

A scoping review of use of wearable devices to evaluate outcomes in survivors of critical illness

Samuel Gluck, Lee-anne S Chapple, Marianne J Chapman, Theodore J Iwashyna and Adam M Deane

Physical activity and function are frequently impaired in survivors of critical illness.¹⁻¹¹ Functional capacity after critical illness is an important outcome but, to date, researchers and clinicians have relied on labour-intensive techniques, such as the 6-minute walk distance test and subjective, patient-reported questionnaires, to quantify quality of life (QOL) and physical function.¹⁻¹⁰ Given the logistical challenges and expense associated with these methods, there is a need to be able to accurately and efficiently assess physical recovery in survivors of critical illness in a way that is meaningful to patients and clinicians.

Technological advances provide the potential to quantify physical activity in a real-life setting and in a cost-effective manner. It is possible that quantifying mobility, using daily step counts, or measuring how much time individuals spend at home, may provide a holistic and patient-centric assessment of physical function.

A number of relatively inexpensive and seemingly accurate pedometers and accelerometers are now available.¹² A pedometer measures the number of steps taken by an individual and an accelerometer responds to acceleration in one, two or three planes (uni-, bi- and tri-axial accelerometers, respectively). With the use of differing body mounting and algorithms, accelerometers can be used to assess sleep, the intensity and duration of activity, body position, steps and energy expenditure. They record data continuously, providing a more representative measure of activity. Furthermore, ambulatory global positioning system (GPS) devices record movement through location data. A smartphone contains a tri-axial accelerometer, a gyroscope, a compass, and a barometer, and combining these sensors with appropriate software applications (apps) and algorithms allows the capacity to wirelessly transmit live data to researchers and clinicians. Such methodology is increasingly described in epidemiological studies, for example, McConnell and colleagues recently reported using a smartphone app to quantify physical activity from more than 20 000 healthy individuals.¹³

Given the recent advances in technology of wearable devices that record physical activity, there has been growth in the number of researchers evaluating these devices across different health care settings. Accelerometers and pedometers have been used to assess physical activity in a variety of conditions, including chronic obstructive pulmonary disease,¹⁴ cystic fibrosis,¹⁵ multiple sclerosis,¹⁶

ABSTRACT

Objective: Wearable devices using new technology may be a cost-effective method to assess functional outcomes in survivors of critical illness. Our primary objective was to review the extent to which wearable devices such as smartphones, pedometers, accelerometers and global positioning systems have been used to evaluate outcomes in survivors of an intensive care unit admission.

Design: We included studies of patients surviving an ICU admission and which measured outcomes using wearable devices. We performed a scoping review of studies found by searching the CINAHL, Embase, MEDLINE and PubMed databases.

Results: The seven studies we identified were published in or after 2012 and were predominantly descriptive ($n = 6$) with one randomised controlled trial. All studies described outcomes in cohorts of relatively few participants (range, 11–51 participants). Duration to follow-up was mostly short, at a median time of 3 months after ICU discharge (range, in-hospital to 27 years). All studies used accelerometers to monitor patient movement: physical activity ($n = 5$), sleep quality ($n = 1$), and infant movement ($n = 1$). The accelerometers were bi-axial ($n = 3$), uni-axial ($n = 2$) combined uni-axial ($n = 1$) and tri-axial ($n = 1$). Common outcomes evaluated were the number of participants walking for < 30 min/day, mean daily step count and walking speed.

Conclusions: Wearable devices have infrequently been used to measure physical activity in survivors of critical illness and all identified studies were published recently, which suggests that the use of wearable devices for research may be increasing. To date, only accelerometry has been reported, and the wide variation in methodologies used and the outcomes measured limits synthesis of these data.

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diabetes¹⁷ and joint replacement preoperative assessment.¹⁸ To date, however, no review has summarised the current literature on wearable devices in survivors of critical illness.

Aims

We conducted a scoping review with the primary objective to evaluate whether wearable devices have been used to measure outcomes in patients who have survived an ICU

admission. For the purpose of our review, wearable devices included smartphones, pedometry, accelerometry and GPS. Our secondary objectives were to compare outcomes evaluated using wearable devices with more conventional methodologies and to evaluate usability in study participants.

Methods

Data sources and searches

On 9 May 2016, we conducted a scoping review of the literature, using four online databases (the Cumulative Index to Nursing and Allied Health Literature [CINAHL], Embase, MEDLINE and PubMed). The search criteria are shown in Supplementary Table 1 (online at cicm.org.au/journal.php). All medical subject heading (MeSH) terms were expanded for further terms and included in the search of all four databases. Reference lists of all retrieved papers were reviewed to identify other eligible studies not captured in the primary search.

Eligibility criteria

We included studies that reported outcomes in survivors of critical illness using wearable devices. We defined wearable devices as smartphones, pedometers, accelerometers, and GPS devices, based on our understanding of current technologies that could be used to assess outcomes after critical illness, which we defined as any condition necessitating an ICU admission, regardless of the presenting problem. No date restrictions were applied. We excluded studies that did not specify whether they were conducted in ICU survivors, did not report on the use of one of the wearable devices, or were not published in English.

Study selection

Duplicate citations were removed and titles and abstracts were independently screened for inclusion by two reviewers (S G and L C). If it was not clear from the abstract if the citation could be excluded, then the full-text article was obtained. Full-text articles were independently evaluated for eligibility. Disagreements were resolved by consensus or consultation with a third reviewer (A D).

Data extraction

Two reviewers (S G and L C) independently extracted data from the included studies using a modified version of a standardised data collection form.¹⁹ Information extracted included study characteristics (author, publication year, country, design and sample size), types of technology used, outcomes from the technology used, conventional outcomes compared with wearable devices and study results.

Quality assessment

Risk of bias for observational studies was assessed using the Newcastle–Ottawa scale, which scores studies on three domains: selection of study groups, comparability of groups, and ascertainment of the exposure or outcome of interest for case–control or cohort studies, respectively.²⁰

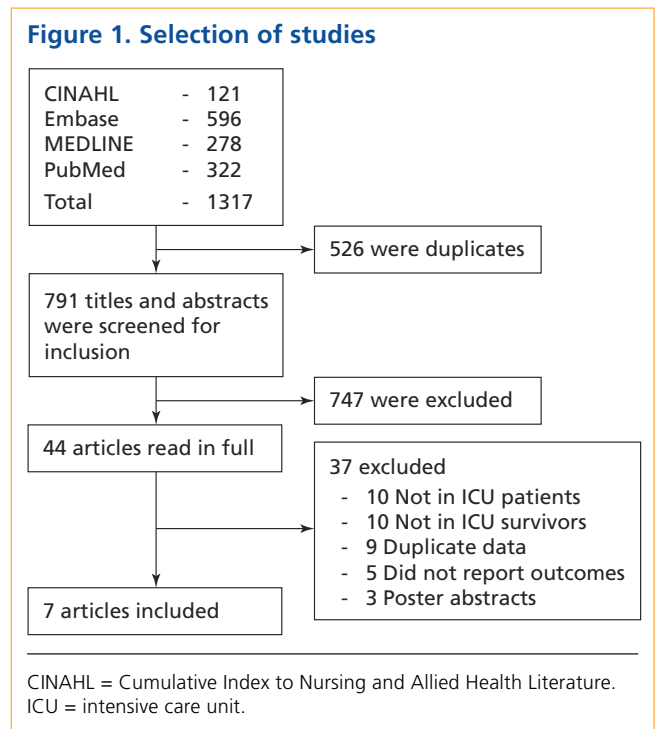
Usability of wearable devices

We defined usability as whether the wearable device provided a data point. We measured usability as the number of incomplete records, due to user or device failure, out of the total number of participant data points, with a lesser number signifying greater usability.

Results

Study selection

Our search returned 1317 references, of which 526 were duplicates. Of the 791 abstracts reviewed, 747 did not meet the defined inclusion criteria and were excluded. Forty-four full-text articles were obtained and assessed for eligibility. Of these, 37 were excluded because: patients were not admitted to the ICU ($n = 10$); studies were conducted during ICU admission and not in survivors ($n = 10$); duplicate data ($n = 9$); outcomes not reported ($n = 5$); and only published as an abstract ($n = 3$). Seven studies were included in our final review (Figure 1).^{21–27}



Study characteristics

There were five prospective observational cohort studies,^{22,23,25-27} one case control study²¹ and one randomised controlled trial (RCT)²⁴ (Table 1). Three studies were nested within larger studies: two within RCTs^{23,27} and one within a longitudinal study.²⁵ All studies were published during or after 2012. Using the Newcastle–Ottawa scale, the quality of all the observational studies were low, with their major limitation being their single cohort and/or descriptive nature.

Cohort studied

One study was conducted in neonates who survived ICU admission²⁴ and one was conducted in adults who had survived an earlier ICU admission as neonates.²¹ The remainder were survivors of admission to an adult ICU (Table 1), and included enrolment criteria such as severe sepsis, mechanical ventilation or ICU length of stay > 5 days. All studies described outcomes in cohorts of relatively few participants (range, $n = 11-51$). Only one study²⁵ included a calculation to determine sample size. Most studies evaluated their outcomes within 3 months of ICU discharge, although one measured at 18 months after ICU discharge, and one at a mean of 26 years after discharge.^{21,25} Borges and colleagues and Guyer and colleagues were the only investigators to report on outcomes at more than one time point.^{24,26}

Usability of wearable devices

Eight of 301 records across all studies failed to complete activity monitoring; four in the study of Denehy and colleagues,²⁷ three in the study of McNelly and colleagues²⁵ and one in the study of Edbrooke and colleagues,²³ which suggests that the devices were usable.

Technology reported

All studies used accelerometers to monitor activity. The bi-axial AMP331 was the most commonly used accelerometer, with bi-axial accelerometers being used by three groups of investigators,^{23,25,27} uni-axial accelerometers by two groups,^{22,24} and combined uni-axial accelerometers²¹ and tri-axial accelerometers were used by one group each.²⁶

Outcomes measured

Studies evaluated physical activity ($n = 5$),^{21,23,25-27} sleep quality ($n = 1$)²² and infant movement ($n = 1$).²⁴ Reported outcome measures are summarised in Table 1. Several studies reported multiple accelerometer outcomes. The physical activity outcomes measured varied and included simple assessments of body position,²⁶ walking speed,^{23,26} duration in dynamic activities,²¹ distance walked,^{23,27} time spent walking,²⁶ time spent inactive^{26,27} and steps.^{23,25,27}

Only daily step count,^{25,27} walking speed,^{23,26} and number of participants walking < 30 minutes a day^{26,27} were reported in more than one study.

Associations with traditional outcome measures

Two studies reported direct correlations between outcomes measured using wearable devices and more “traditional” outcomes, such as global reported QOL measures. There was a modest association between the total Physical Activity Scale for the Elderly (PASE) score and mean daily step count (the Spearman rank coefficient, $r^2 = 0.332$; $P = 0.05$) or distance walked ($r^2 = 0.313$; $P = 0.05$).²⁷ Stronger correlations were shown between mean daily step count and both the physical component summary score ($r^2 = 0.25$; $P < 0.01$) and physical function score ($r^2 = 0.51$; $P < 0.01$) of the SF-36 and with the clinical frailty scale (CFS) ($r^2 = 0.55$; $P < 0.01$).²⁵ The McNelly²⁵ and Denehy²⁷ studies both showed that patients with chronic disease who survived an ICU admission had reduced step counts compared with those without chronic disease.

Discussion

Our scoping review revealed that seven studies have reported on the use of wearable devices to measure outcomes in survivors of critical illness. However, because all identified studies were published within the past 5 years, it appears that the use of wearable devices may be an emerging field of research. The use of wearable devices permits a high degree of usability with only a small number of failed readings and absent data points.

Our review also revealed that most studies in this field have been exploratory in nature, and conducted in small, often single, cohorts of patients, with short-term follow-up. Additionally, the quality of study design was modest. Only one RCT was identified, and three studies were nested in other studies. This is consistent with an emerging field of research in which exploratory studies frequently do not have the methodological rigour of large-scale RCTs.²⁸

Variety in outcomes reported

In all the studies we examined, accelerometry was used to quantify outcomes and a wide variety of outcomes were measured and reported, such as sleep actigraphy²² and movement assessment.²⁴ The outcome most frequently reported was locomotion. Even with this outcome, there was a lack of consensus between investigators on how this should be quantified. While locomotion was recorded in four studies,^{23,25-27} the only commonly reported outcomes were mean daily step count, distance walked, and the number of participants who walked for < 30 min/day. This variation would be expected during the initial phases

Table 1. Details of peer reviewed articles included in review

1st author	Year	Study design	Cohort studied	Number of patients	Wearable device	Follow-up time	Duration of observation	Device observations	Other outcomes	Associations
Solverson ²²	2016	Prospective observational cohort study	Adults, > 4 day ICU LOS. Excluded: TBI, neurocognitive disorder, acute stroke, living distant from hospital	55 (11 sleep actigraphy)	Sleep actigraphy	3 mth after hospital discharge	3 nights	Sleep-wake cycle means: total sleep time, 6.15 h; sleep efficiency, 78%; awakenings, 11; awake duration, 7 min; sleep onset latency, 12 min	Sleep quality (PSQI, ESS); HRQOL, EQ-5D, SF-36; depression/anxiety (HADS)	No association between total sleep time, sleep efficiency or sleep disruptions and PSQI or PSQI-component scores. Significant association with APACHE II score. Total sleep time had no association with HADS, EQ-5D individual domains or MCS or PCS
Edbrooke ²³	2012	Prospective observational cohort study (nested in RCT)	Adults, sourced from a concurrent RCT, able to walk > 5 m unassisted	20	AMP331 biaxial accelerometer	Post-ICU hospital ward	Point in time, in-hospital assessment	Reported distance walked, steps taken, walking speed	Direct observation	Slight underestimations of walking distance (2.79 m [walk 1] to 3.11 m [walk 2] over a total of 90 m) and walking speed (28.87 cm/s), slight overestimation of step count (0.92; 95% CI, -3.27 to 5.11)
Guyer ²⁴	2012	RCT	Neonates < 32 wk gestational age	37	Actiwatch mini, Actiwatch AW4	5 and 11 wk after term, (corrected gestational age)	10 days at each time point	Reduced activity count per 24 h in dim-light group at 5 and 11 wk; no difference for activity count/night or day; age-effect noted with increased activity between 5 and 11 wks	Sleep and crying behaviour every 5 min in auditory diary (3 days), weight	No correlations with wearable devices reported
Van Der Cammen-van Zijp ²¹	2014	Retrospective case control study	Adult survivors of neonatal respiratory distress (27 with CDH, 30 without)	57 (28 activity monitoring)	Four uni-axial accelerometers	Unplanned follow-up of PICU survivors in adulthood (mean age, 26.7 years)	2 days	Reduced duration of dynamic activities in CDH group; no difference for mean motility and motility during walking; no significant differences between groups	Lung function: spirometry exercise testing (CPET); fatigue (FSS) HRQOL (LIFE-H 3.0, SF-36)	No correlations with wearable devices reported

6MWD = 6-minute walk distance. APACHE = Acute Physiology and Chronic Health Evaluation. CDH = congenital diaphragmatic hernia. CFS = clinical frailty scale. CL = cycled light. CPET = cardiopulmonary exercise testing. D_{CO} = Diffusion capacity of the lung for carbon monoxide. EQ-5D = EuroQol-5D. ESS = Epworth Sleepiness Scale. FEV₁ = forced expiratory volume in 1 s. FSS = fatigue severity score. FVC = forced vital capacity. h = hours. HADS = Hospital Anxiety and Depression Scale. ICU = intensive care unit. LIFE-H = assessment of life habits. LOS = length of stay. m = metres. min = minutes. MCS = mental composite score (of SF-36). MIP = maximal inspiratory pressure. PADL = Physical activities of daily life. PASE = Physical activity scale for the elderly. PCS = physical composite score (of SF-36). PF = physical functioning. PSQI = Pittsburgh Sleep Quality Index. RCT = randomised controlled trial. SAH = subarachnoid haemorrhage. SCI = spinal cord injury. SD = standard deviation. SF-36 = Short-Form 36. TBI = traumatic brain injury. TPDA = time post-discharge adjusted. TUG = timed up and go. w = weeks. V_A = alveolar volume. VAT = ventilatory anaerobic threshold.

Table 1. Details of peer reviewed articles included in review (continued)

1st author	Year	Study design	Cohort studied	Number of patients	Wearable device	Follow-up time	Duration of observation	Deive observations	Other outcomes	Associations
McNelly ²⁵	2016	Prospective observational cohort study (nested in longitudinal outcomes study)	Adult, > 48 h ventilation, > 7 days ICU LOS. Excluded: pregnant, lower limb amputation, disseminated cancer, neuromuscular pathology	30 (27 provided data), 30 age and gender-matched controls	SenseWear bi-axial accelerometer	18 mth after ICU discharge	> 5 days including 1 weekend day	Daily step-count was half that of healthy controls; pre-existing chronic disease was associated with lower step-counts	HRQOL (SF-36); frailty (CFS)	Steps/day v SF-36 PF ($r^2 = 0.51$); v SF-36 PCS ($r^2 = 0.25$); v CFS ($r^2 = 0.55$). Variation in steps v SF-36 PF ($r^2 = 0.24$); v CFS ($r^2 = 0.49$)
Borges ²⁶	2015	Prospective observational cohort study	Adult, severe sepsis or septic shock, able to walk unassisted pre-admission, able to complete two assessments at ICU discharge. Excluded: previous stroke, neurological disease, TBI, SAH, SCI, limb fracture or amputation, terminal illness	72 at hospital discharge	Dynaport tri-axial accelerometer	Before hospital discharge and 3 mth after discharge	2 consecutive days at both time points	Septic patients had lower walking time at both time points v healthy individuals; patients were more inactive (sitting or lying) on the ward than at 3 mth; walking intensity was lower after hospital discharge v healthy individuals; 40% of septic patients walked < 30 min/day v 15% of healthy individuals	Muscle strength: inspiratory muscles (MIP), handgrip (dominant hand dynamometry), quadriceps (dynamometry), exercise capacity (6MWD)	No associations between accelerometer data and any other variable during hospital admission or at 3 mth
Denehy ²⁷	2012	Prospective observational cohort study (nested in a RCT)	Adult, > 5 d ICU LOS, English speaker, live within 50 km, participation agreed by attending intensivist. Excluded: neurological, spinal, musculoskeletal dysfunction	49 with accelerometer data, 45 with PASE data	AMP 331 accelerometer	2 mth after ICU discharge	7 days	Participants took 4894 steps/day (SD, 3070 steps/day); 80% took < 7500 steps/day; 6% > 10 000 steps/day; only 54% of steps were taken in the locomotion category. Median distance walked 1.69 km; 90% of time was spent inactive; 3% of time was spent in locative category; 63% of cohort spent < 30 min/d in the locomotive category	Lifestyle (PASE questionnaire), exercise capacity (6MWD), manual muscle strength (TUG test)	Fair correlation between total PASE and mean steps/day ($\rho = 0.332$) and mean distance walked ($\rho = 0.313$). Fair correlation between PASE occupation sub-score and daily steps ($\rho = 0.332$). Fair correlation between walking < 30 min/day from PASE and steps distance ($\rho = 0.345$) and 6MWD and SF-36 PF associated with walking time and steps/day in univariate analysis; in multi-variate analysis confounded by chronic disease

6MWD = 6-minute walk distance. APACHE = Acute Physiology and Chronic Health Evaluation. CDH = congenital diaphragmatic hernia. CFS = clinical frailty scale. CL = cycled light. CPET = cardiopulmonary exercise testing. D_{LCO} = Diffusion capacity of the lung for carbon monoxide. EQ-5D = EuroQol-5D. ESS = Epworth Sleepiness Scale. FEV₁ = forced expiratory volume in 1 s. FSS = fatigue severity score. FVC = forced vital capacity. h = hours. HADS = Hospital Anxiety and Depression Scale. ICU = intensive care unit. LIFE-H = assessment of life habits. LOS = length of stay. m = metres. min = minutes. MCS = mental composite score (of SF-36). MIP = maximal inspiratory pressure. PADL = Physical activities of daily life. PASE = Physical activity scale for the elderly. PCS = physical composite score (of SF-36). PF = physical functioning. PSQI = Pittsburg Sleep Quality Index. RCT = randomised controlled trial. SAH = subarachnoid haemorrhage. SCI = spinal cord injury. SD = standard deviation. SF-36 = Short-Form 36. TBI = traumatic brain injury. TPDA = time post-discharge adjusted. TUG = timed up and go. w = weeks. V_A = alveolar volume. VAT = ventilatory anaerobic threshold.

of research using a new methodology but over time it is important that consistency in core domains is established.²⁹ Our findings highlight the need for the development of core outcome sets for measurement, by new technological means, of physical activity in ICU survivors.

We were surprised there was no use of GPS data to create life spaces,³⁰ activity spaces³¹ or to quantify the percentage of time spent at home.³² These measures have been used in other populations, for example after surgery for peripheral vascular disease,³³ spinal disorders,³⁴ and in people with mental illness.³⁵ The activity space is a geographic information systems construct that represents the environment with which an individual interacts. Such measurements may provide an assessment of recovery from critical illness. We were also surprised that smartphones, with their associated apps, had not been used in any relevant study.

Accelerometer methodologies

Four of the studies we examined reported on locomotion using algorithms to access raw accelerometer data to determine step data. Step data are increasingly reported in other health care settings.³⁶⁻³⁹ It has been shown that uni-axial accelerometers are adequate for detecting heel strike⁴⁰ to calculate physical activity from walking, but this may underestimate when assessing gait in slower walkers, particularly those with a shuffling gait.⁴¹ It does, however, produce data that are patient-centered and easily interpreted by clinicians.

Use of locomotion data may have advantages, but the literature relating to accelerometers suggests that using centrally mounted tri-axial accelerometers to count activity frequency and intensity provides the best estimate of total physical activity.⁴⁰ This also raises the suggestion of using advanced modelling techniques combining accelerometer outputs to produce estimates of activity counts and energy expenditure.⁴²

Although they are less patient-focused, total activity counts, rather than locomotion data, might provide a better assessment of physical activity. This is because they estimate energy expenditure, taking into account intensity and frequency of all movements, rather than just energy expenditure related to walking. Notwithstanding the limitations of each methodology, the use of a single research methodology is ideal.

Relationships between outcomes and other methodologies

It appears that there are fair associations between outcomes after critical illness measured using wearable devices compared with more traditional methodologies, such as self-reported QOL questionnaires. In our review, we found

stronger associations between subjective measures than between subjective and objective measures. The subjective assessment of sleep (Pittsburgh sleep quality index) had stronger correlations with the subjective assessments of health-related QOL (EQ-5D and SF-36), than with objective actigraphy measures.²² This was also true for the subjective assessments of physical function (SF-36) with frailty (CFS) and daily step counts.²⁵ Before the widespread implementation of step data into critical care research, it will be important to establish that measurement of physical activity after critical illness is clinically important and is related to functional outcomes of importance to patients, their care-givers and the community.

Usability as an outcome for large trials

Although two studies^{21,22} reported that only a subset of patients used the wearable devices, which implies a cost limitation, the cost of follow-up using accelerometers has not been explicitly stated in any study. An AMP 331 device (Dynastream Innovations) costs \$1200 and is no longer produced; a SenseWear accelerometer (BodyMedia) costs \$120; and an Actiwatch 2 (Philips Respironics) costs \$1500 (Actiwatch 4 has been discontinued). These devices are likely to be prohibitively expensive for researchers conducting trials involving large numbers of patients and/or sites. Fortunately, however, this cost is likely to decrease over time. An example of the dynamic nature of the technological landscape is that two of the accelerometers used in the identified studies, which were conducted within the last 5 years, have already been discontinued. The rapid evolution of these technologies and dynamic pricing structures are evident in that market leaders in the commercial space, such as the Fitbit One (Fitbit) (\$130) and Flex (Fitbit) (\$89) are comparatively inexpensive, and have been shown to be accurate.¹² These dynamic technological and pricing changes may reduce costs but the rapid evolution of makes, models and function could hinder attempts to develop core outcomes and methodologies using these technologies.

Strengths and limitations

Our review is, to the best of our knowledge, the first to appraise the use of wearable devices in ICU survivors. Strengths include our search technique, which was relatively comprehensive, and that we evaluated studies for bias and quality and used a standardised data extraction tool. Limitations include that we only accessed English language literature and that there may have been other wearable devices we were not aware of that were not included in our search terms. Finally, the considerable heterogeneity of differing populations, wearable device outcomes, and times to follow-up between studies limits any firm conclusions.

Conclusions

Currently, wearable devices are infrequently used to report outcomes from survivors of critical illness. Accelerometry was the only technology reported in the studies we examined, but there was considerable variation in accelerometer types, outcomes reported and the time-points that observations were made.

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Competing interests

None declared.

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Appendix 1. This appendix was part of the submitted manuscript and has been peer reviewed. It is posted as supplied by the authors.

STRING 1	STRING 2
Critical care	Mobile phone\$
Critical\$ ill\$	Cell\$ phone\$
Intensive care\$	Smartphone\$
ICU\$	Smart phone\$
Intensive therapy	Pedometer\$
ITU\$	Step count\$
	Accelerometer\$
	Actigraph\$
	GPS
	Global positioning system\$
	Cell\$ telephone\$
	Life space\$
	Activity space\$

Supplemental Table 1: Search terms used in each database. \$ corresponds to the appropriate truncation command in each database

