living conditions, the output of the ActiGraph 7164 accelerometer was about 7% higher than that of the ActiGraph GT3X in persons with MS (i.e., a mean $\pm$ SD of 10410 ± 29087 counts/day). Regarding the treadmill walking conditions, the ActiGraph 7164 presented an output 30% higher than that of the ActiGraph GT3X for the speed of 54 m/min. For speeds of 67, 80, 94, and 107 m/min, the differences between the outputs from the ActiGraph 7164 and ActiGraph GT3X were 9.0%, -1.3%, 2.3%, and 2.1%, respectively.

These discrepancies might be attributed to the sensing mechanisms included in the 7164 and GT3X accelerometers. The ActiGraph 7164 uses a piezoelectric sensing component, which is more sensitive to slow movement, compared with the microelectromechanical sensing component used by the ActiGraph GT3X accelerometer and the latest models [30,38]. This prompted the importance of comparability of outputs for slow movements among different generations of ActiGraph accelerometers now afforded by the low frequency extension (LFE) option in the ActiLife software. The LFE increases comparability of activity counts between older and newer models of ActiGraph accelerometers for slow movement [39,40]. Without the activation of the LFE, the accuracy of ActiGraph accelerometers for measuring steps is similar to that of spring-loaded pedometers [41]. Accordingly, studies using newer ActiGraphs in MS should use the LFE for more accurate measurement of physical activity.

Nevertheless, considerable measurement error may still occur when using ActiGraph accelerometers for measuring steps under various conditions in persons with MS, even after activation of the LFE. Some slow movements in those individuals with severe ambulatory disability may fall outside the acceleration detectable range of ActiGraph accelerometers. One study [42] examined the accuracy of the ActiGraph GT3X+ with the LFE activated and the StepWatch for measuring steps taken among persons with MS who had mild, moderate, and severe disability during several conditions. Participants completed bouts of 6-minute over-ground walking at their comfortable walking speed (CWS), a slower walking speed (SWS; 0.5 mph below the CWS), and a faster walking speed (FWS, 0.5 mph above the CWS). The results indicated that the percentages of actual steps taken (compared with visual inspection) measured by the ActiGraph GT3X+ ranged from 99.8 to 100.4% (CWS and SWS, respectively) for those with mild MS disability, 95.7 to 99.8% (SWS and CWS, respectively) for those with moderate MS disability, and 87.3 to 90.9% (SWS and FWS, respectively) for those with severe MS disability [42]. Conversely, the percentages of actual steps taken measured by the StepWatch ranged from 99.9 to 100% for those with mild MS disability, 100.1 to 101.8% for those with moderate MS disability, and 95.7% to 100.9% for those with severe MS disability [42]. Such results indicate that the StepWatch is highly accurate for measuring steps taken across the MS disability spectrum, and suggest that even after activation of the LFE, the ActiGraph GT3X+ should be applied with caution for measuring steps at slow walking speeds among persons with severe MS-disability.

Validity of the activPAL3 has been verified in persons with MS who have moderate-to-severe mobility disability (i.e., EDSS scores between 4 and 6.5) during a 20–30 m bout of walking [43]. The overall mean difference between activPAL3 and manually counted steps by trained raters was -4.70 ± 9.09 steps (8.7% underestimation) across the 20–30 m walk [43]. The average $\pm$ standard error difference in steps taken based on EDSS score ranged between -0.50 ± 3.53 for those with an EDSS of 4.0 and -6.90 ± 15.44 steps for those with

an EDSS of 6.5 [43]. This illustrates that, similar to the majority of motion sensors, the accuracy of activPAL3 is highly dependent on walking speed and disability level in persons with MS, whereby accuracy is lowest during slow walking speed in those with substantial MS disability.

Some studies have further verified the reliability of motion sensors in MS. Regarding the number of days required for reliably estimating physical activity in MS, recent evidence indicates that a minimum of 3 days of monitoring is necessary when using ActiGraph accelerometers [44]. Intraclass correlation coefficients of 0.82 and 0.84 were observed for light and moderate-to-vigorous physical activity, respectively, with 3 days of monitoring. Higher ICC values were observed with 4, 5, 6, and 7 days of monitoring (ICC of 0.85–0.92) [44]. Regarding test-retest reliability, recent studies have observed that ActiGraph activity counts and steps/day data collected at baseline and after 6-month of follow-up presented with strong reliability (i.e., ICC of 0.84–0.90) [45,46]. Researchers planning observational and experimental studies should consider these parameters when estimating sample size.

3.2 Updated cut-points and step-rates for MVPA in persons with MS

The first sets of accelerometer cut-points were developed for fully ambulatory persons with MS in 2012. However, these cut-points were not generalizable for persons with more substantial MS-related ambulatory disability. The reason is that disease symptoms and altered gait parameters (i.e., gait velocity, cadence, step length) are associated with elevated oxygen cost (O_2 cost) of walking in persons with MS [47]. This consequently results in higher energy expenditure (METs) for any given number of activity counts per minute when comparing persons across degrees of MS-related mobility disability. To that end, recent research efforts sought to update and revise cut-points that account for disability status in MS. One study [31] established cut-points for classification of physical activity intensity in persons with mild, moderate, and severe MS disability. Participants completed three over-ground 6-minute walk tests – one at self-determined CWS, and the other two at speeds 0.5 mph above and below CWS – while using the ActiGraph GT3X+ on the hip and a portable metabolic system for measuring energy expenditure. After regressing ActiGraph GT3X+ activity counts on energy expenditure data, the researchers derived cut-points for MVPA for those with mild/moderate disability and severe disability, which were 1980 and 1185 counts/min (vertical axis), respectively [31]. Those cut-points provided researchers with the means of quantifying the influence of MVPA on health and functional outcomes in persons with different levels of MS-related mobility disability [31].

One challenge that persisted was the measurement of physical activity in persons at the higher end of the ambulatory disability spectrum in MS (i.e., non-ambulatory individuals). For example, there were no accelerometer cut-points that could be used in wheelchair users. One study recently addressed this concern, wherein 24 manual wheelchair users (including persons with MS) completed three treadmill conditions (wheeling on a motorized wheelchair treadmill at 1.5, 3.0 and 4.5 mph) while wearing an ActiGraph GT3X accelerometer on each wrist and a Cosmed K4b2 portable metabolic system. The regression of accelerometer output on energy expenditure resulted in a cut-point for MVPA of 3644 ± 1339 counts/min that can be applied to either left or right wrist placements [48].

Over the last 5 years, progress has been made on the processing of steps data from motion sensors. Experts have discussed the benefits of using a standard output for creating an equivalent metric for processing data across devices. Accordingly, step counts from different devices are usually highly comparable, which is not the case for activity counts from accelerometers [49]. Additionally, step count is an easy-to-understand output that further can be easily applied in clinical and research settings. Some researchers have supported the use of the step rate feature of newer pedometers to classify physical activity intensity in the general population [50]. Among persons with MS, researchers within the last three years have developed step rate cut-points for classifying MVPA [51,52]. One study used manually-counted step rate and metabolic (i.e., energy expenditure) data collected during three different walking speeds on the treadmill (i.e., 2.0, 3.0, and 4.0 mph) to generate cut-points for MVPA for persons with MS who had minimal walking impairment and for those who had mild-moderate walking impairment [51]. The step rate cut-point for moderate physical activity (3–6 METs) was 99 steps/min for persons with minimal walking impairment and 96 steps/min for those with mild-moderate walking impairment. Regarding vigorous physical activity (> 6 METs), the cut-point was 144 steps/min for persons with MS who had minimal walking impairment and 136 steps/min for those with mild-moderate walking impairment [51].

Using a similar approach in a separate sample, another study [52] generated step rate cut-points for classifying physical activity intensity in persons with a broader range of MS-related ambulatory disability. The following step-rate cut-points for moderate- and vigorous-intensity physical activity, respectively, based on disability status, were generated from manually-counted steps: (a) mild disability: 99 and 170 steps/min; (b) moderate disability: 89 and 160 steps/min; and (c) severe disability: 79 and 150 steps/min. These step rate cut-points represent a convenient and valuable output for assessing ambulatory-related PA in persons with MS, and further might provide a useful metric for remotely monitoring and prescribing PA behavior in this population [53]. As a result, this method will likely gain popularity in the coming years, especially with the relative low-cost of pedometers that incorporate microelectromechanical technology (e.g., resistive and capacitive accelerometers), which is similar to motion sensors of higher price, such as ActiGraph accelerometers.

3.3 Sedentary Behavior Assessment

There has been an increasing interest in sedentary behavior in persons with MS [54], yet the use of motion sensors to measure sedentary behavior in MS has been limited compared with the general population. For example, there are no accelerometer estimates of sedentary behavior in a nationally representative sample of persons with MS, whereas such data in the general population have been available since 2008 [55]. To date, few studies have included accelerometers to measure sedentary behavior in MS; the existing studies have focused on quantifying total time spent in sedentary behavior by applying cut-points developed for the general population. Such paradigms have mainly involved waist-worn ActiGraph activity monitors and have used the cut-point of 100 counts/min to assess sedentary behavior in persons with MS. For example, a study by Ezeugwu et al. [56] examined sedentary behavior in people with MS (n = 439) using the ActiGraph 7164 accelerometer. The results indicated

that those individuals with mobility disability spent 65% (8.9 h/day) of daily time in sedentary behavior compared to 60% (8.4 h/day) for those without mobility disability. Those with mobility disability demonstrated a greater number of bouts in sedentary behavior lasting for more than 30 min compared with those without mobility disability (5.1 vs. 4.3 bouts, $p = 0.02$). Another study using the ActiGraph 7164 accelerometer indicated that older adults with MS spent considerably more time in sedentary behavior than middle-aged and young adults with MS (554.1 vs. 532.8 vs. 509.6 min/day, respectively; $p < 0.01$) [57]. These data are important for characterizing sedentary behavior in MS and for allowing comparisons with the general population.

There is a considerable body of literature on objectively measured sedentary behavior and health outcomes in the general population [58–65]. Comparatively, little is known about specific associations between sedentary behavior and secondary consequences in persons with MS. One of the few studies exploring such relationships examined the association of time spent in sedentary behavior, assessed with the ActiGraph GT3X+ model, and brain volumetric measurements based on MRI [66]. That study reported no significant associations between sedentary behavior and neuroimaging outcomes, but there were associations between MVPA measured by the accelerometer and MRI measures of normalized gray matter volume ($r = 0.370$, $p < 0.05$), normalized white matter volume ($r = 0.433$, $p < 0.01$), hippocampus ($r = 0.499$, $p < 0.01$), thalamus ($r = 0.380$, $p < 0.05$), caudate ($r = 0.539$, $p < 0.01$), putamen ($r = 0.369$, $p < 0.05$), and pallidum ($r = 0.498$, $p < 0.01$) [66]. These data suggest levels of accelerometer-estimated MVPA account for at least a small portion of the variance in regional brain MRI volumes. Another study by Hubbard et al. [67] assessed time spent in sedentary behavior with an ActiGraph GT3X and examined its association with disability status and cognitive function. The results indicated a significant correlation between time spent in sedentary behavior and disability status scores ($r = 0.31$, $p < 0.01$), whereas no significant correlation was observed between time spent in sedentary behavior and cognitive function ($r = -0.12$, $p = 0.29$). [67] These studies attest for the application of objectively measured sedentary behavior in MS; however, some researchers highlight the need to standardize accelerometer data collection procedures for reaching more generalizable conclusions [54]. This includes the number of days of monitoring. There is an indication that 4–6 days of monitoring are necessary for reliably estimating sedentary behavior in MS using ActiGraph accelerometers [44]. Four days of monitoring is sufficient for providing reliable estimates of time spent in sedentary behavior (ICC = 0.81) and average length of sedentary behavior (ICC = 0.86), whereas five days is needed for reliable estimation of number of long (> 30min) sedentary bouts (ICC = 0.80) [44]. For reliable estimates of number of sedentary breaks, 6 days of monitoring is necessary (ICC = 0.82) [44]. Of note, these periods are longer than the period for reliably measuring physical activity data using ActiGraph accelerometers in the general population [68].

3.4 Fitness Trackers, Multisensors, and Others Devices

Fitness trackers are currently the center of attention in research involving motivational and self-awareness strategies for increasing physical activity in the general population [69]. Among the contributing factors for its increasing application in research are the interactivity and easiness of use for participants [70]. There are a considerable number of studies using

fitness trackers in physical activity-related interventions and several others have examined the validity of these devices during laboratory- and free-living based protocols in the general population [69–72]. Overall, fitness trackers have demonstrated high validity for measuring steps and low validity for measuring energy expenditure in adults from the general population [69].

By comparison, validity of fitness trackers in MS has not been examined extensively. Only a few studies have addressed this subject to date. Balto et al. [73] tested the accuracy and precision of different fitness trackers and activity-related applications during locomotion bouts consisting of 500 steps on a motor-driven treadmill in persons with MS. The study demonstrated that fitness trackers in general were accurate in assessing steps taken during the locomotion bouts. Measurement error rates were as low as 1.9% (Fitbit One) and as high as 14.2% (Moves Progeo Oy) for the 500-step walks. This is comparable with the accuracy and precision of pedometers and accelerometers in this population [9,10,42].

Another study examined the accuracy of steps measured by the Fitbit and ActiGraph GT3X during a 2-minute period of over-ground walking in persons with MS, and verified an ICC of 0.69 between Fitbit and manually counted steps [74]. By comparison, the ICC between steps recorded by the ActiGraph and counted manually was 0.76 [74]. When used over 7-days of continuous monitoring (i.e., free-living physical activity), the ICC between Fitbit and ActiGraph-recorded steps was 0.76 [74]. Overall, these results suggest that the Fitbit is moderately accurate in measuring steps in persons with MS. Another important finding of that study was that after 4 weeks, participants had used the Fitbit for 97% of the days, indicating high compliance with using the device [74]. Compliance has been a concern in large-scale studies outside of MS, as a substantial proportion of participants fail to meet the minimum wear-time (e.g., 10h/day) for a representative measurement of daily physical activity [1].

Multisensors have been of interest in MS, given that these devices could improve the accuracy of physical activity estimates over other motion sensors. Multisensor devices incorporate multiple sensors for measuring different motion, physiological, and environmental variables, including body acceleration, temperature, heart rate, respiratory ventilation, and luminosity, as examples [30,75,76]. The SenseWear Armband (SWA), which has been discontinued, is one of the most commonly used multisensor in physical activity research. The SWA includes accelerometry and measures of heat flux, galvanic skin response, and skin temperature. While having multiple sensors, there is indication that the SWA produces significant measurement errors for steps in MS, which might be of similar or greater magnitude than spring-levered pedometers and accelerometers, as indicated by the study from Coote et al. [77] That study reported that the SWA underestimated manually counted steps by 23.2% for persons with MS who used at most a stick to walk and by 29.4% for those needing bilateral support [77]; this may be caused by the placement on the upper arm rather than near the center of mass. Percentage errors for METs estimation were of smaller magnitude, but still concerning. Compared with measures from a portable metabolic system (i.e., Oxycon Mobile), the SWA overestimated METs by 15.4% for individuals using at most a stick to walk and 6.6% for those needing bilateral support [77]. For reliably estimating physical activity in MS using the SWA, a study by Norris et al. [78] provides

indication that at least 2 and 4 days of monitoring are required for reliable estimates of steps and energy expenditure in fully ambulatory persons with MS.

Other research efforts have recently examined psychometric properties of other types of accelerometers. Two of these devices were the BioStamp RC and the MTx inertial sensor. The research demonstrated remarkably low measurement errors (i.e., high accuracy) for capturing actual steps taken compared with estimates from an ActiGraph GT3X during a 6-minute walk on a motorized treadmill in persons with MS (i.e., 0.8% and 0.9%, respectively, vs. 10.1%) [79]. One potential explanation for the superiority of the BioStampRC and MTx relative to the GT3X might involve the positioning of the BioStampRC and MTx inertial sensor on the shanks of the leg, as this allows for assessment of temporal gait parameters such as stride time, swing time, and step time. That study further permitted placement of the hands on hand rails during the 6-minute walk, and this would minimize displacement of the center of mass and influence the accuracy of the ActiGraph worn around the waist, but not the BioStampRC and MTx. Future studies might examine the validity and reliability of these devices in persons with MS during free-living conditions as well as across the disability spectrum.

4. CONCLUSION

A body of research in the past 20 years examined the psychometric properties and applications of motion sensors in MS. The studies provided indication on the validity and reliability of these devices for measuring physical activity in MS. In addition, specific methods for classifying physical activity intensity in MS based on accelerometer and pedometer output (e.g., accelerometer and step-rate cut-points) were developed and are currently ready for use in large-scale studies. More recently, evidence on applications of motion sensors for measuring sedentary behavior and its associations with health outcomes as well as research on fitness trackers and multisensors in MS has emerged, indicating major potential for future research. Taken together, the past 20 years of research have paved the path for the next 5 years and beyond. New research in the upcoming years can substantially advance our understanding of motion sensors for measuring physical activity and sedentary behavior in MS.

5. EXPERT COMMENTARY

We have witnessed a growth in the body of literature regarding the validity and reliability of motion sensors as well as the development of methods to process accelerometry and pedometry data in MS. Yet, the advances that were made are still modest compared to those in the general population. Several key-points on the use of motion sensors in MS will need to be more adequately addressed in future. One of the most important aspects that researchers need to consider when using motion sensors in MS is the disability spectrum of this condition, as mobility directly relates to the level of disability. In addition, features and symptoms of the disease, such as relapsing episodes and fatigue, likely affect device reliability due to more unstable physical activity and sedentary behavior patterns. Consequently, longer periods of monitoring may be necessary for capturing the habitual patterns of these behaviors. This entails further examinations using robust methodology to

better understand the ideal strategies for valid and reliable assessment of physical activity and sedentary behavior in MS.

A multitude of promising applications of activity monitoring in MS is in the horizon. In the next section, we have identified those opportunities that are of major importance for allowing advances in associational and intervention studies.

6. FIVE-YEAR VIEW: WHAT IS NEXT?

We envision the next 5 years representing an opportunity for significant advancement in the application of motions sensors for measuring physical activity in MS and perhaps beyond into other conditions with neurological origins that influence mobility. One area of research involves examining the accuracy of consumer-based devices and applications, and developing cut-points for these devices, across the disability and disease spectrum of MS, including older adults with MS. There is an ever-expanding option of consumer-based devices and applications that are becoming attractive and acceptable for application in MS [73], yet there are limited data on the accuracy of these devices and the meaning of the output. The accuracy of the devices has obvious implications for adoption in clinical research and practice, but has further implications for persons with MS who use a device or application in daily life for behavior monitoring and change. Regarding the meaning of the output, there is clear understanding of common output such as steps per unit time, but the classification of this information into a biologically meaningful metric requires calibration with measures of energy expenditure such as calorimetry. We further require focal efforts on metrics regarding sitting time and sedentary behavior from these devices, and the applicability of these devices across the spectrum of disease type, duration, and severity in MS.

Another area of future research involves comparisons and extensions of research conducted in MS into other disease conditions that influence mobility, including stroke and Parkinson's. That is, there is considerable information available on the accuracy, validity, and reliability of motion sensors in MS, but much less is known about such applications in other diseases and conditions. This is important for understanding the invariance of measurement properties across disease conditions, as this will enable comparability and greater efficiency in developing a body of knowledge that is generalizable across diseases. Indeed, if we develop an understanding of device accuracy across populations with differing etiologies of mobility disability, then we can make direct comparisons of outcomes regarding physical activity and sedentary behavior, as well as begin developing programs and interventions that cut across these conditions. The invariance of devices and comparability of output will be essential for moving the field forward in a manner that crosses diseases and conditions.

The third opportunity for future research involves motion sensor-based systems for monitoring physical activity as a metric of disease activity and/or comorbidity risk/profile. That is, there is evidence that physical activity levels based on steps/day and/or accelerometer counts overall or minutes/day of MVPA decline as MS progresses as a disease [56]. Steps/day from motion sensors further have captured the effect of and recovery from a

relapse in persons with MS [80,81]. This suggests that the output from motion sensors may have clinical utility in MS for monitoring disease progression and activity. Indeed, there has been recent interest in applying motion sensors such as Fitbit for monitoring MS and its manifestations. What is missing is a smart system for ongoing monitoring of the data from a person with MS that can be used as an alarm or early detection system for identifying disease progression and activity. Such a system must be able to record such data in the context of everyday life in a manner that is socially and personally acceptable, and does not provide behavioral reactivity. To that end, motion sensors might play a major role in the provision of a smart system for monitoring MS disease and progression over time, and thereby improve the clinical management of the disease.

We further envision opportunities for using wearable motion sensors to assess patterns of sedentary behavior in MS. There have been studies in the general population examining the impact of different sedentary behavior characteristics (e.g., total time in sedentary behavior, breaks in sedentary time, average length of sedentary bout) on health outcomes [82]. Much less is known on how patterns of sedentary behavior affect health outcomes in MS [54]. Another avenue for application of motion sensors in MS is the examination of potential health benefits of interrupting sedentary time and replacing it with light or moderate physical activity [63,83]. Motion sensors can be used to objectively quantify these changes and provide more accurate dose-response relationships of sedentary behavior and physical activity with health and functional outcomes in MS.

Another important area of future research involves the development of systems for delivery and monitoring of behavioral interventions in MS and other diseases and conditions. This is particularly noteworthy considering a recent review whereby there was a call for better-designed and informed mobile platforms for exercise interventions in persons with mobility disability [84]. That is, we need to develop systems that include motion sensors for mobile sensing, feedback, and data wrangling/analysis to improve rehabilitation for individuals with conditions that restrict mobility. This will permit greater reach of our lifestyle interventions for producing meaningful, life-altering benefits of physical activity and exercise interventions in MS and beyond.

Acknowledgments

Funding

Jeffer E Sasaki was supported by a mentor-based fellowship from the National Multiple Sclerosis Society (MB0011). This paper was further supported by a grant from National Institutes of Health (P2CHD086851)

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* of interest

** of considerable interest

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7.

KEY-ISSUES:

- Spring-levered pedometers are valid in MS for counting steps at normal and fast walking speeds, but not for slow walking speeds. For the latter, piezoelectric pedometers appear to be more appropriate.
- There was indication of the validity of the ActiGraph 7164 activity monitor for assessment of physical activity and perhaps mobility in persons with MS. However, we identified a lack of studies examining the influence of disability level and motion sensor type on the reliability of physical activity measures in MS.
- A fundamental advance in the use of ActiGraph activity monitors in MS was the development of MS-specific cut-points and step-rate cut-points.
- In the most recent years, researchers have examined the accuracy of fitness trackers. These devices may be used as self-monitoring tools in physical activity interventions.
- There are opportunities for further examination regarding the validity of consumer-based activity monitoring and applications in MS. Substantial potential was also identified for developing systems and platforms for delivering and monitoring physical activity interventions.