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Title page

Scholarly Review

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

**Ruth McCullagh ¹, Noeleen M. Brady ¹, Christina Dillon ², N. Frances Horgan ³, Suzanne
Timmons ¹**

¹Centre for Gerontology & Rehabilitation, University College Cork, Ireland

²Dept of Epidemiology and Public Health, University College Cork, Ireland

³School of Physiotherapy, Royal College of Surgeons, Dublin, Ireland.

Corresponding Author: Ruth McCullagh. Centre for Gerontology & Rehabilitation, University
College Cork, Ireland
Tel: 00-353-86-8241280
email: r.mccullagh@ucc.ie

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A review of the accuracy and utility of motion sensors to measure physical

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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

1 In the United States, the United Kingdom and the Republic of Ireland, patients aged
2 65 years and over occupy most acute hospital beds and account for the longest length of stay
3 (30 days or more) (Department of Health in Ireland, 2013; Imison, Poteliakoff, & Thompson,
4 2012; Steiner, Andrews, Barrett, & Weiss, 2013). Frailty, described as a geriatric syndrome
5 with reduced capacity of the individual to resist stress (Fried et al., 2001) includes
6 characteristics of slow mobility, low physical activity (PA) and energy levels (Boyd, Xue,
7 Simpson, Guralnik, & Fried, 2005). Acute illness, medical treatments such as intravenous or
8 oxygen therapy, and the hospital environment can reduce or prevent mobility (Broderick,
9 Savage, McCullagh, Bantry-White, & Timmons, 2013). Low PA in older hospitalised
10 patients has been associated with functional decline, prolonged length of stay and higher re-
11 admission rates (Boyd et al., 2008, Brown, Friedkin, & Inouye, 2004), and walking-aid-users
12 on admission are the least active in hospital (Fisher et al., 2012). However, exercise
13 programmes have shown positive benefits in frail patients (De Morton et al., 2007;
14 McCullagh et al., 2014), and may help preserve independence and quality of life when
15 discharged home (Brovold, Skelton, Sylliaas, Mowe, & Bergland, 2014).

16 PA is a complex, multidimensional behaviour (Rennie & Wareham, 1998) defined as
17 bodily movement produced by skeletal muscles, requiring energy expenditure (Caspersen,
18 Powell, & Christenson, 1985). Both patients and staff have been found to incorrectly
19 overestimate PA (Cheung, Salih, Crouch, Karunanithi, & Gray, 2012). Accurate and precise
20 measurement of PA in frail older patients could help to motivate them to increase activity
21 (Hunt, McCann, Gray, Mutrie, & Wyke, 2013; Mutrie et al., 2012) and measure recovery of
22 functional activity (Fisher et al., 2011). Self-reported measures of PA are feasible and cost-
23 efficient, but also time-consuming and possibly invalid with the high prevalence of delirium
24 in this group (Ryan et al., 2013), while by-proxy reports burdens staff and carers. Direct

1 observation may be possible for research, but it is costly and inefficient for clinical purposes.
2 Therefore, motion sensors would appear to have a role in hospital care. But motion sensors
3 can be time-consuming to attach to the patient (Smith, Galea, Woodward, Said, & Dorevitch,
4 2008), or may need to be removed for showering, or to check for skin irritation, or their
5 outputs may not be clinically relevant. The sensor must be precise, accurate and feasible for
6 clinical use.

7 Many large public health studies have successfully used motion sensors in
8 community-dwellers (Healy et al., 2008; Kearney, Harrington, Mc Carthy, Fitzgerald, &
9 Perry, 2013). Pedometers are readily affordable, easy to apply, and their unit of measurement
10 (step-count) can be interpreted easily. They detect the vertical displacement of the person's
11 hip during the gait cycle, thus counting each step. But, steps are not time-stamped, and may
12 be falsely counted during incidental leg movements (Tudor-Locke et al., 2006). Most
13 importantly, studies have found undercounting of slow, short steps (Grant, Dall, Mitchell, &
14 Granat, 2008; Ryan, Grant, Tigbe, & Granat, 2006; Shephard & Aoyagi, 2010, Tyo et al.,
15 2011), the most prevalent gait pattern in frail older inpatients (Taraldsen et al., 2011).

16 Accelerometers measure body movement in terms of acceleration and are worn at the
17 waist, wrist, ankle or thigh. Outputs include proprietary activity counts, step counts,
18 inclination indicators or raw acceleration data. Activity counts are dimensionless, non-
19 interpretable units which are converted into PA intensity levels and/or energy expenditure
20 (EE). PA intensity is categorised as sedentary, light, moderate and vigorous (Ainsworth et al.,
21 2011). Older inpatients spend most time in sedentary or light PA, and as thresholds between
22 these levels are difficult to discriminate (Bauman et al., 2011; Kozey, Lyden, Howe,
23 Staudenmayer, & Freedson, 2010), the subtle but highly important change from sitting
24 (sedentary) to standing and walking (light) can be missed. The alternative conversion is to

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

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

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

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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

1 were validated in an older adult sample, with ages ranging between 56 and 88 years. Sixteen
2 were laboratory trials, four were free-living trials and four were mixed. Seven studies used
3 direct observation as the criterion measurement, eleven used video-recording and four used
4 other validated measurement tools. Eight studies were conducted in the United States, four in
5 the Netherlands, three in Canada, two in New Zealand and Brazil, and one in Australia,
6 Scotland, Norway, Belgium and Switzerland.

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

14 **Pedometer Validation Studies**

15 Eight studies, validating eight pedometers were included. Studies included a stroke
16 inpatient group (Carroll et al., 2012, n=50), a long-term care resident group (Cyarto et al.,
17 2004, n=52), and the remaining studies included community-dwellers. The accuracy of the
18 Omron HJ113-E (Carroll et al., 2012, n=50), Omron HJ-720ITC (Dondzila, Swartz, Miller,
19 Lenz, & Strath, 2012; Jehn et al., 2010), (n=49 and n=97 respectively), Yamax DW-200
20 (Cyarto et al., 2004, n=52), Yamax SW-200 (Dijkstra, Zijlstra, Scherder, & Kamsma, 2008;
21 Vanroy et al., 2014; Webber, Magill, Schafer, & Wilson, 2014) (n=52, n=30 and n=35,
22 respectively), Yamax PW610 (Sant'Anna et al., 2012, n=30), Kenz Lifecorder (Dondzila et
23 al., 2012, n=49), Digiwalker SW701 (Furlanetto et al., 2010, n=60) and SC Step MX
24 (Webber et al., 2014, n=35) were tested. Each study used its own definition of accuracy such

1 as percentage error, significant differences in percentage error or Pearson correlation.
2 Therefore, each study's own definition has been used to report accuracy. Results showed that
3 the Omron HJ-720ITC was accurate at speeds greater than 0.64m/sec (Jehn et al., 2010) and
4 the SC Step MX was also accurate at speeds of 0.8 m/sec (Webber et al., 2014). The
5 remaining pedometers were less accurate at these slow speeds. The Omron HJ113-E
6 generally did not detect any steps at speeds less than 0.5/sec, all three Yamax pedometers,
7 (the DW-200, the SW-200 and the PW 610) were less accurate at walking speeds less than
8 1.0 m/sec (Cyarto et al., 2004; Dijkstra et al., 2008; Webber et al., 2014). Interestingly,
9 Vanroy et al. (2014) found the step-count of SW200 correlated well with video recorded
10 steps in stroke patients (n=15) if worn at the knee. When stroke patients walked as slowly as
11 0.42m/sec, it remained moderately accurate (r=0.69). This is the only study we found which
12 tested any device's accuracy when knee-worn. Finally, the Digiwalker SW701 and the Kenz
13 Lifecorder lost accuracy below walking speeds of 1.33 m/sec (Dondzila et al., 2012;
14 Furlanetto et al., 2010). Therefore, although the Omron HJ-720ITC, the Yamax SW200 a the
15 knee and the SC Step MX were not tested in older hospitalised patients, it appears that these
16 pedometers show the most accuracy at walking speeds less than or equal to 0.8 m/sec, the
17 typical speed of a walking-aid-user (Webber et al., 2014) and thus, they show promise for
18 hospital use.

19 **Accelerometer Validation Studies**

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

1 **Accurate posture and position changes detection.** Six accelerometers' ability to
2 detect postures and positions was tested: the AugmenTec, (Brown et al., 2008, n=47); the
3 DynaPort (Langer et al., 2009, n=20); the DynaPort Minimod (Dijkstra, Kamsma, & Zijlstra,
4 2010; Langer et al., 2009), (n=37 and n=20, respectively); the DynaPort MoveMonitor
5 (Fokkenrood et al., 2014; Taylor et al., 2014), (n=27 and n=22, respectively); the SmartShoe
6 (Fulk et al., 2012, n=12); the Activity Monitor (VitaPort 3) (White, Wagenaar, & Ellis, 2006,
7 n=11) and the ActivPAL (Taraldsen et al., 2011, n=38).

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

17 The remaining four accelerometers were tested in community-dwellers. The
18 SmartShoe system uses an accelerometer which is clipped onto the side of the shoe, and five
19 force sensitive resistors embedded in a flexible insole. It was validated in a small group
20 (n=12) of community-dwellers with chronic stroke. Results showed that it detected sitting,
21 standing, walking with over 95% accurate identification of all postures, and measured step-
22 count with less than one step error (Fulk et al., 2012). The results indicate excellent accuracy,
23 however this study size was small, and the SmartShoe requires a small cut at the back of the

1 shoe (for the device to be attached), and hospital patients frequently alternate between shoes
2 and slippers, limiting its feasibility.

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

9 Three DynaPort motion sensors were tested in community-dwellers with chronic
10 obstructive pulmonary disease (COPD) (Langer et al., 2009), peripheral arterial disease
11 (PAD) (Fokkenrood et al., 2014), Parkinson's disease (PD) (Dijkstra et al., 2010) and long-
12 term care octogenarians (Taylor et al., 2014). These sensors are worn at the base of the spine,
13 between the iliac crests. The DynaPort and DynaPort Minimod were tested in COPD patients
14 in an outpatient setting and video recordings were used as the criterion measurement. No
15 patient used a walking-aid and the average walking speed was 0.8m/sec. Results showed that
16 both the DynaPort and DynaPort Minimod were 97% accurate in detecting postures and
17 postural changes in COPD patients (Langer et al., 2009). The DynaPort MoveMonitor
18 showed poorer accuracy when tested in patients with PAD (Fokkenrood et al., 2014) and in
19 octogenarians. Its detection of standing was poor in patients with PAD (Intraclass
20 Correlation Coefficient, ICC 46%) (Fokkenrood et al., 2014), and in octogenarians (24.7%
21 error) (Taylor et al., 2014). Interestingly, it accurately detected sitting in patients with PAD
22 (ICC>97%) (Fokkenrood et al., 2014), but not in octogenarians (22.3% error) (Taylor et al.,
23 2014). The reason for this is unclear but suggests that the important postural change from
24 sitting to standing may not be recorded accurately, especially in a frail older group. It is not

1 possible to compare results across different patient groups but in general, the AugmenTec and
2 ActivPAL accurately detected postures and postural changes in hospitalised patients, and the
3 SmartShoe, DynaPort and DynaPort Minimod were accurate for community-dwellers. But the
4 DynaPort MoveMonitor neither accurately detected sitting (in community-dwellers or long-
5 term care residents), nor standing (in long-term care residents). Therefore, the SmartShoe and
6 DynaPort Minimod have proven accuracy in community-dwellers and show promise for
7 hospitalised patients, but the DynaPort MoveMonitor may not be sufficiently accurate for this
8 group.

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

16 Using the default filter (DF), the Actigraph GT3X+ was found to undercount steps of
17 older adult community-dwellers (Storti et al., 2008). Therefore, a low-frequency-extension
18 (LFX) filter option was introduced, specifically designed to detect low force movements and
19 slower walking speeds. Step-count accuracy of the DF and the LFX filter were compared to
20 the research standard pedometer NL-1000 in 15 older community-dwellers for seven days
21 (Barreira et al., 2013). The absolute percentage difference between the DF and pedometer
22 measurements was 16%. The LFX filter estimated almost double the number of actual steps
23 not only during low-intensity movements, but also during high-intensity movements. The
24 authors concluded that step-count measured by GT3X+ using the DF and the LFX filter

1 cannot be compared accurately to the pedometer (Barreira et al., 2013). Another study using
2 video footage as the gold standard, found that the absolute percentage error of the GT3X+
3 varied between 6.7% and 7.6% for non-walking-aid users (n=13) and between 51% and 52%
4 for walking-aid-users in healthy older community-dwellers (Webber et al., 2014) (n=22).
5 Walking-aid-users walked considerably slower at 0.8m/sec compared to non-walking-aid-
6 users at 1.2m/sec. While these studies are relatively small, their results are similar,
7 questioning the usefulness of the Actigraph GT3X+ in frail older hospital patients.

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

12 The step-count accuracy of the Dynaport Minimod (Langer et al., 2009, n=10) and the
13 Dynaport Micromod (Dijkstra et al., 2008, n=32) have been tested for community-dwellers
14 with COPD (Langer et al., 2009) and with PD (Dijkstra et al., 2008). Both studied the step-
15 count accuracy for short walks of 30 and 15 metres respectively in a hospital laboratory
16 setting. No participant used a walking frame. The step-count of only one participant, who
17 walked slower than the others (0.7m/sec versus 0.8m/sec) was underestimated (Langer et al.,
18 2009). These results do not validate their use for frail or hospitalised patients; the
19 participants walked faster and none of them used a walking aid.

20 Only two studies have tested the accuracy of ActivPAL's step-count; one for
21 community-dwellers with COPD (Ng et al., 2012, n=20), the other for older hospitalised
22 patients (Taraldsen et al., 2011, n=38). Both studies compared step-count to direct
23 observation or video footage and were conducted in hospital settings (outpatients and
24 inpatients). Results showed an undercount of steps with slower walkers. For COPD patients,

1 ActivPAL's ability to detect steps reduced with slower speeds: it underestimated an average
2 of four steps per minute when walking at a speed of 0.76 m/sec, compared to an average of
3 seven steps per minute when walking at a speed of 0.56 m/sec. Similarly, Taralden et al.
4 (2011) also found that older hospitalised patients' walking speed was slow at an average
5 speed of 0.46m/sec. They found that the ActivPAL's accuracy lessened with walking speeds
6 less than 0.47m/sec, with an absolute percentage error of 40.3% for slower walkers and of
7 29.1% for faster walkers.

8 The SenseWear Armband (SWA) has been found to accurately measure energy
9 expenditure in older community-dwellers, but not step-count (Furlanetto et al., 2010; Langer
10 et al., 2009; Manns & Vanroy, 2012). The studies compared its recorded step-count to video
11 recordings for community-dwellers with COPD (Furlanetto et al., 2010; Langer et al., 2009;
12 n=43, n=10, respectively) and in patients with stroke (Manns & Haennel, 2012; Vanroy et al.,
13 2014), (n=12, n=15 respectively). Most of these studies were small but all indicate inaccurate
14 step-count measurement. The SWA underestimated step-count by an average of 42% and
15 50% (Langer et al., 2009). Results were similar in stroke patients with the ICC<0.35 (Manns
16 & Haennel, 2012), and ICC >0.6 (Vanroy et al., 2014). This error occurred at any walking
17 speed, but was especially apparent for walking speeds less than 0.62m/sec (Manns &
18 Haennel, 2012). The authors gave the plausible explanation that the SWA is worn on the arm
19 as opposed to other devices at the hip or leg, potentially making it less sensitive to steps
20 (Furlanetto et al., 2010).

21 The accuracy of the Stepwatch Activity Monitor (SAM) has been measured for
22 patients with COPD (Ng et al., 2012, n=20), chronic stroke (Mudge et al., 2007, n=25), older
23 adults using a cane (Wendland & Sprigle, 2012, n=16), and PD and Multiple Sclerosis (MS)
24 (Schmidt et al., 2011, n=20). Overall, it appears that its accuracy is not affected by walking

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

20 **Discussion**

21 There were three main findings from this review. Firstly, postures and postural
22 changes can be measured accurately for older adults in all settings. Secondly, although step-
23 count has been measured accurately for older community-dwellers, it has not been accurately
24 measured for frail older adults in hospital or institutional care. Step-count accuracy of many

1 motion sensors deteriorates when walking speeds reduce to approximately 1.0 to 0.8 m/sec
2 (Cyarto et al., 2004; Dijkstra et al., 2008; Furlanetto et al., 2010; Moy et al., 2008; Sant'Anna
3 et al., 2012; Webber et al., 2014), which is considerably faster than the typical speed of
4 hospitalised, frail older adults (0.5m/sec, Taraldsen et al., 2011). This suggests that many
5 motion sensors are invalid for step-count measurement in frail hospitalised patients. Thirdly,
6 the SAM appears to be the only motion sensor that accurately measures step-count for slow
7 walkers, but it has yet to be validated for frail older hospitalised patients.

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

18 The review found that most accelerometers tested for older adults accurately detected
19 steps in community-dwellers but this accuracy deteriorated when walking was slower than
20 0.5m/sec (Ng et al., 2012; Taraldsen et al., 2011; Webber et al., 2014). The only step-count
21 accuracy study using frail older hospitalised patients (Taraldsen et al., 2011), found that the
22 ActivPal did not measure step-count accurately. Although the SWA has been found accurate
23 in measuring energy expenditure, it did not measure step-count accurately at any walking
24 speed (Furlanetto et al., 2010; Langer et al., 2009). Alternatively, there is strong evidence that

1 the SAM appears the most sensitive for slower walkers (Mudge et al., 2007; Ng et al., 2012)
2 and for cane-users (Wendland & Sprigle, 2012). One reason for the considerable difference
3 might be related to their position on the body. While the SWA is worn on the arm, the
4 Stepwatch Activity Monitor (SAM) is attached to the ankle. This may affect their sensitivity
5 to the trajectories of the foot while stepping. It may also explain its loss of accuracy when
6 cane-mounted or when worn on the paretic limb. Another reason may be that the SAM must
7 be calibrated specifically to each participant; the patient's height and walking pattern are
8 required to set its sensitivity before use, thus potentially improving accuracy.

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

21 **Limitations**

22 This review was limited to the last ten years and to the English language. Hand
23 searching was limited to citations from retrieved articles and did not include conference
24 proceedings. We did not contact experts or ask for unpublished work which may have

1 allowed reporting bias and selective outcome reporting to influence our findings. Therefore,
2 some research in this field may have been missed. However, we did contact the
3 manufacturers of two accelerometers (SAM; Orthocare Innovations and ActivPal and
4 ActivPal3; PalTechnologies) and one pedometer (Piezo StepMV; StepCount) to check
5 whether they were aware of any other relevant studies.

6 **Conclusion**

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

13 Eleven motion sensors showed good step-count accuracy in older community-
14 dwellers walking at speeds greater than approximately 1.0m/sec (Actigraph GT3X+,
15 ActivHealth, ActivPAL, Digiwalker SW710, DynaPort Micromod, DynaPort Minimod,
16 Omron, SAM, SmartShoe, Yamax PW610 and Yamax SW200). However, to date, no motion
17 sensor has shown step-count accuracy in frail hospitalised patients. Step-count accuracy
18 appears to depend greatly on walking speed. Many of these patients walk slower than
19 0.5m/sec, the speed at which arm, waist and thigh mounted accelerometers appear to lose
20 their accuracy. Three pedometers, the Omron HJ-720ITC, the SC Step MX and the Yamax
21 SW200 (worn at the knee) have been found accurate in older adults who walk slower than 0.8
22 m/sec. Their relative in-expense justifies a validation study of their accuracy in the hospital
23 setting and may provide a cheap alternative to accelerometers. The SAM also showed
24 promise as it does not appear to be affected by walking speed, and patients' PA is time-

1 stamped, allowing PA pattern examination. However, this also has to be tested in the hospital
2 setting.

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

10 **Acknowledgements and Conflicts of Interest**

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15 xxxx deleted for blind review purposes.
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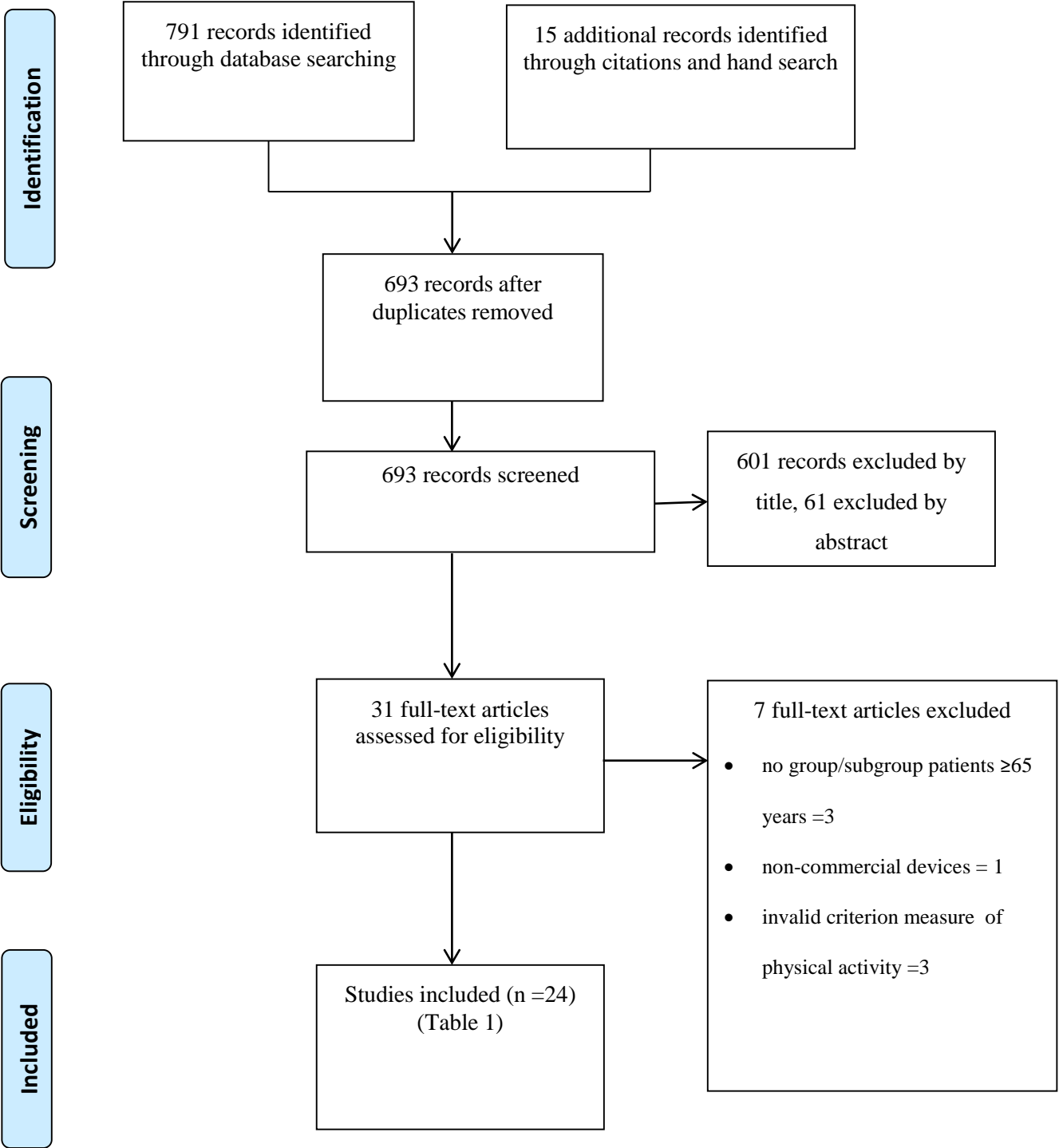
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Figure 1: Flow diagram of the review process

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

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Authors	Physical Activity	Devices	Results
Condition, Dwelling (sample size), Age	Observed Criterion Measurement	(Outputs)	
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 <ul style="list-style-type: none"> • 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 $\kappa=0.92$) between posture classification and observation

MOTION SENSORS FOR FRAIL OLDER HOSPITALISED PATIENTS

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

MOTION SENSORS FOR FRAIL OLDER HOSPITALISED PATIENTS

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

MOTION SENSORS FOR FRAIL OLDER HOSPITALISED PATIENTS

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

MOTION SENSORS FOR FRAIL OLDER HOSPITALISED PATIENTS

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

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DynaPort and DynaPort Minimod

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

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

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66.8 years

GaitMat II

MS CD (n=9)

55.9 years

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

MOTION SENSORS FOR FRAIL OLDER HOSPITALISED PATIENTS

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

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

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4
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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

