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Authors	McCullagh, Ruth;Brady, Noeleen M.;Dillon, Christina B.;Horgan, N. Frances;Timmons, Suzanne
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1	Title page
2	Scholarly Review
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5	physical activity of frail older hospitalised patients.
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7	Ruth McCullagh <sup>1</sup> , Noeleen M. Brady <sup>1</sup> , Christina Dillon <sup>2</sup> , N. Frances Horgan <sup>3</sup> , Suzanne
8	Timmons <sup>1</sup>
9	
10	<sup>1</sup> Centre for Gerontology & Rehabilitation, University College Cork, Ireland
11	<sup>2</sup> Dept of Epidemiology and Public Health, University College Cork, Ireland
12	<sup>3</sup> School of Physiotherapy, Royal College of Surgeons, Dublin, Ireland.
13	
14	Corresponding Author: Ruth McCullagh. Centre for Gerontology & Rehabilitation, University
15	College Cork, Ireland
16	Tel: 00-353-86-8241280
17	email: <u>r.mccullagh@ucc.ie</u>
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7	activity of frail older hospitalised patients.
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1	Abstract
2 3	The purpose of this review was to examine the utility and accuracy of commercially-
4	available motion sensors to measure step-count and time-spent-upright in frail older
5	hospitalised patients. A database search (CINAHL and PubMed, 2004-2014) and a further
6	hand search of papers' references yielded 24 validation studies meeting the inclusion criteria.
7	Fifteen motion sensors (eight pedometers, six accelerometers and one sensor systems) have
8	been tested in older adults. Only three have been tested in hospital patients; two of which
9	detected postures and postural changes accurately but none estimated step-count accurately.
10	Only one motion sensor remained accurate at speeds typical of frail older hospitalised
11	patients but has yet to be tested in this cohort. Time-spent-upright can be accurately measured
12	in the hospital, but further validation studies are required to determine which, if any, motion
13	sensor can accurately measure step-count.
14	Keywords: Aged, frail, hospitalised, physical activity, step count, postures and
15	postural changes
16 17 18	

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 (30 days or more) (Department of Health in Ireland, 2013; Imison, Poteliakoff, & Thompson, 3 4 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 5 6 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 7 oxygen therapy, and the hospital environment can reduce or prevent mobility (Broderick, 8 Savage, McCullagh, Bantry-White, & Timmons, 2013). Low PA in older hospitalised 9 patients has been associated with functional decline, prolonged length of stay and higher re-10 admission rates (Boyd et al., 2008, Brown, Friedkin, & Inouye, 2004), and walking-aid-users 11 12 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; 13 McCullagh et al., 2014), and may help preserve independence and quality of life when 14 discharged home (Brovold, Skelton, Sylliaas, Mowe, & Bergland, 2014). 15 PA is a complex, multidimensional behaviour (Rennie & Wareham, 1998) defined as 16 bodily movement produced by skeletal muscles, requiring energy expenditure (Caspersen, 17 Powell, & Christenson, 1985). Both patients and staff have been found to incorrectly 18 overestimate PA (Cheung, Salih, Crouch, Karunanithi, & Gray, 2012). Accurate and precise 19 20 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 21 functional activity (Fisher et al., 2011). Self-reported measures of PA are feasible and cost-22 efficient, but also time-consuming and possibly invalid with the high prevalence of delirium 23 in this group (Ryan et al., 2013), while by-proxy reports burdens staff and carers. Direct 24

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 7 community-dwellers (Healy et al., 2008; Kearney, Harrington, Mc Carthy, Fitzgerald, & 8 Perry, 2013). Pedometers are readily affordable, easy to apply, and their unit of measurement 9 (step-count) can be interpreted easily. They detect the vertical displacement of the person's 10 hip during the gait cycle, thus counting each step. But, steps are not time-stamped, and may 11 12 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, & 13 Granat, 2008; Ryan, Grant, Tigbe, & Granat, 2006; Shephard & Aoyagi, 2010, Tyo et al., 14 15 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 16 waist, wrist, ankle or thigh. Outputs include proprietary activity counts, step counts, 17 inclination indicators or raw acceleration data. Activity counts are dimensionless, non-18 interpretable units which are converted into PA intensity levels and/or energy expenditure 19 20 (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 21 these levels are difficult to discriminate (Bauman et al., 2011; Kozey, Lyden, Howe, 22 23 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 24

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, Caspersen, & McCurdy, 2013). However, RMR can vary greatly in the oldest-older adults, 3 especially with frailty and chronic illness (Weiss, Cappola, Varadhan, & Fried, 2012), acute 4 infection and altered dietary intake in hospitals (Hall, Howe, Rana, Martin, & Morey, 2013), 5 indicating that EE is not an acceptable option. Alternatively, step-count and postures and 6 postural changes are clinically meaningful measurements indicating progression to functional 7 independence. Time-stamped recordings can indicate the duration of patients' activity and 8 9 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 17 validated or showed most promise for use in frail older hospitalised patients. We reviewed 18 the limited literature on the step-count and posture and postural changes detection accuracy 19 20 of commercially-available motion sensors and we discuss their application and utility. Accelerometers can be expensive, making validation and clinical studies costly. Therefore, 21 researchers need to justify their choice of sensors. This paper provides a comprehensive 22 summary of published validation studies which may help clinicians and researchers to select 23 the best device for their area of interest. 24

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#### Methods

## Database Search

4 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 5 6 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 7 Health Literature (CINAHL) was conducted using relevant keywords including aged, frail, 8 9 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 10 included. Outputs such as physical activity classification, falls or upper limb validation were 11 12 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 13 further searches performed through review of article citations, and removal of duplicates, 24 14 articles were found which validated the measurement of step-count and accurate detection of 15 body postures and postural changes in the target population. The data was independently 16 extracted by two assessors (RMcC, NB) and discrepancies were resolved by a third 17 independent reviewer (ST). We focused our data extraction and report on the following 18 measurements: study size, age, medical condition, walking speed and study setting, task 19 20 duration and complexity, use of walking aids, criterion measurement and accuracy and applicability of the motion sensors (see Table 1). 21

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#### 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.

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#### Pedometer Validation Studies

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

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 remaining pedometers were less accurate at these slow speeds. The Omron HJ113-E 5 6 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 7 1.0 m/sec (Cyarto et al., 2004; Dijkstra et al., 2008; Webber et al., 2014). Interestingly, 8 9 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 10 0.42m/sec, it remained moderately accurate (r=0.69). This is the only study we found which 11 12 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; 13 Furlanetto et al., 2010). Therefore, although the Omron HJ-720ITC, the Yamax SW200 a the 14 15 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 16 typical speed of a walking-aid-user (Webber et al., 2014) and thus, they show promise for 17 hospital use. 18

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## 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),

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).

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

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 measurement, the patients completed tasks in both a fixed and random order. Results showed 5 6 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 7 the sternum and is not waterproof, which would affect compliance in the hospital setting. 8 9 Three DynaPort motion sensors were tested in community-dwellers with chronic obstructive pulmonary disease (COPD) (Langer et al., 2009), peripheral arterial disease 10 (PAD) (Fokkenrood et al., 2014), Parkinson's disease (PD) (Dijkstra et al., 2010) and long-11 12 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 13 in an outpatient setting and video recordings were used as the criterion measurement. No 14 patient used a walking-aid and the average walking speed was 0.8m/sec. Results showed that 15 both the DynaPort and DynaPort Minimod were 97% accurate in detecting postures and 16 postural changes in COPD patients (Langer et al., 2009). The DynaPort MoveMonitor 17 showed poorer accuracy when tested in patients with PAD (Fokkenrood et al., 2014) and in 18 octogenarians. Its detection of standing was poor in patients with PAD (Intraclass 19 20 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 21 (ICC>97%) (Fokkenrood et al., 2014), but not in octogenarians (22.3% error) (Taylor et al., 22 2014). The reason for this is unclear but suggests that the important postural change from 23 sitting to standing may not be recorded accurately, especially in a frail older group. It is not 24

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 longterm care residents), nor standing (in long-term care residents). Therefore, the SmartShoe and 5 6 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 7 8 group.

9 Accurate step-count measurement. Fourteen studies measured the step-count accuracy of accelerometers (Barreira, Brouillette, Foil, Keller, & Tudor-Locke, 2013; Ng, 10 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, Matthess, Lew, & Reilly, 2008; Mudge, Stott, & Walt, 2007; Schmidt, Pennypacker, Thrush, 13 Leiper, & Craik, 2011; Taraldsen et al., 2011; Vanroy et al., 2014; Webber et al., 2014; 14 15 Wendland & Sprigle, 2012) in an older adult sample. Using the default filter (DF), the Actigraph GT3X+ was found to undercount steps of 16 older adult community-dwellers (Storti et al., 2008). Therefore, a low-frequency-extension 17 (LFX) filter option was introduced, specifically designed to detect low force movements and 18 slower walking speeds. Step-count accuracy of the DF and the LFX filter were compared to 19 20 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 21 measurements was 16%. The LFX filter estimated almost double the number of actual steps 22 23 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 24

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,

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.

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 et al., 2009; Manns & Vanroy, 2012). The studies compared its recorded step-count to video 10 recordings for community-dwellers with COPD (Furlanetto et al., 2010; Langer et al., 2009; 11 12 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 13 step-count measurement. The SWA underestimated step-count by an average of 42% and 14 15 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 16 speed, but was especially apparent for walking speeds less than 0.62m/sec (Manns & 17 Haennel, 2012). The authors gave the plausible explanation that the SWA is worn on the arm 18 as opposed to other devices at the hip or leg, potentially making it less sensitive to steps 19 20 (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

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 chronic stroke. The median walking speed of the participants was 0.50 m/sec. Attaching the 5 SAM to the non-paretic ankle, they reported a -1.1% error, but this error increased to -4.9% 6 when worn on the paretic limb. The SAM's accuracy has been measured in cane-users when 7 attached to the participants' leg, attached to their cane, and over different surfaces such as 8 9 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) 10 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 deteriorated over all surfaces when attached to the cane, with the average accuracy at 84.7% 13 (Wendland & Sprigle, 2012). Schmidt et al. (2011) found very strong correlations (r>0.99) 14 15 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 16 reported. Therefore, while some of these studies were small, it appears that the SAM's 17 accuracy is unaffected by walking speed or walking-aid use, and therefore, shows promise for 18 frail older patients. 19

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#### 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 stepcount 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 8 patients by the AugmenTec and the ActivPAL. The DynaPort and the DynaPort Minimod 9 showed good accuracy in community-dwellers with COPD, but they have not been tested in 10 frail patients. The results from the DynaPort MoveMonitor are inconclusive. Its detection of 11 12 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. 13 Accurate objective measurements of time spent in standing/walking have been used in studies 14 15 (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 16 the patients' activity level and physical recovery. 17

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

1 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 2 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 to the trajectories of the foot while stepping. It may also explain its loss of accuracy when 5 6 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 7 required to set its sensitivity before use, thus potentially improving accuracy. 8

9 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 10 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 life in this vulnerable group (Brovold et al., 2014). Time-stamped step-count would provide a 13 meaningful measurement of activity. Furthermore, it would inform clinicians, nurses and 14 15 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 16 during periods of prolonged rest. Physical performance and ability is fundamental to 17 regaining independence, planning for discharge home and improving quality of life. Future 18 research should aim to identify an accurate, precise and feasible motion sensor in frail older 19 20 patients.

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## 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.

6

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

stamped, allowing PA pattern examination. However, this also has to be tested in the hospital
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
10 11	Acknowledgements and Conflicts of Interest This study was funded by a Health Research Board Research Fellowship Training
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1	References
2	Ainsworth, B. E., Haskell, W. L., Herrmann, S. D., Meckes, N., Bassett, D. R., Jr., Tudor-
3	Locke, C., Leon, A. S. (2011). 2011 Compendium of physical activities: A second
4	update of codes and MET values. Medicine & Science in Sports & Exercise, 43, 1575-
5	1581. doi: 10.1249/MSS.0b013e31821ece12
6	Barreira, T. V., Brouillette, R. M., Foil, H. C., Keller, J. N., & Tudor-Locke, C. (2013).
7	Comparison of older adults' steps per day using an NL-1000 pedometer and two
8	GT3X+ accelerometer filters. Journal of Aging and Physical Activity, 21, 402-416.
9	Bauman, A., Ainsworth, B. E., Sallis, J. F., Hagstromer, M., Craig, C. L., Bull, F. C., Grp,
10	I. (2011). The descriptive epidemiology of sitting a 20-country comparison using the
11	international physical activity questionnaire (IPAQ). American Journal of
12	Preventative Medicine, 41, 228-235. doi: DOI 10.1016/j.amepre.2011.05.003
13	Boyd, C. M., Landefeld, C. S., Counsell, S. R., Palmer, R. M., Fortinsky, R. H., Kresevic, D.,
14	Covinsky, K. E. (2008). Recovery of activities of daily living in older adults after
15	hospitalization for acute medical illness. Journal of the American Geriatric Society,
16	56, 2171-2179. doi: 10.1111/j.1532-5415.2008.02023.x
17	Boyd, C. M., Xue, Q. L., Simpson, C. F., Guralnik, J. M., & Fried, L. P. (2005). Frailty,
18	hospitalization, and progression of disability in a cohort of disabled older women. The
19	American Journal of Medicine, 118, 1225-1231. doi: 10.1016/j.amjmed.2005.01.062
20	Broderick, L., Savage, E., McCullagh, R., Bantry-White, E., & Timmons, S. (2013). Frail
21	older adults' perceptions of an in-hospital structured exercise intervention. Irish
22	Journal of Medical Science, 182, S224.
23	Brovold, T., Skelton, D. A., Sylliaas, H., Mowe, M., & Bergland, A. (2014). Association
24	between health-related quality of life, physical fitness, and physical activity in older

1	adults recently discharged from hospital. Journal of Aging and Physical Activity, 22,
2	405-413. doi: 10.1123/japa.2012-0315

- Brown, C. J., Friedkin, R. J., & Inouye, S. K. (2004). Prevalence and outcomes of low
  mobility in hospitalized older patients. *Journal of the American Geriatric Society*, *52*,
  1263-1270. doi: 10.1111/j.1532-5415.2004.52354.x
- Brown, C. J., Roth, D. L., & Allman, R. M. (2008). Validation of use of wireless monitors to
  measure levels of mobility during hospitalization. *Journal of Rehabilitation Research*& *Development*, 45, 551-558. doi: Doi 10.1682/Jrrd.2007.06.0086
- 9 Carroll, S. L., Greig, C. A., Lewis, S. J., McMurdo, M. E., Sniehotta, F. F., Johnston, M., ...
- 10 Mead, G. E. (2012). The use of pedometers in stroke survivors: Are they feasible and
- how well do they detect steps? *Archives of Physical Medicine & Rehabilitation*, *93*,
  466-470.
- Caspersen, C. J., Powell, K. E., & Christenson, G. M. (1985). Physical activity, exercise, and
   physical fitness: Definitions and distinctions for health-related research. *Public Health Reports*, *100*, 126-131.
- 16 Cheung, V. H., Salih, S. A., Crouch, A., Karunanithi, M. K., & Gray, L. (2012). Monitoring
- 17 ambulation of patients in geriatric rehabilitation wards: The accuracy of clinicians'
- 18 prediction of patients' walking time. *International Journal of Rehabilitation Research*,
- 19 *35*, 375-377. doi: 10.1097/MRR.0b013e32835a23e8
- Cyarto, E. V., Myers, A. M., & Tudor-Locke, C. (2004). Pedometer accuracy in nursing
   home and community-dwelling older adults. *Medicine & Science in Sports & Exercise*, 36, 205-209.
- 23 De Morton, N. A., Jones, C. T., Keating, J. L., Berlowitz, D. J., MacGregor, L., Lim, W. K., .
- 24 . . Brand, C. A. (2007). The effect of exercise on outcomes for hospitalised older

1	acute medical patients: An individual patient data meta-analysis. Age & Ageing, 36.
2	210 222 doi: 10 1002/accing/afl118
2	219-222. doi: 10.1093/ageing/aii118
3	Department of Health in Ireland. (2013). Department of Health. Health in Ireland. Key trends
4	2013. Retrieved 14.07.2014, 2014, from http://www.doh.ie
5	Dijkstra, B., Kamsma, Y. P., & Zijlstra, W. (2010). Detection of gait and postures using a
6	miniaturized triaxial accelerometer-based system: Accuracy in patients with mild to
7	moderate Parkinson's disease. Archives of Physical Medicine & Rehabilitation, 91,
8	1272-1277. doi: 10.1016/j.apmr.2010.05.004
9	Dijkstra, B., Zijlstra, W., Scherder, E., & Kamsma, Y. (2008). Detection of walking periods
10	and number of steps in older adults and patients with Parkinson's disease: Accuracy of
11	a pedometer and an accelerometry-based method. Age & Ageing, 37, 436-441. doi:
12	10.1093/ageing/afn097
13	Fisher, S. R., Goodwin, J. S., Protas, E. J., Kuo, Y. F., Graham, J. E., Ottenbacher, K. J., &
14	Ostir, G. V. (2011). Ambulatory activity of older adults hospitalized with acute
15	medical illness. Journal of the American Geriatric Society, 59, 91-95. doi:
16	10.1111/j.1532-5415.2010.03202.x
17	Fisher, S. R., Graham, J. E., Brown, C. J., Galloway, R. V., Ottenbacher, K. J., Allman, R.
18	M., & Ostir, G. V. (2012). Factors that differentiate level of ambulation in
19	hospitalised older adults. Age & Ageing, 41, 107-111. doi: 10.1093/ageing/afr110
20	Fokkenrood, H. J., Verhofstad, N., van den Houten, M. M., Lauret, G. J., Wittens, C.,
21	Scheltinga, M. R., & Teijink, J. A. (2014). Physical activity monitoring in patients
22	with peripheral arterial disease: Validation of an activity monitor. European Journal
23	of Vascular & Endovascular Surgery, 48, 194-200. doi: 10.1016/j.ejvs.2014.04.003

1	Fried, L. P., Tangen, C. M., Walston, J., Newman, A. B., Hirsch, C., Gottdiener, J.,
2	McBurnie, M. A. (2001). Frailty in older adults: Evidence for a phenotype. Journals
3	of Gerontology Series A: Biological Sciences & Medical Sciences, 56, M146-156.
4	Fulk, G. D., Edgar, S. R., Bierwirth, R., Hart, P., Lopez-Meyer, P., & Sazonov, E. (2012).
5	Identifying activity levels and steps of people with stroke using a novel shoe-based
6	sensor. Journal of Neurologic Physical Therapy, 36, 100-107. doi:
7	10.1097/NPT.0b013e318256370c
8	Furlanetto, K. C., Bisca, G. W., Oldemberg, N., Sant'anna, T. J., Morakami, F. K., Camillo,
9	C. A., Pitta, F. (2010). Step counting and energy expenditure estimation in
10	patients with chronic obstructive pulmonary disease and healthy elderly: Accuracy of
11	2 motion sensors. Archives of Physical Medicine & Rehabilitation, 91, 261-267. doi:
12	10.1016/j.apmr.2009.10.024
13	Grant, P. M., Dall, P. M., Mitchell, S. L., & Granat, M. H. (2008). Activity-monitor accuracy
14	in measuring step number and cadence in community-dwelling older adults. Journal
15	of Aging and Physical Activity, 16, 201-214.
16	Hall, K. S., Howe, C. A., Rana, S. R., Martin, C. L., & Morey, M. C. (2013). METs and
17	accelerometry of walking in older adults: standard versus measured energy cost.
18	Medicine & Science in Sports & Exercise, 45, 574-582. doi:
19	10.1249/MSS.0b013e318276c73c
20	Healy, G. N., Dunstan, D. W., Salmon, J., Cerin, E., Shaw, J. E., Zimmet, P. Z., & Owen, N.
21	(2008). Breaks in sedentary time: Beneficial associations with metabolic risk.
22	Diabetes Care, 31, 661-666. doi: 10.2337/dc07-2046
23	Hunt, K., McCann, C., Gray, C. M., Mutrie, N., & Wyke, S. (2013). "You've got to walk
24	before you run": Positive evaluations of a walking program as part of a gender-

1	sensitized, weight-management program delivered to men through professional
2	football clubs. Health Psychology, 32, 57-65. doi: 10.1037/a0029537
3	Imison, C., Poteliakoff, E., & Thompson, J. (2012). Older people and emergency bed use:
4	Exploring variation. King's Fund. Retrieved July 2014, 2014, from
5	http://www.kingsfund.org.uk/publications/older-people-and-emergency-bed-use
6	Jehn, M., Schmidt-Trucksass, A., Hanssen, H., Schuster, T., Halle, M., & Koehler, F. (2011).
7	Association of physical activity and prognostic parameters in elderly patients with
8	heart failure. Journal of Aging and Physical Activity, 19, 1-15.
9	Kearney, P. M., Harrington, J. M., Mc Carthy, V. J., Fitzgerald, A. P., & Perry, I. J. (2013).
10	Cohort profile: The Cork and Kerry diabetes and heart disease study. International
11	Journal of Epidemiology, 42, 1253-1262. doi: 10.1093/ije/dys131
12	Kozey, S. L., Lyden, K., Howe, C. A., Staudenmayer, J. W., & Freedson, P. S. (2010).
13	Accelerometer output and MET values of common physical activities. Medicine &
14	Science in Sports & Exercise, 42, 1776-1784. doi: 10.1249/MSS.0b013e3181d479f2
15	Langer, D., Gosselink, R., Sena, R., Burtin, C., Decramer, M., & Troosters, T. (2009).
16	Validation of two activity monitors in patients with COPD. Thorax, 64, 641-642. doi:
17	10.1136/thx.2008.112102
18	Manns, P. J., & Haennel, R. G. (2012). SenseWear Armband and stroke: Validity of energy
19	expenditure and step count measurement during walking. Stroke Research &
20	Treatment, 1-8. doi: 10.1155/2012/247165
21	McCullagh, R., Fitzgerald, E., O'Connor, K., Broderick, L., Kennedy, C., O'Reilly, N.,
22	Timmons, S. (2014). The functional decline of hospitalised older patients – Are we
23	doing enough? Physiotherapy Practice and Research, 35, 141-142.

1	McMurray, R. G., Soares, J., Caspersen, C. J., & McCurdy, T. (2013). Examining variations
2	of resting metabolic rate of adults: A public health perspective. Medicine & Science in
3	Sports & Exercise, 46. doi: 10.1249/mss.000000000000232
4	Moy, M. L., Garshick, E., Matthess, K. R., Lew, R., & Reilly, J. J. (2008). Accuracy of
5	uniaxial accelerometer in chronic obstructive pulmonary disease. Journal of
6	Rehabilitation Research & Development, 45, 611-617.
7	Mudge, S., Stott, N. S., & Walt, S. E. (2007). Criterion validity of the StepWatch Activity
8	Monitor as a measure of walking activity in patients after stroke. Archives of Physical
9	Medicine & Rehabilitation, 88, 1710-1715. doi: 10.1016/j.apmr.2007.07.039
10	Ng, L. W., Jenkins, S., & Hill, K. (2012). Accuracy and responsiveness of the Stepwatch
11	Activity Monitor and ActivPAL in patients with COPD when walking with and
12	without a rollator. Disability & Rehabilitation, 34, 1317-1322. doi:
13	10.3109/09638288.2011.641666
14	Pedersen, M. M., Bodilsen, A. C., Petersen, J., Beyer, N., Andersen, O., Lawson-Smith, L.,
15	. Bandholm, T. (2013). Twenty-four-hour mobility during acute hospitalization in
16	older medical patients. Journals of Gerontology Series A: Biological Sciences &
17	Medical Sciences, 68, 331-337. doi: 10.1093/gerona/gls165
18	Rennie, K. L., & Wareham, N. J. (1998). The validation of physical activity instruments for
19	measuring energy expenditure: Problems and pitfalls. Public Health Nutrition, 1, 265-
20	271.
21	Ryan, C. G., Grant, P. M., Tigbe, W. W., & Granat, M. H. (2006). The validity and reliability
22	of a novel activity monitor as a measure of walking. British Journal of Sports
23	Medicine, 40, 779-784. doi: 10.1136/bjsm.2006.027276

1	Ryan, D. J., O'Regan, N. A., Caoimh, R. O., Clare, J., O'Connor, M., Leonard, M.,
2	Timmons, S. (2013). Delirium in an adult acute hospital population: Predictors,
3	prevalence and detection. British Medical Journal Open, 3. doi: 10.1136/bmjopen-
4	2012-001772
5	Sant'Anna, T., Escobar, V. C., Fontana, A. D., Camillo, C. A., Hernandes, N. A., & Pitta, F.
6	(2012). Evaluation of a new motion sensor in patients with chronic obstructive
7	pulmonary disease. Archives of Physical Medicine & Rehabilitation, 93, 2319-2325.
8	doi: 10.1016/j.apmr.2012.05.027 10.1016/j.apmr.2012.05.027. Epub 2012 Jun 15.
9	Schmidt, A. L., Pennypacker, M. L., Thrush, A. H., Leiper, C. I., & Craik, R. L. (2011).
10	Validity of the StepWatch Step Activity Monitor: Preliminary findings for use in
11	persons with Parkinson Disease and Multiple Sclerosis. Journal of Geriatric Physical
12	<i>Therapy, 34</i> , 41-45. doi: Doi 10.1519/Jpt.0b013e31820aa921
13	Shephard, R. J., & Aoyagi, Y. (2010). Objective monitoring of physical activity in older
14	adults: Clinical and practical implications. Physical Therapy Reviews, 15, 170-182.
15	Smith, P., Galea, M., Woodward, M., Said, C., & Dorevitch, M. (2008). Physical activity by
16	elderly patients undergoing inpatient rehabilitation is low: An observational study.
17	Australian Journal of Physiotherapy, 54, 209-213.
18	Steiner, C., Andrews, R., Barrett, M., & Weiss, A. (2013). HCUP Projections: Cost of
19	inpatient discharges 2012 to 2013. 2013. HCUP projections report # 2013-01.
20	December 11, 2013. Retrieved 04.07.2014, 2014, from http://www.hcup-
21	us.ahrq.gov/reports/projections/2013-01.pdf
22	Storti, K. L., Pettee, K. K., Brach, J. S., Talkowski, J. B., Richardson, C. R., & Kriska, A. M.
23	(2008). Gait speed and step-count monitor accuracy in community-dwelling older

1	adults. Medicine & Science in Sports & Exercise, 40, 59-64. doi:
2	10.1249/mss.0b013e318158b504
3	Taraldsen, K., Askim, T., Sletvold, O., Einarsen, E. K., Bjastad, K. G., Indredavik, B., &
4	Helbostad, J. L. (2011). Evaluation of a body-worn sensor system to measure physical
5	activity in older people with impaired function. Physical Therapy, 91, 277-285. doi:
6	10.2522/ptj.20100159
7	Taylor, L. M., Klenk, J., Maney, A. J., Kerse, N., Macdonald, B. M., & Maddison, R. (2014).
8	Validation of a body-worn accelerometer to measure activity patterns in
9	octogenarians. Archives of Physical Medicine & Rehabilitation, 95, 930-934. doi:
10	10.1016/j.apmr.2014.01.013
11	Tudor-Locke, C., Sisson, S. B., Lee, S. M., Craig, C. L., Plotnikoff, R. C., & Bauman, A.
12	(2006). Evaluation of quality of commercial pedometers. Canadian Journal of Public
13	Health, 97 Supplement 1, S10-15, S10-16.
14	Tyo, B. M., Fitzhugh, E. C., Bassett, D. R., Jr., John, D., Feito, Y., & Thompson, D. L.
15	(2011). Effects of body mass index and step rate on pedometer error in a free-living
16	environment. Medicine & Science in Sports & Exercise, 43, 350-356. doi:
17	10.1249/MSS.0b013e3181e9b133
18	Vanroy, C., Vissers, D., Cras, P., Beyne, S., Feys, H., Vanlandewijck, Y., & Truijen, S.
19	(2014). Physical activity monitoring in stroke: SenseWear Pro2 activity accelerometer
20	versus Yamax Digi-Walker SW-200 pedometer. Disability & Rehabilitation, 36,
21	1695-1703. doi: 10.3109/09638288.2013.859307
22	Webber, S. C., Magill, S. M., Schafer, J. L., & Wilson, K. C. (2014). GT3X+ Accelerometer,
23	Yamax Pedometer and SC-StepMX Pedometer step count accuracy in community-

1	dwelling older adults. Journal of Aging and Physical Activity, 22, 334-341. doi:
2	10.1123/japa.2013-0002
3	Weiss, C. O., Cappola, A. R., Varadhan, R., & Fried, L. P. (2012). Resting metabolic rate in
4	old-old women with and without frailty: Variability and estimation of energy
5	requirements. Journal of the American Geriatric Society, 60, 1695-1700. doi:
6	10.1111/j.1532-5415.2012.04101.x
7	Weiss, C. O., Seplaki, C. L., Wolff, J. L., Kasper, J. D., & Agree, E. M. (2008). Self-selected
8	walking speed was consistent when recorded while using a caneJournal of Clinical
9	Epidemiology, 61, 622-627. doi: DOI 10.1016/j.jclinepi.2007.07.020
10	Wendland, D. M., & Sprigle, S. H. (2012). Activity monitor accuracy in persons using canes.
11	Journal of Rehabilitation Research & Development, 49, 1261-1268. doi: Doi
12	10.1682/Jrrd.2011.08.0141
13	White, D. K., Wagenaar, R. C., & Ellis, T. (2006). Monitoring activity in individuals with
14	Parkinson Disease: A validity study. Journal of Neurologic Physical Therapy, 30, 12-
15	21.



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

2

Authors	Physical Activity	Devices	Results
Condition, Dwelling (sample	Observed	(Outputs)	
size), Age	Criterion Measurement		
Barreira et al. (2013)	Free-living activity (7	ActiGraph GT3X+	DF: -7.4% error (769 steps/day)
Healthy CD (n=15)	days)	accelerometer	LFX: 121.9% error (8140 steps/day)
Men: 73±9 years	NL-1000 pedometer	• default filter, (DF)	
Women: 67±4 years	(research standard)	• light filter (LFX)	
		(step-count)	
Brown et al. (2008)	lying, sitting,	AugmenTec wireless	Concordance (median κ=0.92) between
Medical IP (n=47) male	standing/walking	monitor	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)	6MWT and short walk	Pedometer $\times$ 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; -

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

	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	Video recordings	(posture classification,	Accurate for lying, sitting, walking (all
(n=27)		step-count)	>90%); moderate for standing (46%);
67±10 years			shuffling virtually undetectable (18%)
Fulk et al. (2012)	Sitting, standing, walking	SmartShoe – shoe based	>95% accuracy for sitting, standing, walking
Chronic stroke CD (n=12)	and step-count	sensor system	Step-count mean difference <1
62.1±8.2 years	Video recordings	(posture classification	
		and step-count)	
Furlanetto et al. (2010)	Treadmill walking at	Digiwalker SW701	High speed (1.33±0.2m/sec): pedometer
COPD CD (n=30)	various set speeds	(pedometer)	accurately measured step-count; poor step-
67±8 years	Video recordings	(step-count)	count accuracy with multisensor

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

# DynaPort and DynaPort Minimod

Manns & Haennel (2012)	$6$ MWT $\times$ 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%)

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 $\times$ 2 (slow, fast)	Yamax Power Walker	Correlations of step-count: slow walking
COPD CD (n=30)	Circuits $\times$ 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)	

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	-40.31% error in walkers <0.47m/sec
79.7±7.3 years		and step-count)	
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≥0.89)

60.4±10.26 years	Video recordings	(step-count)	Treadmill: Yamax (knee): correlation for
Healthy CD (n=15) 58.07±10.37		Yamax Digi-Walker SW200 pedometer (hip and knee)	healthy (r≥0.90), stroke (speed 0.42m/sec, r=0.69) Yamax underestimated steps for other
		(step-count)	activities, reliability (0.66-0.98)
			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
Healthy CD (n=35)	Direct observation	ActiGraph GT3X+ accelerometer	independent walkers: w/s 1.21±0.2m/sec (% error 0.8 to 2.6)
walking aid (n=13)			Significant difference in step-count accuracy
No walking aid (n=22)		SC-Step MX pedometer	in w/sid users: w/s 0.8+0.2m/sec. (% error
81.5±5 years		(step-count)	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)	various surfaces	Monitor (SAM) (leg and	mounted)
75.6	Direct observation	cane mounted)	Accurate 84.7% on all surfaces (cane
		(step- and cane-count)	mounted)
			Stairs least accurate
White et al. (2006)	Set and random order tasks	Activity Monitor (AM)	Correlations AM ranged from r=0.63 to
White et al. (2006) Parkinson's Disease CD	Set and random order tasks Video recordings	Activity Monitor (AM) (VitaPort 3)	Correlations AM ranged from r=0.63 to r=0.98
White et al. (2006) Parkinson's Disease CD (n=11)	Set and random order tasks Video recordings	Activity Monitor (AM) (VitaPort 3) ( <b>posture classification</b> )	Correlations AM ranged from r=0.63 to r=0.98 AM reports longer durations

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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