Title page

Scholarly Review

A review of the accuracy and utility of motion sensors to measure physical activity of frail older hospitalised patients.

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Abstract

The purpose of this review was to examine the utility and accuracy of commercially-available motion sensors to measure step-count and time-spent-upright in frail older hospitalised patients. A database search (CINAHL and PubMed, 2004-2014) and a further hand search of papers' references yielded 24 validation studies meeting the inclusion criteria. Fifteen motion sensors (eight pedometers, six accelerometers and one sensor systems) have been tested in older adults. Only three have been tested in hospital patients; two of which detected postures and postural changes accurately but none estimated step-count accurately. Only one motion sensor remained accurate at speeds typical of frail older hospitalised patients but has yet to be tested in this cohort. Time-spent-upright can be accurately measured in the hospital, but further validation studies are required to determine which, if any, motion sensor can accurately measure step-count.

Keywords: Aged, frail, hospitalised, physical activity, step count, postures and postural changes

In the United States, the United Kingdom and the Republic of Ireland, patients aged 65 years and over occupy most acute hospital beds and account for the longest length of stay (30 days or more) (Department of Health in Ireland, 2013; Imison, Poteliakoff, & Thompson, 2012; Steiner, Andrews, Barrett, & Weiss, 2013). Frailty, described as a geriatric syndrome with reduced capacity of the individual to resist stress (Fried et al., 2001) includes characteristics of slow mobility, low physical activity (PA) and energy levels (Boyd, Xue, Simpson, Guralnik, & Fried, 2005). Acute illness, medical treatments such as intravenous or oxygen therapy, and the hospital environment can reduce or prevent mobility (Broderick, Savage, McCullagh, Bantry-White, & Timmons, 2013). Low PA in older hospitalised patients has been associated with functional decline, prolonged length of stay and higher re-admission rates (Boyd et al., 2008, Brown, Friedkin, & Inouye, 2004), and walking-aid-users on admission are the least active in hospital (Fisher et al., 2012). However, exercise programmes have shown positive benefits in frail patients (De Morton et al., 2007; McCullagh et al., 2014), and may help preserve independence and quality of life when discharged home (Brovold, Skelton, Sylliaas, Mowe, & Bergland, 2014).

PA is a complex, multidimensional behaviour (Rennie & Wareham, 1998) defined as bodily movement produced by skeletal muscles, requiring energy expenditure (Caspersen, Powell, & Christenson, 1985). Both patients and staff have been found to incorrectly overestimate PA (Cheung, Salih, Crouch, Karunanithi, & Gray, 2012). Accurate and precise measurement of PA in frail older patients could help to motivate them to increase activity (Hunt, McCann, Gray, Mutrie, & Wyke, 2013; Mutrie et al., 2012) and measure recovery of functional activity (Fisher et al., 2011). Self-reported measures of PA are feasible and cost-efficient, but also time-consuming and possibly invalid with the high prevalence of delirium in this group (Ryan et al., 2013), while by-proxy reports burdens staff and carers. Direct observation may be possible for research, but it is costly and inefficient for clinical purposes. Therefore, motion sensors would appear to have a role in hospital care. But motion sensors can be time-consuming to attach to the patient (Smith, Galea, Woodward, Said, & Dorevitch, 2008), or may need to be removed for showering, or to check for skin irritation, or their outputs may not be clinically relevant. The sensor must be precise, accurate and feasible for clinical use.

Many large public health studies have successfully used motion sensors in community-dwellers (Healy et al., 2008; Kearney, Harrington, Mc Carthy, Fitzgerald, & Perry, 2013). Pedometers are readily affordable, easy to apply, and their unit of measurement (step-count) can be interpreted easily. They detect the vertical displacement of the person’s hip during the gait cycle, thus counting each step. But, steps are not time-stamped, and may be falsely counted during incidental leg movements (Tudor-Locke et al., 2006). Most importantly, studies have found undercounting of slow, short steps (Grant, Dall, Mitchell, & Granat, 2008; Ryan, Grant, Tigbe, & Granat, 2006; Shephard & Aoyagi, 2010, Tyo et al., 2011), the most prevalent gait pattern in frail older inpatients (Taraldsen et al., 2011).

Accelerometers measure body movement in terms of acceleration and are worn at the waist, wrist, ankle or thigh. Outputs include proprietary activity counts, step counts, inclination indicators or raw acceleration data. Activity counts are dimensionless, non-interpretable units which are converted into PA intensity levels and/or energy expenditure (EE). PA intensity is categorised as sedentary, light, moderate and vigorous (Ainsworth et al., 2011). Older inpatients spend most time in sedentary or light PA, and as thresholds between these levels are difficult to discriminate (Bauman et al., 2011; Kozey, Lyden, Howe, Staudenmayer, & Freedson, 2010), the subtle but highly important change from sitting (sedentary) to standing and walking (light) can be missed. The alternative conversion is to

EE, which requires Resting Metabolic Rate (RMR) to be determined. The use of a single RMR value for all individuals has become an acceptable practice (McMurray, Soares, Caspersen, & McCurdy, 2013). However, RMR can vary greatly in the oldest-older adults, especially with frailty and chronic illness (Weiss, Cappola, Varadhan, & Fried, 2012), acute infection and altered dietary intake in hospitals (Hall, Howe, Rana, Martin, & Morey, 2013), indicating that EE is not an acceptable option. Alternatively, step-count and postures and postural changes are clinically meaningful measurements indicating progression to functional independence. Time-stamped recordings can indicate the duration of patients' activity and functional fitness.

Motion sensors have undergone testing in older community-dwellers, but testing is limited in frail older inpatients. Older inpatients stand and walk less (Smith et al., 2008) and walk slower than older community-dwellers (0.46 m/sec and 1.27 m/sec respectively) (Smith et al., 2008; Taraldsen et al., 2011). Furthermore, many are walking-aid-users, reducing walking speed to less than 0.41m/sec (Weiss, Seplaki, Wolff, Kasper, & Agree, 2008), emphasising the need for validation studies and appraisal of motion sensors in this population.

This review study was conducted to identify those sensors which had either been validated or showed most promise for use in frail older hospitalised patients. We reviewed the limited literature on the step-count and posture and postural changes detection accuracy of commercially-available motion sensors and we discuss their application and utility. Accelerometers can be expensive, making validation and clinical studies costly. Therefore, researchers need to justify their choice of sensors. This paper provides a comprehensive summary of published validation studies which may help clinicians and researchers to select the best device for their area of interest.

Methods

Database Search

Validation or accuracy reports of step-count or posture and postural changes in the older adult population were specifically of interest. Due to the anticipated small number of studies, a review was conducted to assess all studies found in the review process, irrespective of the size/quality of the study. A search of PubMed, Cumulative Index to Nursing and Allied Health Literature (CINAHL) was conducted using relevant keywords including aged, frail, elderly, measurement of physical activity, accelerometers, pedometers and motion sensors. All validation or accuracy studies which included a group of patients aged 65 and over were included. Outputs such as physical activity classification, falls or upper limb validation were excluded. Full details of the search strategy are given in Appendix A, and Figure 1 illustrates the literature search process. The titles and abstracts were screened by RMcC. Following further searches performed through review of article citations, and removal of duplicates, 24 articles were found which validated the measurement of step-count and accurate detection of body postures and postural changes in the target population. The data was independently extracted by two assessors (RMcC, NB) and discrepancies were resolved by a third independent reviewer (ST). We focused our data extraction and report on the following measurements: study size, age, medical condition, walking speed and study setting, task duration and complexity, use of walking aids, criterion measurement and accuracy and applicability of the motion sensors (see Table 1).

Findings

Twenty four studies were included in the review, many of which validated more than one motion sensor. In total, six pedometers, eight accelerometers and one shoe-based sensor were validated in an older adult sample, with ages ranging between 56 and 88 years. Sixteen were laboratory trials, four were free-living trials and four were mixed. Seven studies used direct observation as the criterion measurement, eleven used video-recording and four used other validated measurement tools. Eight studies were conducted in the United States, four in the Netherlands, three in Canada, two in New Zealand and Brazil, and one in Australia, Scotland, Norway, Belgium and Switzerland.

Although the accuracy of many devices have been tested on community-dwelling adults, only three studies included hospitalised patients (Brown, Roth, & Allman, 2008; Carroll et al., 2012; Taraldsen et al., 2011), (n=47, n=50 and n=38, respectively), and two included long-term care patients (Cyarto, Myers, & Tudor-Locke, 2004; Taylor 2014), (n=28 and n=22, respectively). Sixteen studies validated step-count accuracy, six validated postures and postural change detection and two validated both step-count and postures and postural changes.

Pedometer Validation Studies

Eight studies, validating eight pedometers were included. Studies included a stroke inpatient group (Carroll et al., 2012, n=50), a long-term care resident group (Cyarto et al., 2004, n=52), and the remaining studies included community-dwellers. The accuracy of the Omron HJ113-E (Carroll et al., 2012, n=50), Omron HJ-720ITC (Dondzila, Swartz, Miller, Lenz, & Strath, 2012; Jehn et al., 2010), (n=49 and n=97 respectively), Yamax DW-200 (Cyarto et al., 2004, n=52), Yamax SW-200 (Dijkstra, Zijlstra, Scherder, & Kamsma, 2008; Vanroy et al., 2014; Webber, Magill, Schafer, & Wilson, 2014) (n=52, n=30 and n=35, respectively), Yamax PW610 (Sant'Anna et al., 2012, n=30), Kenz Lifecorder (Dondzila et al., 2012, n=49), Digiwalker SW701 (Furlanetto et al., 2010, n=60) and SC Step MX (Webber et al., 2014, n=35) were tested. Each study used its own definition of accuracy such as percentage error, significant differences in percentage error or Pearson correlation. Therefore, each study's own definition has been used to report accuracy. Results showed that the Omron HJ-720ITC was accurate at speeds greater than 0.64m/sec (Jehn et al., 2010) and the SC Step MX was also accurate at speeds of 0.8 m/sec (Webber et al., 2014). The remaining pedometers were less accurate at these slow speeds. The Omron HJ113-E generally did not detect any steps at speeds less than 0.5/sec, all three Yamax pedometers, (the DW-200, the SW-200 and the PW 610) were less accurate at walking speeds less than 1.0 m/sec (Cyarto et al., 2004; Dijkstra et al., 2008; Webber et al., 2014). Interestingly, Vanroy et al. (2014) found the step-count of SW200 correlated well with video recorded steps in stroke patients (n=15) if worn at the knee. When stroke patients walked as slowly as 0.42m/sec, it remained moderately accurate (r=0.69). This is the only study we found which tested any device's accuracy when knee-worn. Finally, the Digiwalker SW701 and the Kenz Lifecorder lost accuracy below walking speeds of 1.33 m/sec (Dondzila et al., 2012; Furlanetto et al., 2010). Therefore, although the Omron HJ-720ITC, the Yamax SW200 a the knee and the SC Step MX were not tested in older hospitalised patients, it appears that these pedometers show the most accuracy at walking speeds less than or equal to 0.8 m/sec, the typical speed of a walking-aid-user (Webber et al., 2014) and thus, they show promise for hospital use.

Accelerometer Validation Studies

The remaining 15 studies validated accelerometers. Two studies included medical hospitalised patients (Brown et al., 2008; Taraldsen et al., 2011), (n=38 and n=47 respectively), one included patients in long-term residential care (Taylor et al., 2014, n=22), while the remainder included community-dwellers.

Accurate posture and position changes detection. Six accelerometers' ability to detect postures and positions was tested: the AugmenTec, (Brown et al., 2008, n=47); the DynaPort (Langer et al., 2009, n=20); the DynaPort Minimod (Dijkstra, Kamsma, & Zijlstra, 2010; Langer et al., 2009), (n=37 and n=20, respectively); the DynaPort MoveMonitor (Fokkenrood et al., 2014; Taylor et al., 2014), (n=27 and n=22, respectively); the SmartShoe (Fulk et al., 2012, n=12); the Activity Monitor (VitaPort 3) (White, Wagenaar, & Ellis, 2006, n=11) and the ActivPAL (Taraldsen et al., 2011, n=38).

The AugmenTec and the ActivPAL have been tested in older medical hospitalised patients. The AugmenTec uses a sensor at the ankle and thigh, and was tested using direct observation as the criterion measurement. Results showed that the levels of agreement between AugmenTec and the direct observation of lying, sitting, standing/walking were excellent (median κ=0.92) (Brown et al., 2008). The ActivPAL, worn on the thigh, uses an in-built inclinometer to detect upright positions. Its accuracy was compared to video-recordings in older medical patients and community-dwellers with a hip fracture that had occurred three months previously (Taraldsen et al., 2011). The ActivPAL showed near perfect accuracy in detecting lying/sitting and standing/walking.

The remaining four accelerometers were tested in community-dwellers. The SmartShoe system uses an accelerometer which is clipped onto the side of the shoe, and five force sensitive resistors embedded in a flexible insole. It was validated in a small group (n=12) of community-dwellers with chronic stroke. Results showed that it detected sitting, standing, walking with over 95% accurate identification of all postures, and measured step-count with less than one step error (Fulk et al., 2012). The results indicate excellent accuracy, however this study size was small, and the SmartShoe requires a small cut at the back of the shoe (for the device to be attached), and hospital patients frequently alternate between shoes and slippers, limiting its feasibility.

The Activity Monitor (VitaPort 3) was validated in community-dwellers with Parkinson's Disease (PD) (White et al., 2006). Using video recordings as the criterion measurement, the patients completed tasks in both a fixed and random order. Results showed good correlations between the Activity Monitor and the video, but showed less accuracy for tasks lasting less than five seconds. The system uses three sensors attached at both thighs and the sternum and is not waterproof, which would affect compliance in the hospital setting.

Three DynaPort motion sensors were tested in community-dwellers with chronic obstructive pulmonary disease (COPD) (Langer et al., 2009), peripheral arterial disease (PAD) (Fokkenrood et al., 2014), Parkinson's disease (PD) (Dijkstra et al., 2010) and long-term care octogenarians (Taylor et al., 2014). These sensors are worn at the base of the spine, between the iliac crests. The DynaPort and DynaPort Minimod were tested in COPD patients in an outpatient setting and video recordings were used as the criterion measurement. No patient used a walking-aid and the average walking speed was 0.8m/sec. Results showed that both the DynaPort and DynaPort Minimod were 97% accurate in detecting postures and postural changes in COPD patients (Langer et al., 2009). The DynaPort MoveMonitor showed poorer accuracy when tested in patients with PAD (Fokkenrood et al., 2014) and in octogenarians. Its detection of standing was poor in patients with PAD (Intraclass Correlation Coefficient, ICC 46%) (Fokkenrood et al., 2014), and in octogenarians (24.7% error) (Taylor et al., 2014). Interestingly, it accurately detected sitting in patients with PAD (ICC>97%) (Fokkenrood et al., 2014), but not in octogenarians (22.3% error) (Taylor et al., 2014). The reason for this is unclear but suggests that the important postural change from sitting to standing may not be recorded accurately, especially in a frail older group. It is not possible to compare results across different patient groups but in general, the AugmenTec and ActivPAL accurately detected postures and postural changes in hospitalised patients, and the SmartShoe, DynaPort and DynaPort Minimod were accurate for community-dwellers. But the DynaPort MoveMonitor neither accurately detected sitting (in community-dwellers or long-term care residents), nor standing (in long-term care residents). Therefore, the SmartShoe and DynaPort Minimod have proven accuracy in community-dwellers and show promise for hospitalised patients, but the DynaPort MoveMonitor may not be sufficiently accurate for this group.

Accurate step-count measurement. Fourteen studies measured the step-count accuracy of accelerometers (Barreira, Brouillette, Foil, Keller, & Tudor-Locke, 2013; Ng, Jenkins, & Hill, 2012; Dijkstra, Zijlstra, Scherder, & Kamsma, 2008; Fulk et al., 2012; Furlanetto et al., 2010; Langer et al., 2009; Manns & Haennel, 2013; Moy, Garshick, Matthess, Lew, & Reilly, 2008; Mudge, Stott, & Walt, 2007; Schmidt, Pennypacker, Thrush, Leiper, & Craik, 2011; Taraldsen et al., 2011; Vanroy et al., 2014; Webber et al., 2014; Wendland & Sprigle, 2012) in an older adult sample.

Using the default filter (DF), the Actigraph GT3X+ was found to undercount steps of older adult community-dwellers (Storti et al., 2008). Therefore, a low-frequency-extension (LFX) filter option was introduced, specifically designed to detect low force movements and slower walking speeds. Step-count accuracy of the DF and the LFX filter were compared to the research standard pedometer NL-1000 in 15 older community-dwellers for seven days (Barreira et al., 2013). The absolute percentage difference between the DF and pedometer measurements was 16%. The LFX filter estimated almost double the number of actual steps not only during low-intensity movements, but also during high-intensity movements. The authors concluded that step-count measured by GT3X+ using the DF and the LFX filter cannot be compared accurately to the pedometer (Barreira et al., 2013). Another study using video footage as the gold standard, found that the absolute percentage error of the GT3X+ varied between 6.7% and 7.6% for non-walking-aid users (n=13) and between 51% and 52% for walking-aid-users in healthy older community-dwellers (Webber et al., 2014) (n=22). Walking-aid-users walked considerably slower at 0.8m/sec compared to non-walking-aid-users at 1.2m/sec. While these studies are relatively small, their results are similar, questioning the usefulness of the Actigraph GT3X+ in frail older hospital patients.

The ActiHealth accelerometer is attached to the shoe and its accuracy has been tested in community-dwelling men with COPD (n=46) and healthy older males (n=15). Results showed that it detected steps well with 86% accuracy in the COPD group, but its accuracy deteriorated at walking speeds less than 0.9 m/sec.

The step-count accuracy of the Dynaport Minimod (Langer et al., 2009, n=10) and the Dynaport Micromod (Dijkstra et al., 2008, n=32) have been tested for community-dwellers with COPD (Langer et al., 2009) and with PD (Dijkstra et al., 2008). Both studied the step-count accuracy for short walks of 30 and 15 metres respectively in a hospital laboratory setting. No participant used a walking frame. The step-count of only one participant, who walked slower than the others (0.7m/sec versus 0.8m/sec) was underestimated (Langer et al., 2009). These results do not validate their use for frail or hospitalised patients; the participants walked faster and none of them used a walking aid.

Only two studies have tested the accuracy of ActivPAL’s step-count; one for community-dwellers with COPD (Ng et al., 2012, n=20), the other for older hospitalised patients (Taraldsen et al., 2011, n=38). Both studies compared step-count to direct observation or video footage and were conducted in hospital settings (outpatients and inpatients). Results showed an undercount of steps with slower walkers. For COPD patients, ActivPAL's ability to detect steps reduced with slower speeds: it underestimated an average of four steps per minute when walking at a speed of 0.76 m/sec, compared to an average of seven steps per minute when walking at a speed of 0.56 m/sec. Similarly, Taralden et al. (2011) also found that older hospitalised patients' walking speed was slow at an average speed of 0.46m/sec. They found that the ActivPAL's accuracy lessened with walking speeds less than 0.47m/sec, with an absolute percentage error of 40.3% for slower walkers and of 29.1% for faster walkers.

The SenseWear Armband (SWA) has been found to accurately measure energy expenditure in older community-dwellers, but not step-count (Furlanetto et al., 2010; Langer et al., 2009; Manns & Vanroy, 2012). The studies compared its recorded step-count to video recordings for community-dwellers with COPD (Furlanetto et al., 2010; Langer et al., 2009; n=43, n=10, respectively) and in patients with stroke (Manns & Haennel, 2012; Vanroy et al., 2014), (n=12, n=15 respectively). Most of these studies were small but all indicate inaccurate step-count measurement. The SWA underestimated step-count by an average of 42% and 50% (Langer et al., 2009). Results were similar in stroke patients with the ICC<0.35 (Manns & Haennel, 2012), and ICC >0.6 (Vanroy et al., 2014). This error occurred at any walking speed, but was especially apparent for walking speeds less than 0.62m/sec (Manns & Haennel, 2012). The authors gave the plausible explanation that the SWA is worn on the arm as opposed to other devices at the hip or leg, potentially making it less sensitive to steps (Furlanetto et al., 2010).

The accuracy of the Stepwatch Activity Monitor (SAM) has been measured for patients with COPD (Ng et al., 2012, n=20), chronic stroke (Mudge et al., 2007, n=25), older adults using a cane (Wendland & Sprigle, 2012, n=16), and PD and Multiple Sclerosis (MS) (Schmidt et al., 2011, n=20). Overall, it appears that its accuracy is not affected by walking speed. All participants were community-dwellers. Ng et al. (2012) found its step-count accuracy for patients with COPD to be within two steps per minute and this was not affected by either slow walking speed or the use of a walking frame. Mudge et al. (2007) measured its accuracy against direct observation and three-dimensional gait analysis in patients with chronic stroke. The median walking speed of the participants was 0.50 m/sec. Attaching the SAM to the non-paretic ankle, they reported a -1.1% error, but this error increased to -4.9% when worn on the paretic limb. The SAM's accuracy has been measured in cane-users when attached to the participants' leg, attached to their cane, and over different surfaces such as grass, pavement, stairs and carpet. Although walking speed was not reported, self-selected walking speed using a cane has been previously reported as 0.41 m/sec (95% CI 0.38-0.44) (Weiss et al., 2008). When the SAM was attached to the participants' leg, overall accuracy was reported at 93.4%, with poorest accuracy on stair-climbing at 85.9%. Accuracy deteriorated over all surfaces when attached to the cane, with the average accuracy at 84.7% (Wendland & Sprigle, 2012). Schmidt et al. (2011) found very strong correlations (r>0.99) between step-count and strides measured by the GaitMat II for older patients with PD and MS (n=20); however the study size was small and the patients' walking speed was not reported. Therefore, while some of these studies were small, it appears that the SAM's accuracy is unaffected by walking speed or walking-aid use, and therefore, shows promise for frail older patients.

Discussion

There were three main findings from this review. Firstly, postures and postural changes can be measured accurately for older adults in all settings. Secondly, although step-count has been measured accurately for older community-dwellers, it has not been accurately measured for frail older adults in hospital or institutional care. Step-count accuracy of many motion sensors deteriorates when walking speeds reduce to approximately 1.0 to 0.8 m/sec (Cyarto et al., 2004; Dijkstra et al., 2008; Furlanetto et al., 2010; Moy et al., 2008; Sant'Anna et al., 2012; Webber et al., 2014), which is considerably faster than the typical speed of hospitalised, frail older adults (0.5m/sec, Taraldsen et al., 2011). This suggests that many motion sensors are invalid for step-count measurement in frail hospitalised patients. Thirdly, the SAM appears to be the only motion sensor that accurately measures step-count for slow walkers, but it has yet to be validated for frail older hospitalised patients.

Postures and postural changes can be accurately measured in frail older medical patients by the AugmenTec and the ActivPAL. The DynaPort and the DynaPort Minimod showed good accuracy in community-dwellers with COPD, but they have not been tested in frail patients. The results from the DynaPort MoveMonitor are inconclusive. Its detection of sitting and standing appears poor, especially in the older-old. The SmartShoe shows excellent accuracy in a small community-based study, but its feasibility for hospital use is limited. Accurate objective measurements of time spent in standing/walking have been used in studies (Fisher et al., 2011; Pedersen et al., 2012; Smith et al., 2008). While this information characterises the duration and patterns of activity, step-count would be a better indication of the patients' activity level and physical recovery.

The review found that most accelerometers tested for older adults accurately detected steps in community-dwellers but this accuracy deteriorated when walking was slower than 0.5m/sec (Ng et al., 2012; Taraldsen et al., 2011; Webber et al., 2014). The only step-count accuracy study using frail older hospitalised patients (Taraldsen et al., 2011), found that the ActivPal did not measure step-count accurately. Although the SWA has been found accurate in measuring energy expenditure, it did not measure step-count accurately at any walking speed (Furlanetto et al., 2010; Langer et al., 2009). Alternatively, there is strong evidence that the SAM appears the most sensitive for slower walkers (Mudge et al., 2007; Ng et al., 2012) and for cane-users (Wendland & Sprigle, 2012). One reason for the considerable difference might be related to their position on the body. While the SWA is worn on the arm, the Stepwatch Activity Monitor (SAM) is attached to the ankle. This may affect their sensitivity to the trajectories of the foot while stepping. It may also explain its loss of accuracy when cane-mounted or when worn on the paretic limb. Another reason may be that the SAM must be calibrated specifically to each participant; the patient's height and walking pattern are required to set its sensitivity before use, thus potentially improving accuracy.

Older patients tend to be inactive in hospital and institutional care settings (Cyarto et al., 2004; Fisher et al., 2011). There are many reasons for this inactivity, such as lack of encouragement to exercise and lack of knowledge of hospital layout (Fisher et al., 2012). Increasing physical activity levels in hospital may help preserve independence and quality of life in this vulnerable group (Brovold et al., 2014). Time-stamped step-count would provide a meaningful measurement of activity. Furthermore, it would inform clinicians, nurses and therapists of the progression of recovery - whether each patient is able to remain active for longer bursts over time and the daily patterns - whether patients need more encouragement during periods of prolonged rest. Physical performance and ability is fundamental to regaining independence, planning for discharge home and improving quality of life. Future research should aim to identify an accurate, precise and feasible motion sensor in frail older patients.

Limitations

This review was limited to the last ten years and to the English language. Hand searching was limited to citations from retrieved articles and did not include conference proceedings. We did not contact experts or ask for unpublished work which may have allowed reporting bias and selective outcome reporting to influence our findings. Therefore, some research in this field may have been missed. However, we did contact the manufacturers of two accelerometers (SAM; Orthocare Innovations and ActivPal and ActivPal3; PalTechnologies) and one pedometer (Piezo StepMV; StepCount) to check whether they were aware of any other relevant studies.

Conclusion

This review provides a comprehensive summary of the published validation studies of motion sensors in older adults. The DynaPort, DynaPort Minimod and the Smartshoe, have shown accurate detection of postures and postural changes in community-dwellers but have not been validated for use in frail hospitalised patients. The AugmenTec and ActivPAL, have been shown to detect postures and postural changes in older hospitalised patients, but not step-count.

Eleven motion sensors showed good step-count accuracy in older community-dwellers walking at speeds greater than approximately 1.0m/sec (Actigraph GT3X+, ActivHealth, ActivPAL, Digiwalker SW710, DynaPort Micromod, DynaPort Minimod, Omron, SAM, SmartShoe, Yamax PW610 and Yamax SW200). However, to date, no motion sensor has shown step-count accuracy in frail hospitalised patients. Step-count accuracy appears to depend greatly on walking speed. Many of these patients walk slower than 0.5m/sec, the speed at which arm, waist and thigh mounted accelerometers appear to lose their accuracy. Three pedometers, the Omron HJ-720ITC, the SC Step MX and the Yamax SW200 (worn at the knee) have been found accurate in older adults who walk slower than 0.8 m/sec. Their relative in-expense justifies a validation study of their accuracy in the hospital setting and may provide a cheap alternative to accelerometers. The SAM also showed promise as it does not appear to be affected by walking speed, and patients' PA is time-stamped, allowing PA pattern examination. However, this also has to be tested in the hospital setting.

To conclude, postures and postural changes can be accurately measured in frail older hospitalised patients. A motion sensor to measure time-stamped step-count has yet to be identified for this cohort. This activity information would inform clinicians of physical recovery from illness and patients' ability to progress their rehabilitation and retain independence at home. Therefore, further validation studies of accelerometers and pedometers which accurately estimate steps of slower, older community-dwellers should be completed in frail hospitalised patients.

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Figure 1: Flow diagram of the review process

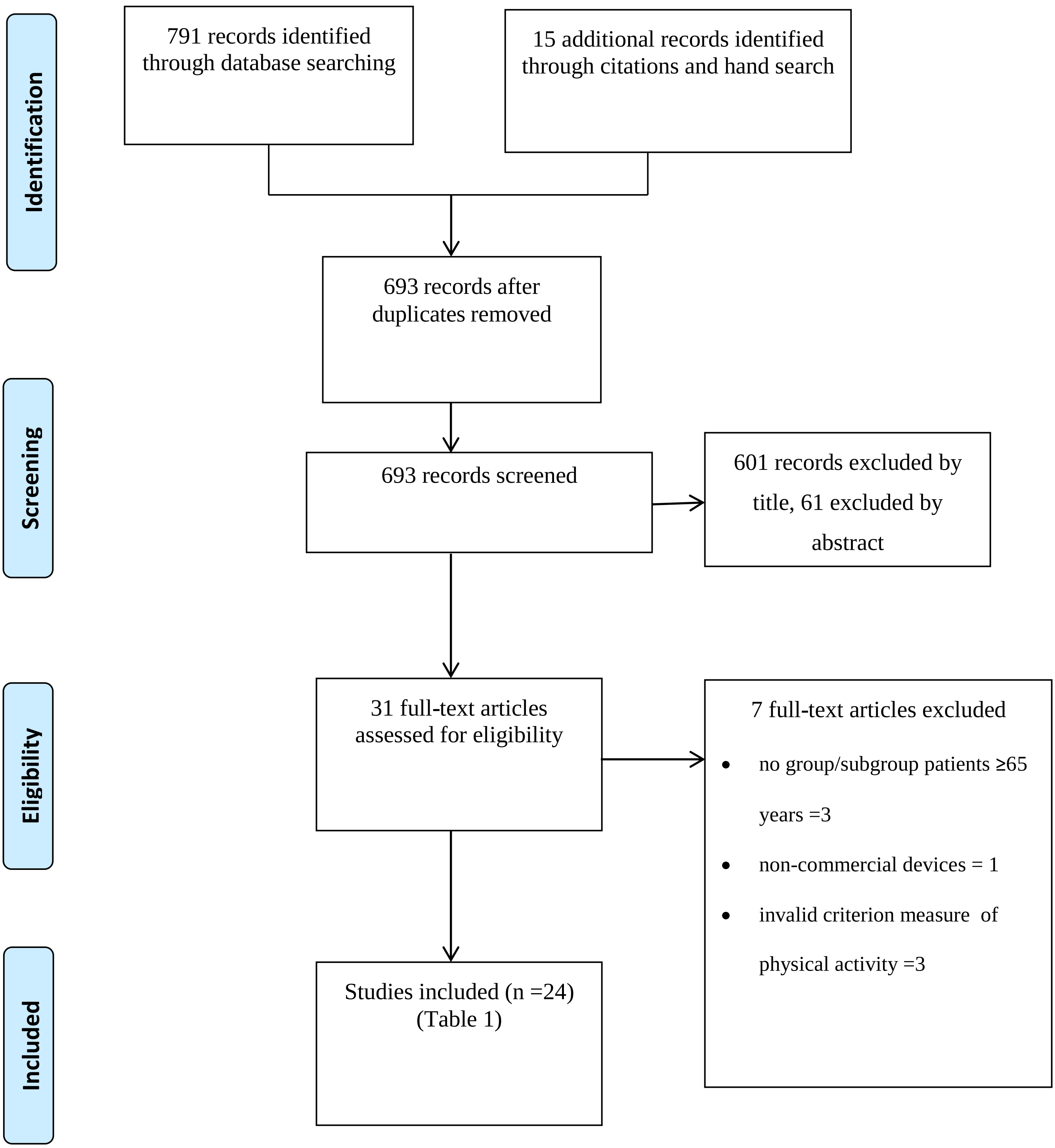

Table 1: Studies included in the review (all reported walking speeds have been converted to metres per second (m/sec))

Authors **Condition, Dwelling (sample size), Age**	**Physical Activity Observed** **Criterion Measurement**	**Devices** **(Outputs)**	**Results**
Barreira et al. (2013) Healthy CD (n=15) Men: 73±9 years Women: 67±4 years	Free-living activity (7 days) NL-1000 pedometer (research standard)	ActiGraph GT3X+ accelerometer • default filter, (DF) • light filter (LFX) **(step-count)**	DF: -7.4% error (769 steps/day) LFX: 121.9% error (8140 steps/day)
Brown et al. (2008) Medical IP (n=47) male	lying, sitting, standing/walking	AugmenTec wireless monitor	Concordance (median κ=0.92) between posture classification and observation

73±6.5 years	Direct observation	**(posture classification)**	Standing/walking, sitting, lying (r>0.90) Unable to detect walking periods
Carroll et al. (2012) Stroke IP (n=50) 72.4 ±12.3 years	6MWT and short walk Video recordings	Pedometer × 3 (Omron HJ113-E) 1 around neck & 1 at each hip **(step-count)**	20% could not use pedometers without assistance. Steps virtually undetected at w/s <0.5m/sec Steps undercounted at w/s >0.5m/sec
Cyarto et al. (2004) Healthy CD (n=28) 70.6±5.5 years NHR (n=26) 79.4±8.2 years	Various self-paced walks (13m) Direct observation	Yamax pedometer (DW 200) **(step-count)**	Healthy: -25% error (0.95m/sec) to -7% error (1.61m/sec) NHR: error -74% error (0.42m/sec) to -46% (0.8m/sec)
Dijkstra et al. (2008)	Various self-paced walks;	DynaPort Micromod	DynaPort: -7.4% error in healthy adults; -

Healthy CD (n=20) 68.5±7.4 years PD CD (n=32) 67.3±6.6 years Excl. pts using w/aids	various distances; while doing secondary tasks. Video recordings	**(step-count)** Yamax (SW-200) pedometer **(step-count)**	6.9% error in PD Yamax: -6.8% error in healthy adults; -11.1% error in PD. Accuracy decreased with trajectories <5m.
Dijkstra et al. (2010) PD CD (n=32); (n=5) 67.3±6.6 years; 76±3 years	ADLs in movement lab (n=32); at home (n=5) Video recordings	DynaPort Minimod accelerometer **(posture classification, step-count)**	Lying and walking most accurately detected (81.7% to 99.9%). Poor accuracy for slow or shuffled walking Short periods of sitting hard to identify
Dondzila et al. (2012) Healthy CD (n=49) 65.4±6.9 years	Treadmill walk (0.9-1.8m/sec) Overground various self-	Omron pedometer (OM) **(step-count)** Kenz Lifecorder EX (LC)	OM: mean error step-count, -12.4 to 4.5 LC: mean error step-count -64.5 to -3.2 Both OM and LC increasingly accurate as

	paced walks Direct observation	pedometer **(step-count)**	walking speed increased
Fokkenrood et al. (2014) Peripheral Arterial Disease CD (n=27) 67±10 years	Free living hospital visit Video recordings	DynaPort MoveMonitor **(posture classification, step-count)**	Gait speed not reported Accurate for lying, sitting, walking (all >90%); moderate for standing (46%); shuffling virtually undetectable (18%)
Fulk et al. (2012) Chronic stroke CD (n=12) 62.1±8.2 years	Sitting, standing, walking and step-count Video recordings	SmartShoe – shoe based sensor system **(posture classification and step-count)**	>95% accuracy for sitting, standing, walking Step-count mean difference <1
Furlanetto et al. (2010) COPD CD (n=30) 67±8 years	Treadmill walking at various set speeds Video recordings	Digiwalker SW701 (pedometer) **(step-count)**	High speed (1.33±0.2m/sec): pedometer accurately measured step-count; poor step-count accuracy with multisensor

Healthy CD (n=30) 68±7 years		SenseWear Armband (multisensor) **(step-count)**	Slow speeds (0.3±0.1m/sec & 0.8±0.1,/sec): multisensor & pedometer underestimated step-count
Jehn et al. (2011) Chronic heart failure CD (n=97) 60.7±13.4 years	Free and treadmill walk (40-80 m/min) (n=10) 6MWT (n=97) Direct observation	Omron HJ-720ITC **(step-count)**	Speeds <0.64m/sec, significant % error Self-paced 6MWT, significant % error at distances <400 m.
Langer et al. (2009) COPD CD (n=10) 65±8 years Healthy CD (n=10) 65±9 years	Sitting, standing, walking. Video recordings	DynaPort, DynaPort Minimod & Sensewear Pro Armband (SWA) **(step-count, posture classification)**	Minimod: mean step-count accuracy (-43 steps); less accurate for slow walker (<0.7 m/sec) SWA: mean step-count accuracy (-486 steps) 97% of postures accurately detected by

			DynaPort and DynaPort Minimod
Manns & Haennel (2012) Stroke CD (n=12) 64.2±10.4	6MWT × 2 over 25m StepWatch Activity Monitor (SAM)	SenseWear Pro (SWA) armband **(step-count)**	SWA and SAM step-count agreement poor (ICC<0.35); particularly at speeds less than 0.62m/sec.
Moy et al (2008) Healthy CD males (n=15) 56±12 years COPD CD males (n=46) 71±9 years	Walk 244m at self-selected speed Direct observation	ActiHealth accelerometer **(step-count)**	Healthy: step-count accuracy 98% COPD: step-count accuracy 86% Accuracy decreased at speeds less than 0.98m/sec
Mudge et al. (2007) Physical disability post stroke CD (n=25)	8m indoor walk; outdoor walk over various surfaces 3D Gait Analysis (gait lab) and footswitches (outdoor	SAM **(step-count)**	Step-count accuracy 95% % error increased when attached to the paretic limb; indoors (-2.6% vs -7.3%), outdoors (-1.3% vs -4.2%)

Med 69 years	walks)		
Ng et al. (2012) COPD CD (n=20) 73±9 years	4 walks (5 mins) with and without rollator Direct observation	Stepwatch Activity Monitor (SAM) **(step-count)** ActivPAL **(step-count)**	SAM: Mdiff 2 steps/min; unaffected by speed or aid use. ActivPAL: Mdiff 7 steps/min; worsened with slower walking <0.56m/sec; unaffected by aid use.
Sant'Anna et al. (2012) COPD CD (n=30) 67±7 years	Walk × 2 (slow, fast) Circuits × 3 (set tasks) Video recordings	Yamax Power Walker (PW) (610) (pedometer combined accelerometry) **(step-count)**	Correlations of step-count: slow walking (1.05m/sec; r=0.79); fast walking (1.3m/sec; r=0.95)
Schmidt et al. (2011) PD CD (n=11)	Self-selected walks over GaitMat II	SAM **(step-count)**	Correlation: PD (r=1.0), MS (r=0.99)

66.8 years MS CD (n=9) 55.9 years	GaitMat II		
Taraldsen et al. (2011) Medical IP (n=38) 79.7±7.3 years	Set tasks (20-60mins) Video recordings	ActivPAL **(posture classification and step-count)**	100% accuracy in classifying postures. -40.31% error in walkers <0.47m/sec
Taylor et al. (2014) Octogenarians RVR (n=22) 88.1±5 years	Set tasks (4-6mins) Free movement (5-9mins) Video recordings	DynaPort MoveMonitor (accelerometer) **(posture classification)**	Med error <1% for lying and walking, sitting (med 22.3%), standing (med 24.7%) Agreement of duration >85% for all except standing (med 56.1%)
Vanroy et al. (2014) Stroke CD (n=15)	Set tasks (3-4mins) Direct observation	SenseWear Pro2 (SWP2A) Armband (both arms)	Even surface: Yamax (knee): correlation for healthy and stroke (r≥0.89)

60.4±10.26 years Healthy CD (n=15) 58.07±10.37	Video recordings	**(step-count)** Yamax Digi-Walker SW200 pedometer (hip and knee) **(step-count)**	Treadmill: Yamax (knee): correlation for healthy (r≥0.90), stroke (speed 0.42m/sec, r=0.69) Yamax underestimated steps for other activities, reliability (0.66-0.98) SWP2A poor correlation (-0.78 to 0.6)
Webber et al. (2014) Healthy CD (n=35) Walking aid (n=13) No walking aid (n=22) 81.5±5 years	Self-paced walk (100m) Direct observation	Yamax SW200 pedometer ActiGraph GT3X+ accelerometer SC-Step MX pedometer **(step-count)**	No difference in step-count accuracy in independent walkers: w/s 1.21±0.2m/sec (% error 0.8 to 2.6) Significant difference in step-count accuracy in w/aid users: w/s 0.8±0.2m/sec (% error 1.0 to 68.9): the SC-Step MX most accurate
Wendland et al. (2012)	Indoor and outdoor walks;	StepWatch Activity	Accuracy 93.4% on all surfaces (leg

Older CD with cane (n=16) 75.6	various surfaces Direct observation	Monitor (SAM) (leg and cane mounted) **(step- and cane-count)**	mounted) Accurate 84.7% on all surfaces (cane mounted) Stairs least accurate
White et al. (2006) Parkinson's Disease CD (n=11) 66.1±9.1 years	Set and random order tasks Video recordings	Activity Monitor (AM) (VitaPort 3) **(posture classification)**	Correlations AM ranged from r=0.63 to r=0.98 AM reports longer durations Kappa low for durations <5secs

Legend **w/aid(s)**: walking aid(s), **m**: metres, **m/sec:** metres per second, **w/s**: walking speed, **6MWT:** 6 minute walk test, **Mdiff:** Mean difference, **ICC**: Intraclass correlation coefficient, **med**: median, **IQR**: interquartile range, **% error**: percentage error, **PD**: Parkinson's Disease, **MS**: Multiple Sclerosis **COPD:** chronic obstructive airways disease, **PAD:** peripheral arterial disease, **CD:** Community-dwellers, **RVR:** Retirement village resident, **IP:** inpatient, **NHR:** Nursing home resident