Advancing the objective measurement of physical activity and sedentary behaviour context

By

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Doctoral thesis

Submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University

September 2016

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Abstract

Objective data from national surveillance programmes show that, on average, individuals accumulate high amounts of sedentary time per day and only a small minority of adults achieve physical activity guidelines. One potential explanation for the failure of interventions to increase population levels of physical activity or decrease sedentary time is that research to date has been unable to identify the specific behavioural levers in specific contexts needed to change behaviour. Novel technology is emerging with the potential to elucidate these specific behavioural contexts and thus identify these specific behavioural levers. Therefore the aims of this four study thesis were to identify novel technologies capable of measuring the behavioural context, to evaluate and validate the most promising technology and to then pilot this technology to assess the behavioural context of older adults, shown by surveillance programmes to be the least physically active and most sedentary age group.

Study one

Purpose: To identify, via a systematic review, technologies which have been used or could be used to measure the location of physical activity or sedentary behaviour. **Methods:** Four electronic databases were searched using key terms built around behaviour, technology and location. To be eligible for inclusion papers were required to be published in English and describe a wearable or portable technology or device capable of measuring location. Searches were performed from the inception of the database up to 04/02/2015. Searches were also performed using three internet search engines. Specialised software was used to download search results and thus mitigate the potential pitfalls of changing search algorithms. **Results:** 188 research papers met the inclusion criteria. Global positioning systems were the most widely used location technology in the published research, followed by wearable cameras and Radio-frequency identification. Internet search engines identified 81 global positioning systems, 35 real-time locating systems and 21 wearable cameras. **Conclusion:** The addition of location information to existing measures of physical activity and sedentary behaviour will provide important behavioural information.

Study Two

Purpose: This study investigated the Actigraph proximity feature across three experiments. The aim of Experiment One was to assess the basic characteristics of the Actigraph RSSI signal across a range of straight line distances. Experiment Two aimed to assess the level of receiver device signal detection in a single room under unobstructed conditions, when various obstructions are introduced and the impacts these obstructions have on the intra and inter unit variability of the RSSI signal. Finally, Experiment Three aimed to assess signal contamination across multiple rooms (i.e. one beacon being detected in multiple rooms). **Methods:** Across all experiments, the receiver(s) collected data at 10 second epochs, the highest resolution possible. In Experiment One two devices, one receiver and one beacon, were placed opposite each other at 10cm increments for one minute at each distance. The RSSI-distance relationship was then visually assessed for linearity. In Experiment Two, a test room was demarcated into 0.5 x 0.5 m grids with receivers simultaneously placed in each demarcated grid. This process was then repeated under wood, metal and human obstruction conditions. Descriptive tallies were used to assess the signal detection achieved for each receiver from each beacon in each grid. Mean RSSI signal was calculated for each condition alongside intra and inter-unit standard deviation, coefficient of variation and standard error of the measurement. In Experiment Three, a test apartment was used with three beacons placed across two rooms. The researcher then completed simulated conditions for 10 minutes each across the two rooms. The percentage of epochs where a signal was detected from each of the three beacons across each test condition was then calculated. **Results:** In Experiment One, the relationship between RSSI and distance was found to be non-linear. In Experiment Two, high signal detection was achieved in all conditions; however, there was a large degree of intra and inter-unit variability in RSSI. In Experiment Three, there was a large degree of multi-room signal contamination. **Conclusion:** The Actigraph proximity feature can provide a binary indicator of room level location.

Study Three

Purpose: To use novel technology in three small feasibility trials to ascertain where the greatest utility can be demonstrated. **Methods:** Feasibility Trial One assessed the concurrent validity of electrical energy monitoring and wearable cameras as measures of television viewing. Feasibility Trial Two utilised indoor location monitoring to assess where older adult care home residents accumulate their sedentary time. Lastly, Feasibility Trial Three investigated the use of proximity sensors to quantify exposure to a height adjustable desk **Results:** Feasibility Trial One found that on average the television is switched on for 202 minutes per day but is visible in just 90 minutes of wearable camera images with a further 52 minutes where the participant is in their living room but the television is not visible in the

image. Feasibility Trial Two found that residents were highly sedentary (sitting for an average of 720 minutes per day) and spent the majority of their time in their own rooms with more time spent in communal areas in the morning than in the afternoon. Feasibility Trial Three found a discrepancy between self-reported work hours and objectively measured office dwell time. **Conclusion:** The feasibility trials outlined in this study show the utility of objectively measuring context to provide more detailed and refined data.

Study Four

Purpose: To objectively measure the context of sedentary behaviour in the most sedentary age group, older adults. **Methods:** 26 residents and 13 staff were recruited from two care homes. Each participant wore an Actigraph GT9X on their non-dominant wrist and a LumoBack posture sensor on their lower back for one week. The Actigraph recorded proximity every 10 seconds and acceleration at 100 Hz. LumoBack data were provided as summaries per 5 minutes. Beacon Actigraphs were placed around each care home in the resident's rooms, communal areas and corridors. Proximity and posture data were combined in 5 minute epochs with descriptive analysis of average time spent sitting in each area produced. Acceleration data were summarised into 10 second epochs and combined with proximity data to show the average count per epoch in each area of the care home. Mann-Whitney tests were performed to test for differences between care homes. **Results:** No significant differences were found between Care Home One and Care Home Two in the amount of time spent sitting in communal areas of the care home (301 minutes per day and 39 minutes per day respectively, $U=23$, $p=0.057$) or in the amount of time residents spent sitting in their own room (215 minutes per day and 337 minutes per day in Care Home One and Two respectively, $U=32$, $p=0.238$). In both care homes, accelerometer measured average movement increases with the number of residents in the communal area. **Conclusion:** The Actigraph proximity system was able to quantify the context of sedentary behaviour in older adults. This enabled the identification of levers for behaviour change which can be used to reduce sedentary time in this group.

Overall conclusion: There are a large number of technologies available with the potential to measure the context of physical activity or sedentary time. The Actigraph proximity feature is one such technology. This technology is able to provide a binary measure of proximity via the detection or non-detection of Bluetooth signal: however, the variability of the signal prohibits distance estimation. The Actigraph proximity feature, in combination with a posture sensor, is able to elucidate the context of physical activity and sedentary time.

Acknowledgements

Anyone who knows me will know that I'm not an emotional person but as I near the end of an eight year journey that I never thought I would start I want to express my gratitude to a number of people. Each of them deserves more thanks from me that a few words can do justice to.

Firstly, to my supervisors Dr Dale Esliger and Dr Lauren Sherar. Dale, thank you for spotting something in me that deserved a chance. Your constant stream of new ideas, genuine enthusiasm for student supervision and eclectic taste in research and enterprise have given me a great and varied start in academia. Lauren, thanks for filtering out Dales (and my) ideas and providing a sounding board on the practicalities of research. I hope I have taken the best mix of these qualities from you both.

To the undergraduate lot; Josh, Dan, Simon, Ant and Lis. Thanks for making the first three years of university so memorable. I doubt I would have carried on for another 5 years otherwise.

To Emily and Amy, thanks for always cheering me up whenever I'm home and helping me stay in touch with the real world outside university. I honestly can't tell you how many times you've helped me see the big picture over the last few years.

To the Loughborough group; Jess (who will hit me if she isn't first), James, Andy, Emily, Jose, Vero, Carl, Louisa, Sam and everybody else. Thanks for making work and non-work life in Loughborough so enjoyable over the last few years. For the record, the correct answers are ninja; get out of the city and concentric circles.

Special mention must go to James. From the days when we would drive everybody else in our MSc class crazy before exams to starting our PhD's to finishing our PhD's, we have done it all in lockstep. Thanks for the countless hours we have spent chatting through every detail of both of our PhDs and, more importantly, your friendship. Jess, thanks for tolerating us over the last 4 years. Now, let's sack it all off and hire a barge.

Lastly, and most importantly, to my family; Mum, Dad, Marc, Zoe and Sam. Thank you for always supporting me in everything I do, and for at least trying to understand what a PhD is. I promise I will get a real job now.

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List of abbreviations

AOA Angle of arrival

API Application programming interface

BEACHES Behaviours of eating and activity for children's health evaluation system

BLE Bluetooth low energy

CHES Comprehensive home environment scale

CI Confidence interval

CM centimetre

CPE Counts per epoch

CPM Counts per minute

CSV Comma separated file

CV Coefficient of variation

EMA Ecological momentary assessment

FITT frequency, intensity, time, time

FPS Frames per second

G Grams

GIS Geographic information system

GPS Global positioning system

Hz Hertz

IC Integrated circuit

ICC Intra-class correlation coefficient

IPAQ International physical activity questionnaire

IR Infrared

M Metre

MAPE Mean absolute percent error

MB Megabyte

MET's Metabolic equivalents

MM Millimetre

MVPA Moderate-to-vigorous physical activity

NHS National health service

OR Odds ratio

Oz Ounce

RCT Randomised controlled trial

RF Radiofrequency

RFID Radio frequency identification

RSSI Received signal strength indicator

RTLS Real time locating system

SD Standard deviation

SEM Standard error of the measurement

SOPARC System for observing play and recreation in communities

SOPLAY System for observing play and leisure activity in youth

SPACES Systematic pedestrian and cycling environmental scan

TOA Time of arrival

TOF Time of flight

TDOA Time difference of arrival

TV Television

TWR Two way ranging

UWB Ultra wide band

1 Introduction and literature review

1.1 Introduction

Physical inactivity, in other words not meeting moderate-to-vigorous physical activity (MVPA) guidelines, is a significant risk factor in the aetiology of major non-communicable diseases such as coronary heart disease, type 2 diabetes and certain types of cancer (1,2). Many of the initial epidemiological studies which established these relationships utilised self-reported measures of physical activity which are susceptible to both random and systematic bias resulting in imprecise quantification of these associations (3). These biases include recall bias (difficulty in accurately recalling the behaviour) and social desirability bias (providing answers which are believed to be socially acceptable even if they are not truthful). Objective measures of physical activity are less susceptible to these biases and can therefore provide a more precise quantification of these associations (3).

An emerging body of cross sectional and experimental evidence (4-8) suggests that large amounts of sedentary time may confer an unfavourable cardio-metabolic risk profile and thus contribute to the aetiology of non-communicable disease; however the degree to which this relationship is independent of physical activity is currently unclear. For example, a harmonised meta-analysis of more than one million adults found self-reported sitting time to be associated with an increased risk of all-cause mortality in the least physically active quartile (Hazard Ratio (HR) 1.27, 95% Confidence intervals (CI) 1.22-1.31); however, there was no association between sitting time and all-cause mortality in the most active quartile of physical activity (HR 1.04, 95% CI 0.99-1.10) (9). Similarly, a meta-analysis of 10 studies showed sedentary time to be associated with a higher risk of all-cause mortality in those with low levels of physical activity (HR 1.46, CI 1.22-1.75) than those with a high level of physical activity (HR 1.16, CI 0.84-1.59) (7). Guideline fulfilling, or higher, levels of physical activity may therefore attenuate the deleterious effects of sedentary behaviour.

Unfortunately, objectively measured data from national surveillance programmes have shown that only a small minority of adults are meeting physical activity guidelines; for example, in the United States just 5% of adults (3) and in the United Kingdom just 6% of men and 4% of women achieved national guidelines (10). These accelerometry data further show that adults spend the majority of their waking hours sedentary; for example, adults spend approximately 10 hours sedentary per day in the United Kingdom (10) and approximately 8 hours sedentary in the United States (11). It should be pointed out that accelerometers assess movement and that a lack of movement (i.e. time spent under 100 or 199 counts per minute (CPM)) may not be true sedentary time spent in a seated or reclined posture (12); however, these sedentary time figures are broadly comparable to the sedentary time figures found in a recent study conducted in the Netherlands of ~2500 participants with objectively measured posture via the ActivPAL (8).

Within the movement continuum (13) it has been suggested that, at least initially, it may be more palatable for individuals to replace sedentary time with standing and light intensity physical activity (14). Replacing sedentary time with light intensity physical activity may therefore be a “gateway” to eventual increases in MVPA, although this proposition has not been tested. Furthermore, experimental studies have shown improvements in a number of health biomarkers by interspersing prolonged sedentary time with short bouts of standing and light physical activity in inactive or clinical populations (15-17); however, the optimal frequency at which to introduce a break in sedentary time has yet to be established with many studies using a somewhat arbitrary break frequency of 20-30 minutes. Replacing sedentary time with light activity is therefore not only beneficial to health in its own right but may also facilitate subsequent uptake of MVPA.

Displacing sedentary time first requires an understanding of current levels, patterns and opportunities for change. Levels and patterns of sedentary time have been objectively assessed using accelerometers and posture sensors (12); however, identifying the opportunities for reducing sedentary time requires an understanding of the behavioural context. Context is defined as including the who, what, where, when and why of behaviour (18). The contents of this thesis are primarily concerned with where behaviour occurs (i.e. location) although who (Study Four), what (Feasibility Trial One of Study Three) and when (Study Four) are also investigated in specific parts of the thesis. Crude estimates of the behavioural location have previously been obtained using domain specific questionnaires (19,20). These have been sufficient to provide a simple measure of sedentary time spent in domains such as the workplace, home and in motorised transport; however, uncertainties exist about the subjective nature of the data and the validity of the questionnaires (21). Furthermore, questionnaires are unable to provide subdomain level data (i.e. the location within the workplace or home) or continuous time-stamped data.

Global positioning systems (GPS) have previously been used to provide objective and time-stamped outdoor location data which can then be combined with accelerometry or a posture sensor to provide an objective measure of the behaviour and its context; for example, the amount of MVPA accumulated in green space (22,23). Unfortunately, GPS require clear visibility to orbiting satellites and are therefore unable to assess indoor location (24). This is a significant gap given that the majority of an individual's day is spent indoors (25,26). Additionally, the major domains of sedentary time (i.e. workplace, school and home) are all indoor venues. This suggests that measuring the indoor environment, and individuals location within the indoor environment, is key to identifying opportunities to reduce sedentary time. For example, identifying whether children spend more time sedentary in their bedrooms or in their family living room will provide intervention designers with the requisite knowledge to target the most sedentary areas of the home and, potentially, more effectively reduce total sedentary time. To achieve this, an "indoor GPS" is required; therefore, the purpose of this four study thesis was to identify novel technologies that could fulfil this "indoor GPS" requirement, appraise their validity and reliability and develop innovative methodologies to extract behaviourally relevant data.

Aims of Study One

The purpose of Study One was to perform a systematic review which aimed to provide an overview of devices and technology currently used, or could potentially be used, to assess the indoor or outdoor location of physical activity and/or sedentary time.

Aims of Study Two

Utilising promising technologies identified in Study One, the purpose of Study Two was to assess, via a series of experiments, the characteristics of the Actigraph proximity feature and its intra and inter device reliability under normal conditions and when confounders are introduced. The primary hypothesis was that the proximity feature would show high levels of signal detection across all conditions. The secondary hypothesis was that intra and inter unit reliability would be reduced when confounders were introduced.

Aims of Study Three

The purpose of Study Three was to feasibility trial a number of novel measurement technologies across varied use cases to ascertain potential research utility. Feasibility Trial One investigated the use of electrical energy monitoring and wearable cameras as measures of television viewing time. Feasibility Trial Two investigated the use of proximity sensors and a posture sensor to assess the locations in which sitting occurs. Feasibility Trial Three assessed the use of proximity and posture sensors to determine office dwell time as a surrogate of height adjustable desk usage.

Aims of Study Four

The purpose of this study was to apply a novel measurement paradigm to profile the locations in which older adult care home residents spend their sedentary time and the effect of residents simultaneously being in the same location on movement levels. The primary hypothesis was that residents would spend the majority of their day sedentary. The secondary hypothesis was that residents would spend more time sedentary in their own room than in communal areas. The tertiary hypothesis was that residents would show less movement when simultaneously in communal areas of the care homes with other residents.

1.2 Defining physical activity, physical inactivity and sedentariness

Physical activity is defined as "any bodily movement produced by skeletal muscles that results in caloric expenditure above resting levels" (27). Sub-dimensions of physical activity include the frequency, intensity, time and type, collectively referred to as the FITT formula. Frequency of physical activity refers to the rate at which physical activity occurs over a period of time such as a day, week or month. Intensity refers to the effort required to perform physical activity expressed as energy expenditure. Time, or duration, refers to the time spent in physical activity over a period of time such as a day, week or month. Type, or mode, refers to the physical activity being engaged in such as walking, running or swimming.

Traditionally, the term "sedentary" has been used to denote individuals who did not engage in MVPA (28). The emergence of sedentary behaviour as a potentially distinct risk factor for chronic disease has necessitated the formalisation of its definition (6). Sedentary behaviour is now defined as "any waking behaviour characterised by an energy expenditure $\leq$ 1.5 metabolic equivalents (MET's) while in a sitting or reclining posture" (29). The definition therefore incorporates three components; that the participant be awake (i.e. sleep is not included), with very low energy expenditure and in certain postures. The combination of these parameters ensures that seated activities such as rowing or cycling are not included due to their energy expenditure and wakeful nature. Physical inactivity is used to denote those who do not achieve physical activity guidelines (29). The current definition of physical inactivity therefore means that individuals of different age such as young people, adults and older adults can be classified as physically inactive by different criteria due to their respective physical activity guidelines.

1.3 Measurement of physical activity and sedentary behaviour

Measurement of physical activity could be achieved through the use of self-reported measures, direct observation or device based measurement. Self-reported measures are able to provide broad estimates and trends at a population level (30) but may be unsuitable to detect behavioural changes in intervention studies or discern subtle differences amongst groups. Self-reported measures are subject to both recall and social desirability biases (12,21) whereby participants are unable to accurately recall the activity they have engaged in or are prone to report activities they perceive they should be engaged in rather than activities they have actually engaged in. Direct observation is able to overcome the problem of social desirability bias but requires trained observers and may create an artificial environment in which participants alter their behaviour under the knowledge that they are being observed. Direct observation can also be used to generate important contextual information such as the type of behaviour alongside when, where and with whom it occurs (31). Ecological momentary assessment (EMA) captures self-report data in real time and is thus able to negate the impact of recall bias. This method can use paper and pen based systems or electronic systems using tablet computers or mobile phones. For example, a prompted electronic EMA survey on a mobile phone has been used to assess the type of children’s physical activity and sedentary behaviour in conjunction with an accelerometer to assess frequency, duration and intensity (32). Likewise, EMA has been successfully used to assess the physical activity and sedentary behaviour of Scottish adolescents (33).

Objective measurement of physical activity relies primarily on the use of accelerometers, with the Actigraph (Actigraph LLC, Pensacola, Florida) the most popular unit amongst physical activity researchers. Accelerometers are able to measure the amplitude and frequency of acceleration of the body through one, two or three planes of movement (34). Modern Actigraph units are small, lightweight devices incorporating a tri-axial accelerometer alongside other sensors, worn on either the waist or wrist. These devices are typically deployed for one week to enable the assessment of habitual physical activity (34). Newer models of accelerometer are able to capture and store raw acceleration data, typically recorded in units of acceleration due to gravity and expressed as acceleration in metres per second squared (31). This overcomes the limitation of previous models which required the researcher to identify an epoch, such as 1 minute, over which the raw acceleration would be summed to provide a unit known as a ‘count’ (34,35). These counts are then related to energy expenditure in laboratory studies to provide cut points as a measure of the intensity of physical activity. Various cut points have been developed among different populations to denote sedentary time, light, moderate and vigorous intensity physical activity. The variety of available cut-points is a significant challenge as different cut-points can substantially alter guideline compliance figures and the proportion of time spent in different components of the movement continuum (36). Standardisation of data collection, processing and analytical procedures would therefore be a welcome development (37). Accelerometers are able to provide a valid and reliable measure of physical activity (38). Many devices include proprietary algorithms and units of measurement, with little information on these provided to researchers. Recent efforts have therefore stressed the desirability of creating a uniform unit amongst the plethora of available devices to facilitate cross-study generalizability (38). The availability of raw acceleration data should facilitate this undertaking. Whilst the Actigraph to date is the most widely used accelerometer in a research setting, there has been a proliferation of devices in recent years amongst both consumer and research markets. The pace of device validation research has thus far failed to match the pace of new accelerometer release. Therefore there are many commercially available accelerometers with limited or no validation data (39).

Self-reported measures have been developed to assess sedentary behaviour; however, the lack of conscious processing associated with sedentary behaviour may limit the ability of individuals to accurately recall their sitting time. Despite this limitation, self-reported measures of sitting time remain the most feasible measures for use in large, epidemiological studies (40). Self-reported measures of sedentary time can be highly variable in their validity and reliability, although they are generally of comparable magnitude to self-reported measures of physical activity (21). These measures generally show stronger reliability for sedentary activities performed frequently and for extended periods of time such as occupational sitting whilst validity is generally stronger for measures assessing domain specific sitting (21,41). Self-reported measures may therefore be most useful to provide estimates of sitting in specific domains (42,43) alongside device based measures to assess total sitting time. Self-reported measures have also been suggested as the most convenient method to assess the type and context of sedentary behaviour (44). Whilst self-report measures are arguably more convenient, device based measures of physical activity and sedentary time unarguably offer more refined and objective information to the researcher. Similarly, using device based measures to assess the context of physical activity and sedentary time is also likely to offer more refined and comprehensive information over self-reported context. Technological development to date and in the near future is also likely to facilitate device based measures of context (35,45).

Primarily a measure of physical activity, an accelerometer cut-point below 100 CPM has been widely used to denote sedentary time (40,46). However this cut-point does not necessarily denote sedentary time but instead infers this from a lack of movement; thereby leading to potential misclassification of stationary standing activities with sedentary activities (12,43,47). Further difficulties emerge in that commonly used data criteria have emerged for physical activity, such as the use of 10 hours of device wear to be a valid day or the use of four valid days as a measure of habituality, and have been used as the default criteria in the absence of specific criteria for sedentary behaviour (44). It is possible that four valid days of data may not be representative of habitual sedentary behaviour and that fewer or a greater number of days may be needed. The inability of accelerometers to differentiate between postures has led to the use of inclinometers such as the activPAL (PAL technologies Ltd, Glasgow, UK). The activPAL is a small device attached to the midline of the thigh using adhesive patches which uses proprietary algorithms to determine posture on the basis of thigh acceleration (12). In adults, Kozey-Keadle and colleagues (48) found activPAL measured sitting to be highly correlated with direct observation. Likewise Grant et al (49) found the activPAL to have a mean percentage error of 0.19% compared to direct observation. Whilst the activPAL appears to be a valid measure of sitting time, the adhesive dressing may prove irritable and uncomfortable for a small number of participants, negatively impacting participant compliance (50). Newer versions of the Actigraph accelerometer also have an integrated inclinometer. Preliminary findings indicate mixed evidence on the validity of this function (51,52).

Recently, pressure sensors have been used to develop a sit pad. This device demonstrates excellent validity and reliability under prescribed and free-living conditions (53). Whilst this device may be useful for assessing sitting time in a particular domain, such as occupational sitting, due to limited mobility it is highly unlikely to be a suitable measure of total sitting time. Interest in the development of sedentary behaviour measurement devices is considerable. The LumoBack (Lumo Body Tech, Mountain View, California) is a small (4.15

x 10 x 0.8cm, 25g) posture sensor which is worn on the small of the lower back via an elasticated belt and continuously tracks the amount of time spent lying, sitting, standing and stepping via inertial sensors collecting data at a constant 25Hz (39,54). The LumoBack has shown strong correlations in free living conditions against the activPAL in total time spent standing (R^2 = 0.86) and sitting (R^2 = 0.89) (55) with a mean absolute percentage error (MAPE) of 9.5% when assessing total sitting time (56). Furthermore, the LumoBack has shown excellent agreement in step counting under controlled laboratory conditions against the Optogait treadmill test (MAPE 0.2%, Intraclass correlation coefficient (ICC = 0.99) and under free living conditions against the activPAL (MAPE 0.4%, ICC = 0.99) (57). Interestingly this device also incorporates a vibration setting when participants display poor posture, therefore offering the possibility that this setting could be modified to vibrate when participants have been seated for a period of time.

1.4 Measurement of the outdoor built environment

The built environment can be defined as encompassing urban design, land use and the transport system (58). Urban design refers to the design of a locality and the physical elements within it, including arrangement and appearance, and is concerned with the function and appeal of spaces (58). Land use refers to the distribution of activities across space such residential, commercial, office or industrial. (58) The transport system refers to the physical infrastructure of roads, pavements, bike paths etc., and the service provided such as traffic levels or bus frequencies (58). The built environment therefore inherently encompasses patterns of human activity and movement such as urban design aesthetics or use of the transport system. This relationship and the process of encouraging and empowering individuals and communities to collaboratively shape their environments is known as place making.

Several audit instruments have been developed to assess various environmental attributes. A review (59) identified 31 instruments to assess the walkability and cyclability of an environment. These instruments vary by complexity, environmental variables assessed and method of reporting. The systematic pedestrian and cycling environmental scan (SPACES) instrument shows high agreement for 45 of 67 items when assessing total agreement (60). When assessing the test-retest reliability of telephone instruments administered to participants developed in San Diego, South Carolina and St Louis simultaneously, it was found that most questions from the three instruments showed moderate to high reliability (61). Brownson and colleagues (62) subsequently used trained auditors to implement a Likert scale version and a dichotomous scale version of the same instrument; however, most questions designed to capture broad environmental attributes had moderate to poor agreement (62). Most transport and land use mix questions showed high agreement whilst aesthetic and social environment questions showed moderate to fair agreement (62). Despite the moderate to high reliability of some variables assessed by some instruments, environmental audits still require trained auditors and are subject to substantial levels of error (59). Audits may also be most suitable to the area in which they are developed due to differences in the built environment across neighbourhoods, cities and countries.

A recent review of questionnaires to assess the neighbourhood environment for youth physical activity found just three questionnaires with substantial test-retest reliability and two with acceptable convergent validity; however, no single instrument displayed acceptable levels of validity and reliability (63). Whilst questionnaires are important to assess perceptions of the environment, they should be used with caution and alongside objective measures of the environment (64). In summary, subjective measures of the outdoor environment, such as environmental audits, show marked differences in their validity and reliability depending on the instrument used and the parameters it assesses. Furthermore, these measures require trained observers, can be time consuming to complete over large areas and require repeated completion to obtain more than a single snapshot of the potentially changing environment.

Geographic information systems (GIS) are able to overcome several of the limitations of environmental audits, allowing users to incorporate spatial information from a range of disparate sources into a single framework (65). This information could include environmental features such as facilities or the topography of an area. Particularly relevant to behavioural researchers, GIS allows the integration of GPS data. Whilst the integration of GIS and GPS alongside measures of physical activity such as accelerometers is certainly challenging (66), it holds exceptional promise for elucidating the features of environments in which people engage in physical activity and sedentary behaviour (67). For instance, in reviewing GIS measured environmental correlates of active travel in young people, it was found that only distance was consistently negatively associated with active travel (68). No consistent relationship was observed in either a positive or negative direction for land use mix, residential density or intersection density (68). In reviewing GIS measures of the physical activity built environment, built environment features were grouped into accessibility, availability, accommodation, affordability and acceptability (69). Land use data, street network data and commercial data can provide measures of availability, accessibility and accommodation whilst census and self-report data can provide measures of affordability and acceptability (69). However GIS is not without limitations. The data used in GIS is often collected for purposes entirely unrelated to physical activity such as town planning, the data is dependent upon the skills and expertise of the person collecting and entering the data, the data available may vary by region and, lastly, the data may be outdated and not match more contemporaneous measures of physical activity collected by the researcher (70). Furthermore, GIS is limited in assessing the temporal element of spatio-temporal data (71). Fully realising the potential of GIS for measuring the physical activity-built environment relationship is likely to require the close co-operation of a number of disciplines including behavioural science, geography and architecture (71-73).

1.5 Measurement of outdoor location

The measurement of outdoor location is important in delineating the amount of physical activity or sedentary behaviour accumulated in specific locations; enabling a more robust assessment of which environmental characteristics are associated with physical activity or sedentary behaviour (74). Without this information, environmental characteristics would be associated with total physical activity or sedentary behaviour, potentially diluting the association; for example, researchers may associate neighbourhood environmental characteristics with total physical activity and find a weak relationship but may find a stronger relationship when assessing activity which is only accumulated in the neighbourhood (75).

Measurement of where individuals engage in physical activity and sedentary behaviour has primarily relied on self-reported or direct observation instruments. Self-reported instruments are generally seen as adequate for assessing population trends and estimates in large, epidemiological studies (30); however, they are subject to both recall and social desirability bias and are unlikely to be suitable for detecting subtle variation or change. Direct observation systems are able to overcome both recall and social desirability bias (76). Several direct observation systems have been developed to assess physical activity performed in different settings, these include the behaviours of eating and activity for children's health evaluation system (BEACHES) (77), the system for observing play and leisure activity in youth (SOPLAY) (78) and the system for observing play and recreation in communities (SOPARC) (79). However, direct observation systems require trained observers, are unsuitable for long term monitoring and risk creating an artificial environment in which participants may alter their behaviour due to the presence of the observer (76).

The search for a more habitual measure of where physical activity and sedentary behaviour occur has led to the use of GPS alongside more traditional measures of physical activity. Originally developed by the United States Department of Defense, the GPS system consists of 24 satellites orbiting Earth (22). These satellites transmit signals to GPS receivers and are able to determine the location, direction and speed of the receiver based on trilateration between three or more satellites (24). Due to the original military application of GPS, a deliberate error was embedded into the system to reduce the risk of enemy forces using the system. This deliberate error was removed in 2000, thus making the system available to civilian users. The use of GPS has since proliferated into areas such as criminal offender tracking, vehicle tracking and vehicle navigation (24). Such has been the widespread adoption of GPS, that the European Union is currently investing substantial amounts of money into its own satellite system to ensure it is not reliant on American satellites. Early GPS devices possessed limited battery life, limited memory capacity and form factors unsuitable for wear for long periods of time and were thus adopted in sports before being adopted in health research (80).

The earliest GPS study in a sporting domain was conducted in 1997 (80). It was found from this initial evaluation that GPS could be used to assess human locomotion (80). Following this early study, GPS has been used to assess movement characteristics in sports such as Australian football (81), Orienteering (82), Hockey (83) and rugby (84). These studies have generally found GPS to be a suitable measure of movement patterns such as speed and distance. Physiological measures such as heart rate are often included alongside GPS to provide further data on the demands of a particular sport. GPS devices used in sport are often worn on the back via a custom made vest and are therefore unlikely to be suitable for long term wear. These sports studies therefore provide very little insight into the applicability of GPS for assessing free living physical activity.

The earliest study to use GPS to investigate free living physical activity was conducted in 2005 (22). The GPS units were found to provide valid and reliable measures of location when compared to a known geodetic point (22). Following the validation of these units, a small pilot study examined the feasibility of integrating GPS, GIS and accelerometer data. It was found that GPS and accelerometer data could be successfully integrated, with GPS data available for 67% of all MVPA time (22). Accelerometer, GIS and GPS data have since been successfully integrated in further studies to assess active commuting to school (85) and time spent outdoors after school (86). However few studies have progressed beyond a descriptive analysis of where individuals engage in physical activity, often mapping the data of individual participants (87). In reviewing 24 studies which used GPS in physical activity research, Krenn and Colleagues (88) found GPS data loss to be highly correlated with device wear time ($r=0.81$, $p<0.001$). Common reasons for data loss include signal dropout, limited battery power and poor protocol adherence (88). A review of 14 studies of GPS and accelerometry in young people found that roads, school grounds, general land use and active travel were the most frequently researched topics and that roads, school grounds and the home location appear to be important locations for physical activity and MVPA in young people (89).

Due to devices requiring a line of sight to the orbiting satellites, signal dropout can occur when this line of sight is broken. The necessity for GPS devices to have a clear line of sight to orbiting satellites also results in the devices being poor measures in an indoor environment. Participants are often required to remain stationary outside before commencing a journey to ensure that the GPS device can acquire satellite signal, failure to adhere to this can result in data loss. Whilst GPS can be used to successfully augment accelerometer measurement of physical activity, several shortcomings need to be addressed. One of the most significant challenges is determining where to ‘cut’ a series of longitude and latitude coordinates into meaningful locations and trips (75).

There is currently no established approach to the analysis and interpretation of GPS data (89), many studies have yet to progress beyond relatively simple descriptive measures of where physical activity occurs and there is currently no standard approach to the capture of GPS data (24). For example, in a recent review of 14 studies using GPS and accelerometry in young people, studies used different methods to integrate data, very few studies mentioned how missing or inconsistent data was dealt with and all studies had different inclusion and exclusion criteria for GPS and/or accelerometer data (89). The field may therefore benefit from establishing common approaches to data reduction, as has happened in the accelerometry field. Fully integrating GPS with physiological and behavioural sensors to provide a more comprehensive profile is a potentially powerful approach (90). For example, the PALMS system (Centre for Wireless and Population Health Systems, San Diego, California) seeks to combine GPS and accelerometer data for analyses and offers the potential to begin standardising approaches across studies. However, it is possible that even with more detailed measurement of where people spend their time, it may not be possible to conclusively demonstrate causal relationships between built environment characteristics and health behaviours (67).

Recent interest has accumulated in the use of wearable cameras in physical activity and sedentary behaviour research, mirroring the growth of the life-logging and quantified-self communities. The most popular of these devices is the Microsoft Sensecam. Worn on a lanyard round the neck and containing sensors such as passive infra-red, accelerometer and gyroscope, this device automatically captures a first person picture at a frequency of approximately 20 seconds. The device has a battery life of approximately 16 hours with sufficient memory capacity to store approximately 32,000 images (91). From initial small scale, pilot studies it appears that images generated from wearable cameras are a feasible means of assessing active travel behaviour (91,92).

Despite the encouragement offered by these initial studies, significant ethical, privacy and analytical issues remain. There is a possibility that participants may be wearing the device during situations in which they do not wish to be photographed. To overcome this, the device is equipped with a sleep feature which allows the user to power down the device for several minutes should they require privacy. There is also the possibility that the device may take pictures of individuals that participant’s encounter who do not wish to be photographed; these individuals may then become confrontational to the user. Linked to this is the possibility that individuals may be wearing the device in situations that are unsuitable for photography, such as dropping off or picking up children from school. In an effort to overcome some of these issues, Kelly and colleagues (93) proposed an ethical framework for the use of wearable cameras in research. The frame work includes the issues of informed written consent from participants, privacy and confidentiality, non-maleficence and the autonomy of third parties (93).

Alongside these privacy issues is the issue of data analysis. Current data analysis methods are laborious, involving the manual trawling and coding of images. For long term monitoring this may prove to be prohibitive in the adoption of wearable cameras. Efforts are therefore needed to integrate pattern recognition algorithms to semi-automate this process. Despite these issues, wearable cameras can be used to assess where behaviour occurs both indoors and outdoors and may therefore be able to supplement GPS to provide a more comprehensive profile of behaviour. The assessment of where behaviour occurs indoors is particularly important as on average, 90% of our time is spent indoors (25).

1.6 Influence of outdoor environment on physical activity and sedentary behaviour

A substantial body of literature has accumulated on the potential relationship between physical activity and aspects of the environment. This literature has been reviewed by several authors (94), with a review of reviews identifying 36 review articles (95). An initial review found accessibility, opportunities and aesthetic environmental attributes to be significantly associated with physical activity in adults (96). Features of weather and safety showed less strong relationships with physical activity (96). A subsequent review grouped the environment features assessed by primary studies into four groups of variables: functionality, safety, aesthetics and destinations (97). Positive associations were found for aesthetic features, general functionality of neighbourhoods such as sidewalks and the availability, accessibility and convenience of destinations and facilities (97). The SMARTRAQ study (98) was among the first to bring together experts from the behavioural sciences and urban planning fields and to utilise objective measures of both the environment and the behaviour. The study found measures of land use mix, residential density and intersection density were positively related to minutes of accelerometer measured MVPA per day (98). These features were subsequently combined to form a walkability index; the index was then able to explain additional variance in the behaviour over socio-demographic factors alone (98). Just 18% of individuals in the lowest walkability index quartile met the physical activity guideline of the time (30 minutes of MVPA per day) compared to 37% of individuals in the highest walkability index quartile (98).

Reviewing the leisure sciences literature, it was concluded that there is mixed evidence for a relationship between trails, parks, open space, recreation centres and physical activity (99). Reviewing 31 articles examining the environment-physical activity relationship in older adults led Van Cauwenberg et al (100) to conclude that there are inconsistent findings but most environment variables appear to be unrelated to physical activity in this age group. The review also identified a lack of prospective studies, a majority of studies originating in the US, a focus on total physical activity, a limited range of environment variance in this age group and the use of self-reported physical activity (100).

In an attempt to infer causality for the built environment-physical activity relationship, McCormack et al (101) reviewed only quasi-experimental or cross sectional studies that controlled for neighbourhood self-selection. Most studies included in the review reported null findings; however land use mix, connectivity and population density were found to be important correlates of physical activity (101). The built environment was more likely to be related to transport related physical activity than other types of physical activity (101).

To ensure the applicability of findings to a European context, Van Holle et al (102) examined only studies in European adults. Across 70 studies convincing evidence for several domains of physical activity was found for walkability, access to amenities such as shops and services and the composite factor of environmental quality (102). Access to recreational facilities, aesthetic attributes and traffic or crime related safety were unrelated to physical activity (102). Mirroring previous findings (101), transport related physical activity was more frequently associated with the built environment than recreational physical activity (102). A possible positive relationship was found for transport related physical activity and the provision of walking or cycling facilities whilst a possible negative relationship was found for hilliness (102).

In the United States, 5 articles reported a significant positive association between proximity and density of parks and objectively measured physical activity with 9 articles finding no association and 6 studies with mixed findings (103). Interestingly, the review found stronger associations between objectively measured physical activity and perceived environmental attributes than with objectively measured environmental attributes (103).

Considered collectively the above reviews show that there is a substantial body of literature documenting a relationship between the built environment and physical activity, indeed a review article (104) found that 89.2% of 169 studies showed a relationship between an aspect of the built environment and increased physical activity. However, almost all of these studies were cross-sectional therefore prohibiting the determination of the direction of causality.

Studies and reviews discussed thus far have all investigated physical activity; however, the outdoor environment may also be related to sedentary behaviour. Reviewing 17 studies, with 89 “instances” (i.e. Tests of association between two variables), significant associations were found in just 25 instances with none significant associations reported in 50 instances (105). The majority of included studies (n=14) relied solely on self-report measures of sedentary behaviour (105); future studies may therefore benefit from using objective measures. Sedentary behaviour therefore appears less closely associated with neighbourhood environmental attributes than physical activity, potentially due to the lack of direct concordance between sedentary behaviour settings (e.g. predominantly inside at work or home) and settings in which the environmental attributes were measured (e.g. neighbourhood environmental attributes) (105). This simultaneously points toward a lack of conceptually matched behavioural and environmental attributes (95) and the need to assess indoor environmental attributes for sedentary behaviour.

In children, positive associations have been found with time spent outdoors on physical activity, sedentary behaviour and cardiorespiratory fitness, although not necessarily causally (106). Furthermore, studies have found children were more physically active and less sedentary while outside than they were while inside (106). However, it should be pointed out that this review looked at outdoor and indoor time in general and did not consider the quality or type of those environments.

Examining the evidence for the environment-physical activity relationship in children and adolescents, Davison and colleagues (107) used three dimensions of environmental variables: recreational infrastructure, transport infrastructure and local conditions. A positive relationship with physical activity was found for the provision of recreational infrastructure and transport infrastructure such as sidewalks, controlled intersections and public transport (107). A negative relationship was found for local conditions, such as crime level and area deprivation, and transport infrastructure such as number of roads to cross and traffic density or speed (107).

Urban design, land-use patterns and transportation systems that promote walking and cycling have been found to be related to physical activity in children (108). Looking specifically at 24 studies of active travel in youth, Panter et al (109) found a positive relationship between physical activity and facilities to assist active travel, urban form in the neighbourhood, shorter route length and road safety en route. Extending this review to include broader social, economic and cultural factors led Pont et al (110) to include 38 studies. Greater distance, higher household income and increased car ownership were consistently associated with lower levels of active travel (110). Provision of recreational facilities and walking or cycling paths may also be associated with higher levels of active transport in youth (110).

Examining the relationship of the neighbourhood environment and physical activity in young people, it was concluded that the most supported features for children are walkability, traffic speed or volume, access or proximity to facilities, land use mix and residential density whilst the most supported features for adolescents are land use mix and residential density (111). Interestingly the most consistent relationships were found when using objective environmental measures and self-reported physical activity (111). When considering GPS measured greenspace and accelerometer measured physical activity, absolute MVPA time in greenspace is low but can be quite high when framed as a proportion of total MVPA (89).

The preceding discussion of the environment-physical activity relationship demonstrates that whilst the relationship is complex and reciprocal, there is convincing evidence that the built environment is related to physical activity in adults but that this relationship is less clear in young people. Many studies are cross-sectional and therefore unsuitable for determining causality, longitudinal and experimental designs would therefore be beneficial (74). Cross sectional studies also produce challenges in developing specific guidelines for (re)designing environments to support physical activity (74).

Several issues and problems were identified with early review articles, including the omission of potentially eligible studies, incomplete reporting of methodologies, incorrect reporting of the results of primary studies and a collation of the physical environment with social or cognitive factors (112). Caution should therefore be exercised when interpreting the findings of these reviews. More recently, a review of reviews across age ranges identified the following issues: neighbourhood self-selection, the definition of a place and the differing relationship with physical activity between objective and perceived measures of the environment (95). The authors therefore provided the following recommendations for future review and primary studies: develop more complex conceptual and statistical models, improve the rigour of review methodologies, improve the specificity of reporting, including age range and environmental features, give greater emphasis to measurement mode and a greater conceptual match between constructs of the behaviour and constructs on the environment (95). A fundamental issue within the current literature is that most studies examine non-location specific activity, potentially underestimating the association between environment and behaviour (113). The addition of a location measurement technology will allow the quantification of location specific activity and environmental attribute relationships.

In summary, the most robust method of assessing physical activity and/or sedentary behaviour and the outdoor environment in which they occur encompasses an objective behavioural measure, an objective measure of the environment and an objective measure of outdoor location. The preceding overview of the outdoor environment, physical activity and sedentary behaviour measurement demonstrate that there has been an emergence of technologies which are able to measure the behaviour, the outdoor environment and outdoor location. This is summarised in Figure 1.1.

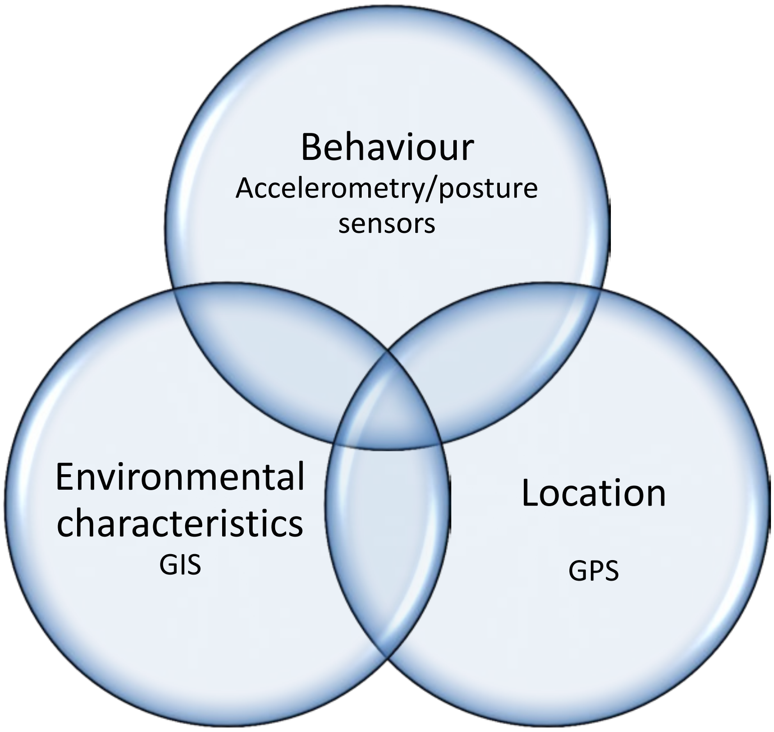

Figure 1.1 Representation of outdoor environment research

The integration of these disparate measurement areas is in its infancy; with best practice for the collecting and merging of these data streams still to be established. The integration of physical activity, sedentary behaviour and environmental measurement is vital to further understanding of where behaviour occurs; information which can subsequently be used to inform the development of effective intervention strategies. A particular requirement is the addition of an analogous technology to GPS capable of assessing where behaviour occurs in an indoor environment. The average individual spends up to 85% of their day indoors, where

GPS cannot measure location. Despite this, within a physical activity and sedentary behaviour context, the indoor environment is much less studied than the outdoor environment.

1.7 Measurement of the indoor environment

Similar to the early stages of outdoor environment research, the indoor environment has been assessed exclusively using self-report methods. In a recent review of 38 studies investigating the home environment and children's physical activity and sedentary behaviour, 19 studies used self-report, 14 used parental proxy-report and 5 studies included both (114). The most commonly reported measures of the home environment include availability of media equipment in the whole home and the child's bedroom, availability of physical activity equipment (e.g. treadmills) and the parameters of the garden (114). Many scales also seek to assess the wider obesogenic environment by including items related to nutrition; for example, the comprehensive home environment scale (CHES) assesses items such as fruit and vegetable availability, fat and sweets accessibility and physical activity equipment availability (115).

Similar to outdoor environment research, a common approach is then to associate the availability of media equipment with whole day objectively measured physical activity and/or sedentary behaviour. This non-location specific approach is likely to underestimate the effect of indoor environment features. For example, the amount of time a child spends in their bedroom may influence the strength of association between the presence of a television set and the amount of sedentary behaviour. The addition of an indoor location measurement technology would therefore allow location-specific associations to be drawn. In a review of studies in adults, all studies used self-report measures of equipment availability including televisions and exergaming equipment (116). A review of 37 articles in older adults considered studies using a variety of measures including environmental surveys and qualitative methods such as focus groups or open ended interviews (117). Overall many of the existing measures of the home environment focus on one or two constructs, are brief measures and lack transparency in their psychometric properties (118). Measures of media availability also fail to take account of the exponential growth of mobile technologies and video-on-demand services and the influence these may have on screen based sedentary time.

In relation to the indoor built environment, the school setting is poorly investigated with a recent review finding just six studies; three of which involved the installation of standing desks in an effort to reduce sitting time (119). Studies largely focused on the potential of pedagogic approaches and environmental modification for behaviour change with no explicit mention of how the indoor environment was assessed.

In the workplace setting, more feasible alternatives to space syntax have been sought; for example, the development of a self-report instrument to assess the office layout as a correlate of sitting including measures of local connectivity, overall connectivity, visibility of co-workers and proximity of co-workers (120). All measures showed acceptable-to-good internal consistency (Chronbach's $\alpha \geq 0.7$) and test re-test reliability (ICC ≥ 0.7) (120).

There is currently no indoor version of GIS; for behavioural researchers the assessment of indoor environmental attributes is therefore challenging and limited to self-report measures of equipment presence and access. It is possible that there may never be a universal indoor GIS due to the vast differences between indoor environments; researchers may instead have to rely on individual building-by-building measures.

Overall, few studies have gone beyond very simplistic counting of equipment availability. These brief, simplistic measurement tools are unlikely to capture the full range of possible influences across wider availability of furniture (for example, seats on which to watch television), the influence of the social environment or the fluid nature of indoor building layout. The field has yet to consider detailed and technical elements of spatial layout, size and accessibility (121). This is not surprising given the relative dearth of indoor environment research and when borne in mind that a far more developed body of work in the outdoor environment has yet to truly move beyond descriptive work and tackle the complexity of spatio-temporal data.

1.8 Measurement of indoor location

Domain specific questionnaires are commonly used to assess behaviour performed across workplace/school, travel and home; however, these questionnaires are not able to assess important sub-domain behaviour; for example, which rooms within the workplace, school or home the behaviour occurred (122). Wearable cameras have also been used to assess the type and context of objectively measured physical activity (123) and could provide a measure of indoor location if the captured image contains an identifying feature; however, this identifying feature may not always be present in the image and requires an extensive knowledge of the participants environment on the part of the image coder. Sociometers are novel devices which include a sensor network designed to measure face-to-face interactions between people. These devices incorporate an accelerometer, Bluetooth proximity sensor and audio recorder to collect data on an individual's interactions and communications (124). The inclusion of an accelerometer to measure movement and Bluetooth sensor to measure proximity between two Bluetooth devices make these devices consistent with other available technologies such as iBeacons; however, the inclusion of an audio recorder provides an extra data stream over other technologies. This extra data stream may therefore offer further utility over other technologies in elucidating not only when two individuals are in proximity but the purpose of them being in proximity through the audio recording. The validity of these devices has previously been assessed under simulated conditions within environments such as hospital emergency departments with the devices able to distinguish body movement and proximity between individuals but showing poor validity at detecting face-to-face interactions (125). Furthermore, in free living conditions the continuous recording of audio may be off putting to participants and may create an artificial environment in which participants are highly mindful of what they say.

Indoor location and sedentary time within a workplace have been measured using a radio-frequency identification (RFID) system in conjunction with a posture sensor; however, practical and technical challenges meant that the use of analogous system of indoor location monitoring cannot yet be recommended (126). In summary, an "indoor GPS" has yet to emerge.

1.9 Influence of indoor environment on physical activity and sedentary behaviour

Investigating the influence of the home environment on children's physical activity and sedentary behaviour, it was found that media equipment in the home and to a lesser extent the bedroom were associated with children's sedentary time. The presence of physical activity equipment was not associated with physical activity (114). However, the study of the home environment in children is limited by a lack of objective assessment and no investigation beyond the availability of equipment (114). Expanding on this review to include studies in adults, it was found that the quantity of physical activity equipment correlated with physical activity and the quantity of television sets correlated with sedentary time with greater effects in females (116). A recent review of 37 articles in older adults found pathway and corridor design and environmental cues, such as signs, that convey the function of a space were able to facilitate active living (117). However, the characteristics of the building were rarely described and potentially confounding factors such as the proximity of other individuals are rarely examined (117). This may be a consequence of there being little theoretical discussion of the relationship between micro-level indoor environment characteristics and their relationship with physical activity and sedentary behaviour.

The influence of the indoor environment on physical activity and sedentary behaviour raises the prospect of altering the environment in order to alter behaviour; one area which has received considerable recent attention is the use of standing desks in place of traditional desks (127). In a recent review of standing desks to reduce office based sitting, all five included studies showed reductions in occupational sitting (128). However, this effect may be influenced by including time, for example working hours, which is not spent at the desk. This becomes particularly important in intervention studies. For example, in pharmaceutical interventions the researcher is able to quantify the dose of medicine being taken. In behavioural interventions with an environmental component such as a height adjustable desk, where the intervention is the ‘medicine’ to change behaviour, and ultimately improve health, it is currently not possible to quantify the ‘dose’ of ‘medicine’ being taken.

Overall, although there is a paucity of evidence and poor measurement relative to the outdoor environment, the indoor environment, particularly the availability of equipment, appears to be related to physical activity and sedentary behaviour. Despite this, an indoor GPS equivalent has yet to emerge, limiting the study of the indoor environment. The state of indoor environment research is shown in Figure 1.2.

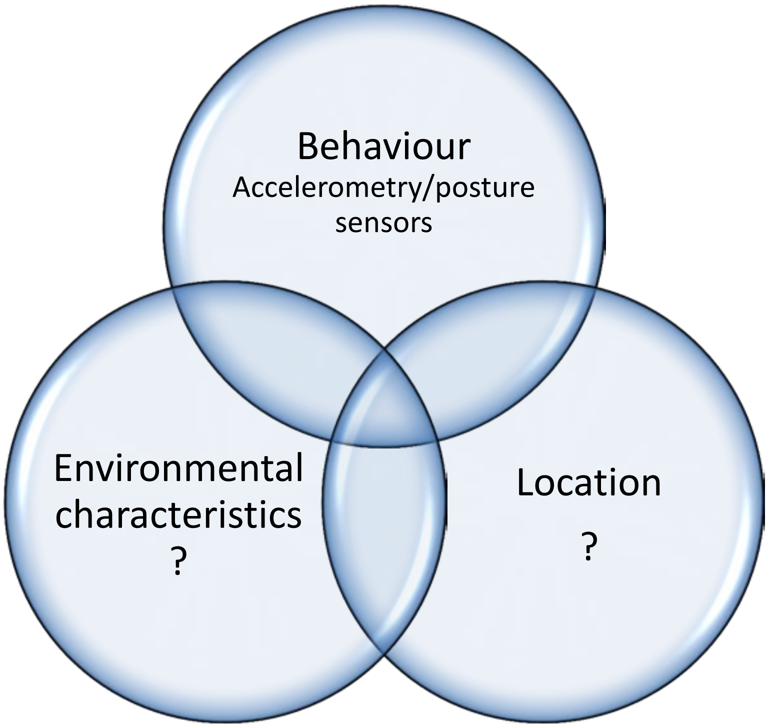

Figure 1.2 Representation of indoor environment research

1.10 Summary and overview of thesis

In summary, the preceding literature review provides evidence that both the outdoor and indoor environment are associated with physical activity and sedentary behaviour. In relation to the outdoor environment, several authors have reviewed the literature (94), with a review of reviews identifying 36 review articles (95). Considered collectively these reviews show that there is a substantial body of literature documenting a clear relationship between the outdoor built environment and physical activity; for example, one review article (104) found that 89.2% of 169 studies showed an association between an aspect of the built environment and increased physical activity. Objective measurement of the outdoor environment and its characteristics is commonly accomplished using GIS with GPS providing an objective measure of outdoor location in order to quantify exposure to those environments and characteristics. The measurement of outdoor location has shown utility in delineating the amount of physical activity or sedentary behaviour accumulated in specific outdoor locations; enabling a more robust assessment of which environmental characteristics are associated with physical activity or sedentary behaviour (74). Without this outdoor location, environmental characteristics would be associated with total physical activity or sedentary behaviour, potentially diluting the association; for example, researchers may associate neighbourhood environmental characteristics with total physical activity and find a weak relationship but may find a stronger relationship when assessing only physical activity which is accumulated in the neighbourhood (75). This location specific approach is more theoretically robust and enables a more specific assessment of a behaviour in the time and space in which it occurs (129).

In relation to the indoor environment, there is a paucity of evidence and poor measurement relative to the outdoor environment; however, several studies have shown associations between physical activity and sedentary behaviour and features of the indoor environment such as the availability of equipment including televisions or exercise equipment (116). Similar to previous outdoor environment research, a common approach is then to associate the availability of equipment with whole day objectively measured physical activity and/or sedentary behaviour. This non-location specific approach is likely to underestimate the effect of indoor environment features. For example, the amount of time a child spends in their bedroom may influence the strength of association between the presence of a television set and the amount of sedentary behaviour. To overcome this, an “indoor GPS” is required which is able to quantify time spent in specific areas of the indoor environment in a similar way to which GPS is able quantify time spent in specific areas of the outdoor environment. This four study thesis therefore seeks to improve the assessment of indoor location within physical activity and sedentary behaviour research.

1.11 Aims of thesis

The purpose of this four study thesis was to identify novel technologies that could fulfil this “indoor GPS” requirement, appraise their validity and reliability and develop innovative methodologies to extract behaviourally relevant data.

Aims of Study One

The purpose of Study One was to perform a systematic review which aimed to provide an overview of devices and technology currently used, or could potentially be used, to assess the indoor or outdoor location of physical activity and/or sedentary time.

Aims of Study Two

Utilising promising technologies identified in Study One, the purpose of Study Two was to assess, via a series of experiments, the characteristics of the Actigraph proximity feature and its intra and inter device reliability under normal conditions and when confounders are introduced. The primary hypothesis was that the proximity feature would show high levels of signal detection across all conditions. The secondary hypothesis was that intra and inter unit reliability would be reduced when confounders were introduced.

Aims of Study Three

The purpose of Study Three was to feasibility trial a number of novel measurement technologies across varied use cases to ascertain potential research utility. Feasibility Trial One investigated the use of electrical energy monitoring and wearable cameras as measures of television viewing time. Feasibility Trial Two investigated the use of proximity sensors and a posture sensor to assess the locations in which sitting occurs. Feasibility Trial Three assessed the use of proximity and posture sensors to determine office dwell time as a surrogate of height adjustable desk usage.

Aims of Study Four

The purpose of this study was to apply a novel measurement paradigm to profile the locations in which older adult care home residents spend their sedentary time and the effect of residents simultaneously being in the same location on movement levels. The primary hypothesis was that residents would spend the majority of their day sedentary. The secondary hypothesis was that residents would spend more time sedentary in their own room than in communal areas. The tertiary hypothesis was that residents would show less movement when simultaneously in communal areas of the care homes with other residents.

2 Study One: systematic review of indoor location systems

Study One has been published as an original article in a peer reviewed journal (130). With the exception of some minor wording and/or formatting changes that were necessary for the conversion to thesis format, it is presented in its published form.

This chapter contributes to the overall aims of the thesis through a systematic review of technologies which have been used in previous research to measure the location of physical activity and/or sedentary behaviour. Furthermore, a systematic website search was also used to identify technologies which have not been used in previous research due to the fast pace of technological development compared to research publication. This therefore fulfils the overall thesis aim of identifying relevant and novel technologies.

2.1 Introduction

Physical activity has a long established relationship, in both primary and secondary prevention, with several chronic conditions including diabetes, heart disease and certain forms of cancer (2). Recent evidence suggests that sedentary behaviour carries deleterious effects on health outcomes independently of MVPA in young people (4) and adults (131), although this is not a uniform finding (132). Sedentary behaviours are defined as any waking activity with an energy expenditure ≤1.5 MET's whilst in a sitting or reclining position (29). A paradigm shift is underway towards an increasing appreciation of the importance of reducing sedentary time alongside increasing physical activity (133).

Within the behavioural epidemiology framework (134), the location of a behaviour may influence the correlates of the behaviour and the intervention strategies needed to change behaviour. Discerning the varying contribution of multiple locations to physical activity and sedentary time will also allow researchers to target interventions to locations which are associated with the lowest levels of physical activity or highest levels of sedentary time. Understanding the contribution of multiple locations to health behaviours first requires the accurate measurement of location, as suggested by the behavioural epidemiology framework (134,135).

Sedentary behaviour and physical activity differ in the domains and locations in which they are likely to occur. Sedentary behaviour is likely, though not exclusively, to occur indoors at the home, at work or school or in leisure pursuits such as eating a meal or going to the cinema. Conversely, MVPA may occur through active transport, housework or purposeful exercise. This differentiating can be illustrated through the close link between adults on average spending approximately 90% of time indoors (25,26) and approximately 60% of time in sedentary activities (136). The large proportion of time spent indoors and the increasing research focus on sedentary behaviour suggest that an accurate measure of where behaviour occurs within the indoor environment would be particularly valuable.

Determining where physical activity and sedentary time are performed will provide valuable information in isolation; however, it can also act in a synergistic manner with other avenues of research. For example, much recent effort has focused on the use of complex pattern recognition techniques to determine the mode or type of activity being performed from raw acceleration data. Researchers in this area typically look to identify and classify the most common activities of daily living such as stair climbing, brushing teeth and vacuuming. Depending on the classification method used, classification accuracies between 50-90% have been achieved (137). Given the probabilistic nature of these activity classification methods, the inclusion of location based data into the current algorithms may provide greater levels of accuracy. For instance, the likelihood of stair climbing is greatly increased if an individual is near a staircase; likewise, the likelihood of brushing teeth is higher in the bathroom. Similarly, context sensitive questioning via EMA (138), can be enhanced by using location to trigger desirable questions in place of time based cues.

Furthermore, measurement of indoor location could benefit research into the correlates of physical activity or sedentary behaviour. For example, the presence of a television set in a child's bedroom may be a correlate of higher screen time (139); however, this may be a stronger correlate for those who spend more time in their bedrooms. Establishing how much time a child spends in their bedroom, via objective indoor location, could therefore fully elucidate the strength of this correlate. The accurate measurement of location could therefore greatly enhance several active research areas within physical activity and sedentary behaviour; both in and of itself and as an adjunct to other research areas.

Individuals may be able to accurately report the broad location of their physical activity and sedentary behaviour (122); however, self-report location instruments may be unable to provide detailed and temporally patterned location information. Objective monitoring may therefore provide the more robust means to measure the location of physical activity and sedentary behaviour. The precise and objective measurement of location will allow researchers to investigate both indoor and outdoor behaviours, therefore providing macro and micro level behavioural information. To date, time indoors has been inferred through the lack of GPS signal (85) or through the use of a light (LUX) sensor incorporated into activity monitors (140). However these methods are only able to differentiate indoor from outdoor and do not provide room or sub-room level location. Alongside measures of outdoor location, there is therefore a need for measures of room and sub-room level indoor location which are feasible for use in this field of research. The present review therefore aims to provide an overview of devices and technology currently used, or could potentially be used, to assess the indoor or outdoor location of physical activity and/or sedentary behaviour.

2.2 Methodology

2.2.1 Search strategy

Search strategies to identify potentially relevant articles were built around three key groups of keywords: behaviour, measurement and context. Key terms were: ‘sedentary lifestyle’ or ‘sedentary lifestyles’ or ‘sedentary behav*’ or ‘screen time’ or ‘seden*’ or ‘sitting time’ or ‘motor activity’ or ‘motor activities’ or ‘physical activity’ or ‘activities of daily living’ and ‘measur*’ or ‘assess*’ or ‘patterns’ or ‘monitor’ or ‘sensor’ and ‘context*’ or ‘setting’ or ‘location’ or ‘mode’ or ‘domains’ or ‘environment’. Scopus, Web of Science, PubMed, IEEE and OpenGrey were searched using the key terms up to January 2015. Subsequently, forward and backward searching of included articles (i.e. references and articles citing the included article) was conducted to identify any further eligible articles. In addition, manual searches of personal files were conducted.

2.2.2 Inclusion and exclusion criteria

To be included in the present review studies were required to meet the following criteria: [1] be published in English language; [2] either describe a tool used to measure the location of physical activity and/or sedentary behaviour or provide sufficient information to discern whether the instrument could be modified to measure location; [3] be a portable/wearable tool. Technologies were required to be portable or wearable to ensure that the technology is always with the participant and that the scope of the review was not so broad as to be unmanageable with non-wearable technologies (e.g. CCTV). A minimum of one part of the measurement system, not the whole system, was required to be wearable/portable for inclusion. For example, GPS systems consist of a wearable unit and orbiting satellites i.e. one part of the system is wearable but the whole system also consists of unwearable components. Wearable technologies is also an area which is experiencing rapid growth in the consumer sector, as technology increasingly becomes increasingly smaller, more powerful and multi-purpose. Wearable technologies therefore give this review a contemporary positioning. No date restriction was placed on search results. Studies erroneously defining sedentary behaviour as the absence of sufficient physical activity rather than activities undertaken in a sitting or reclined position (29), were treated as physical activity studies.

2.2.3 Identification of relevant studies

Titles and then abstracts of identified articles were screened to determine eligibility based on the above inclusion criteria. Titles and abstracts which did not meet the inclusion criteria were excluded. Following this, the full text of any potentially relevant article was obtained for full reading to determine conformity to the inclusion criteria. A 10% sub-sample of potentially relevant articles retrieved for full paper screening were extracted by a second author (JPS) to determine inter-rater agreement. If any discrepancies arose, these were resolved by discussion between authors. Inter-rater agreement was high (Cohen's Kappa = 0.81).

2.2.4 Data extraction and synthesis

Data of eligible papers were extracted via standardised forms developed for this review. All available information was extracted. Identified devices which assessed where physical activity and sedentary behaviour occur were tabulated to highlight the available literature in this research area and to showcase the array of measurement technologies.

2.2.5 Internet search engines

To ensure that the widest possible range of devices were included, systematic searches of internet search engines were performed for devices and technologies that are able to measure location but may not have made their way into the published research to date. This was necessary due to the relatively slow pace of research and publication compared to the pace of technological advance (i.e. new research papers may use old technology which has been surpassed by newer models). Google, Bing and Yahoo were searched using the following key terms: 'RTLS', 'GPS tracking device', 'RFID tracking', ' wearable camera', 'wearable GPS' and 'wearable RFID'. These search terms were chosen based on the results of the academic literature searches. Freely available specialist software (http://www.seoquake.com/) was used to export the first 300 results of each search to Microsoft Excel. This ensured that the results were unaffected by the changing algorithms of search engines. Searches were completed on 04/02/2015. The retrieved website addresses were screened to determine eligibility. Only manufacturer websites were included to ensure the accuracy of the information. All other websites, including blogs and consumer review websites were excluded. Eligible websites were then browsed for location monitoring devices. Only devices and fully integrated systems which are ready to use (i.e. not bespoke designs or electrical component sellers) were included in an attempt to address the practicalities of deployment to assess where physical activity and sedentary time occur. The specifications of these devices were then extracted using standardised forms developed for this review. If available, specifications were obtained from device manuals. If device manuals were not available, any specifications shown on the website regarding the device were extracted. Only available information was extracted (i.e. gaps in tables indicate a lack of available information). By note of caution, readers should be mindful that device characteristics, as supplied by manufacturers, are often generated under ideal conditions. Real world pilot testing with participants may therefore be required to establish real world device characteristics.

2.3 Results

The number of research papers included and excluded at each stage of the systematic review process is shown in Figure 2.1. This review began with 61,009 potentially eligible papers, eventually resulting in the full inclusion of 98 papers. A further 90 papers were then identified through reference searching, citation tracking and the searching of personal files.

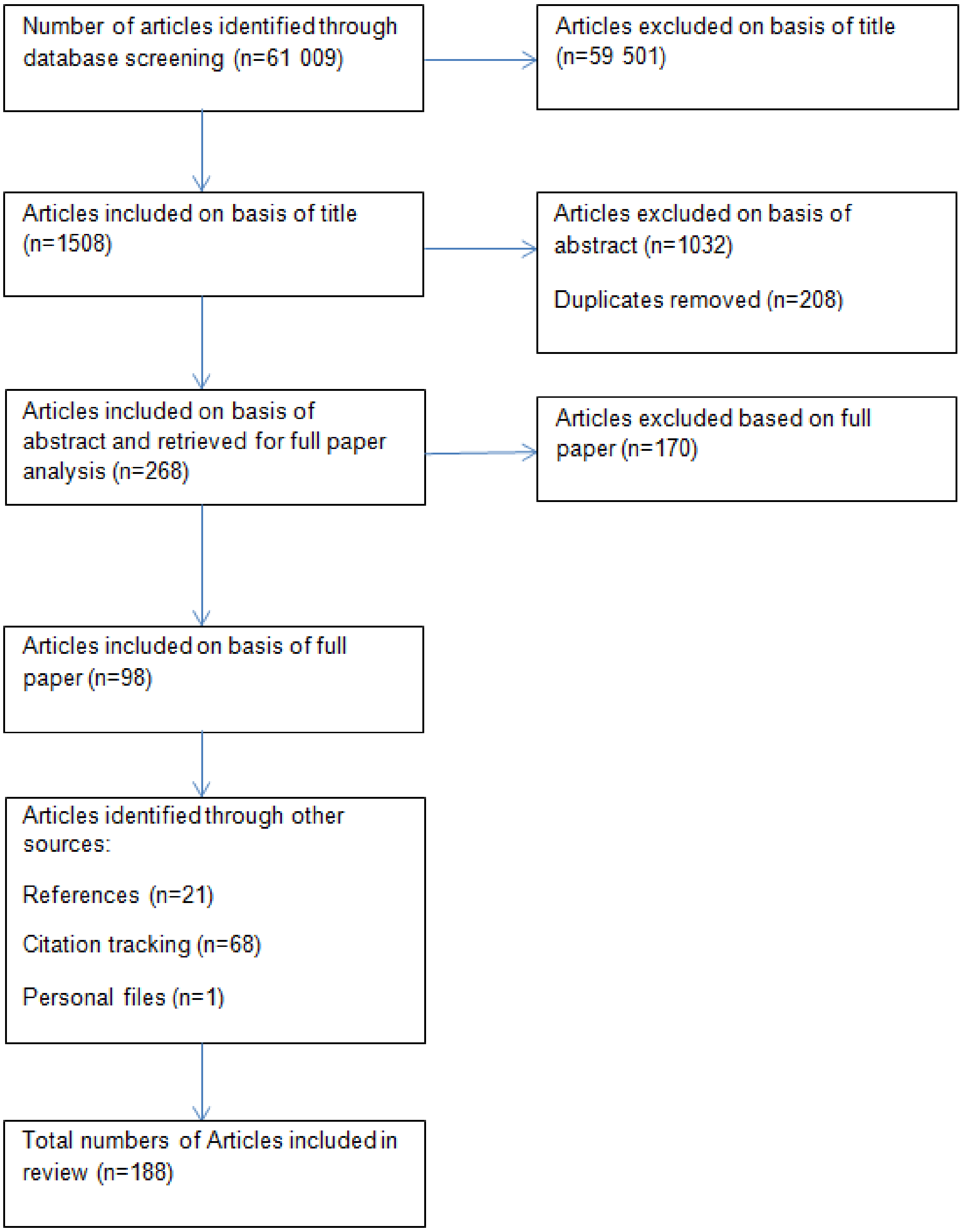

Figure 2.1 Flow chart of study selection

A breakdown by year and technology is depicted in Figure 2.2. The present review found 12 types of technology capable of assessing where physical activity and sedentary behaviours occur. GPS was the most widely used location monitoring technology, comprising 119 of the total 188 papers. Wearable cameras and RFID were the second and third most popular forms of location technology, contributing 23 and 20 studies respectively. The remaining 9 technologies each contributed a small number of studies (8 or less) to the total sample. GPS has the longest history of use, initially being used within sports science in 1997. Conversely wearable cameras and Wi-Fi based localisation technologies appear to be the most recent debut within research.

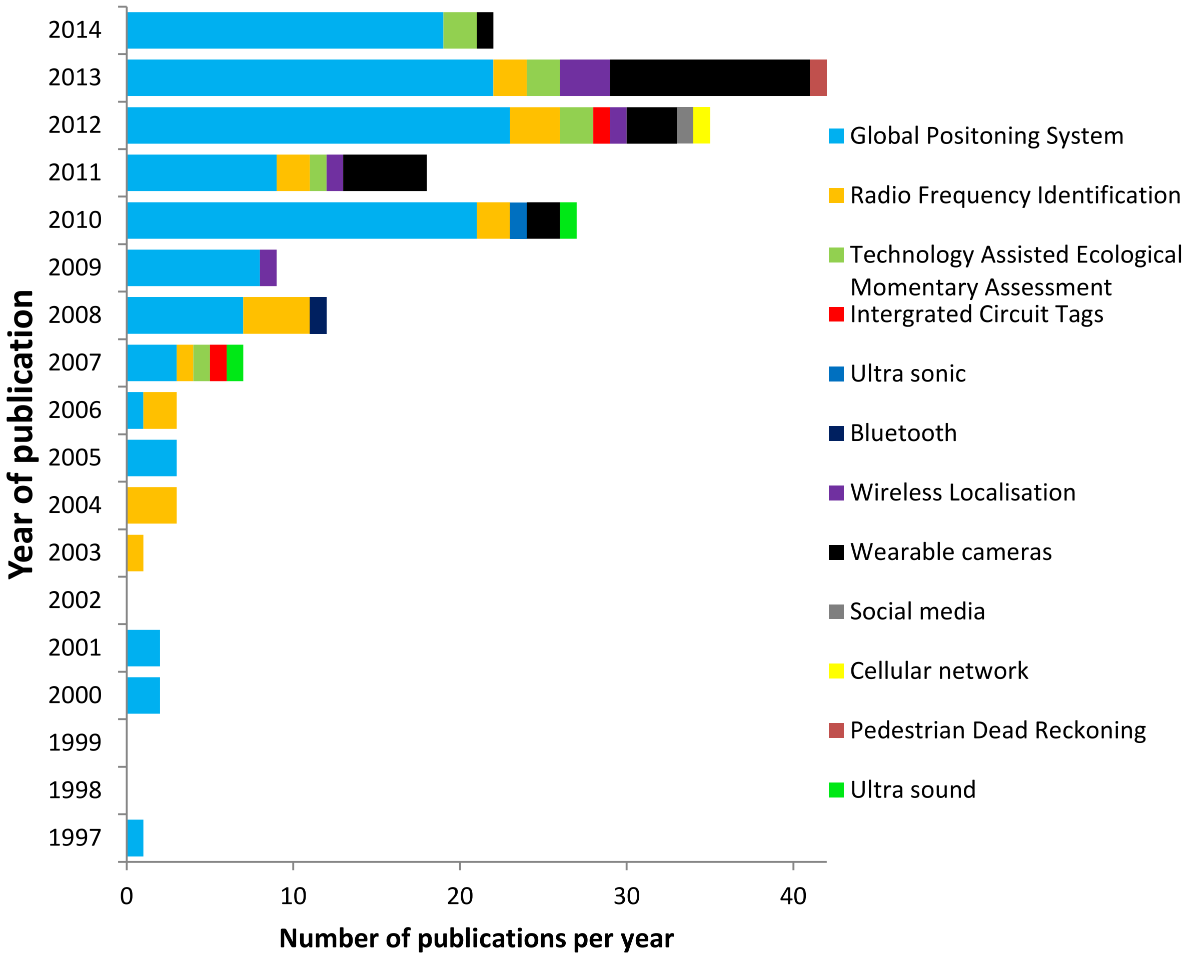

Figure 2.2 Number of studies published each year covering different types of technology

12 kinds of technology were found during the course of this review. Radio-frequency identification covers both active and passive systems. Technology assisted ecological momentary assessment covers mobile phones and PDA's. Integrated circuit tags transmit magnetic waves to determine location. Ultrasonic covers the BAT system which uses ultrasonic waves to determine location. Bluetooth was used in one study to determine location based on the received signal between a mobile device and base station. Wireless localisation covers various systems which determine location based on characteristics of the wireless signal within buildings. Social media covers one study in which participants 'checked in' to locations whenever they visited them. Cellular network was used to determine location via the service provider's radio towers and the mobile device. The pedestrian dead reckoning system uses several wearable sensors to determine the distance and direction that the wearer travels. Ultrasound utilises beacons programmed with a unique identification number placed around the environment that communicate with a wearable component.

Selective details of devices used within research are shown in Table 2.1 (wearable cameras), Table 2.2 (GPS) and Table 2.3 (other).

Tables 2.4, 2.5 and 2.6 show selective characteristics of the results of the internet search engine searches for wearable cameras, real time locating systems (RTLS) and GPS respectively. These searches found 21 wearable cameras, 78 RTLS tags from 35 companies and 82 GPS devices. GPS devices were marketed for a variety of purposes, including the tracking of children by parents, elder monitoring to limit wandering and the tracking of young drivers. RTLS companies positioned their products as suitable for asset management applications in warehouses and to a lesser extent, equipment and patient tracking in healthcare settings. Wearable cameras were targeted towards extreme sports, life-logging and law enforcement applications.

Table 2.1 Summary of wearable cameras used to date in published research

Manufacturer	Model	Indoor or outdoor	Battery life	Camera resolution	Dimensions	Weight	Wear site	Sampling frequency	References and notes
Natural point inc	Opti-track-PRIME 17W	Indoor		1.7 MP	12.6 x 12.6 x 11cm	1.32 kg		30-360 FPS	(141)
Vicon	Motion Capture system			Up to 16 MP				Up to 1000 FPS	(142,143)
Prototype	E-button	Both	Approximately 10 h		6.2cm diameter	42 g	Pin onto shirt	10 FPS	(144-146)
Prototype	Prototype	Both	Approximately 7 h				Wrist	6 FPS	(147,148)
Microsoft	Sensecam (Vicon revue)	Both	Up to 16 h				Lanyard around neck	Change in sensor readings	(91,92,123,149-160)
Looxcie	Looxcie 2	Both	1-4 h		2.31 x 1.7 x 8.46 cm	22 g		15/30 FPS	(161)

MP = Megapixel; FPS = Frames per Second; g = grams; cm = centimetre; kg = kilogram; h = hours

Table 2.2 Summary of GPS used to date in published research

Manufacturer	Model	Battery life	Dimensions	Weight	Wear site	Cold start time	Storage capacity	References and notes
Garmin	Foretrex 201	15 h	8.4 x 4.3 x 1.8cm	78 g	wrist	45 seconds	10,000 points	(22,23,85,86,162-170)
Garmin	Forerunner 305	Typically 10 h	5.3 x 6.8 x 1.7 cm	77 g	Wrist	45 seconds		(87,171-173)
Garmin	Etrex	22 h			Neck and thigh			(174,175)
Garmin	Forerunner 201				Wrist	3-55 seconds		(176,177)
Garmin	Foretrex 101	12 h			Wrist	10 seconds		(178,179)
Garmin	Forerunner 205	10 h	53 x 69 x 18 mm	77 g	Wrist	45 seconds	72,00 points	(163,168,180-183)
Garmin	60				Pocket of backpack	0.5 Hz		(184,185)
Garmin	12CX				Harness	2 seconds		(82,186)
Garmin	Forerunner 305				Wrist	1 Hz		(173,187)
Garmin	Forerunner 110							(188)
Telespial systems	Trackstick II	16-36 h in full power, 2days-1 week in power save	11.4 x 3.1 x 1.9 cm			Maximum of 52 seconds	1mb of flash memory	(66,189)
Global sat	DG100	20-24 h			Waist	5, 15 or 30 seconds	Up to 50,000 data points	(163,185,190-195)

GPSports	SPI-Elite				On back via a harness	1 Hz		(81,83,196-203)
GPSports	WI SPI				In harness on back	1 Hz		(200,204)
GPSports	SPI-PRO				In harness on back	5Hz		(84,205-207)
GPSports	SPI-10				In harness on back	1Hz		(81,200,206,208-210)
Catapult innovations	MinimaxX	5 h	8.8 x 5 x 1.9 cm	67 g	On back via a harness		1gb flash memory	(198,206,211-220)
Telespial systems	Super	4-8 days			Waist	5 or 15 seconds		(221,222)
Qstarz	BT1000X	42 h	72 x 47 x 20 mm	65 g	Pouch on belt	35 seconds, 5 seconds, 15 seconds	400,000 points	(156,159,168,195,223-237)
Leica	System 500				In a rucksack	5Hz		(238,239)
Geostats	Geologger				In a rucksack	1 second		(240,241)

Wintec	Easy showily	Up to 15 h			Wrist	5, 15 or 30 seconds		(163)
Wintec	WBT-202	28 h	64 x 40 x 14 mm	55 g		34 seconds	260,000 points	(242)
Globalsat	BT335	25 h			Waist	30 seconds		(243-247)
Globalsat	TR203	8 h	79 x 42 x 18 mm	70 g		36 seconds	150,000 points	(168)
IGotU	GT 600	30 h	46 x 41 x 14 mm	37 g		35 seconds	262,000 points	(168)
IGotU	GT120	3 days		<50 g	Lanyard around neck		3 days	(248)
FRWD	B100	12 h	95 x 55 x 15 mm	85 g		42 seconds		(168)
Starsnav	BTS-110	22 h	76 x 46 x 20 mm	57 g		42 seconds	250,000 points	(168)
Adeo	GPS fitness trainer				Right arm			(187)
Polar	RS 800 G3 Heart rate monitor				Wrist			(187)
Mobitest GSL		Up to 100 h					128-512 Mb	(249)

Transystem inc	GPS logger 747A	32 h	46.5 x 72.2 x 20 mm	64 g	Handbag or trouser pocket	35 seconds	125,000 points	(250)
Sparkfun electronics	Kinetamap	Approximately 20 h			Waist	42 seconds		(251)
Miscellaneous systems including prototypes, mobile phone based systems and receivers								(80,173,252-265)

GB = gigabyte; h = hours; mm = millimetre; g = gram; cm = centimetre; Hz = hertz; Mb = megabyte;

Table 2.3 Summary of other measures used to date in published research

Type of measure	Indoor/outdoor	References and notes
Radio-frequency identification	Indoor	(266-285)
Wireless localisation	Indoor	(286-291)
Technology assisted ecological momentary assessment / Experience sampling	Both	(292-299)
Integrated circuit tags	Indoor	(300,301)
Ultrasonic (BAT system)	Indoor	(302)
Cellular networks	Outdoor but works indoor	(303)
Bluetooth	Indoor	(304)
Social media check in	Both	(305)
Ultrasound	Indoor	(306,307)
Pedestrian dead reckoning system	Indoor	(308)

Table 2.4 Summary of commercially available wearable cameras unused in research to date

Manufacturer	Model	Battery life of wearable component	Dimensions	Weight	Wear site
Autographer (309)	N/A	10 h	37.4 x 90 x 22.93 mm	58 g	Via clip or lanyard
Narrative (Formally Memoto) (310)	Clip		36 x 36 x 9 mm	20 g	Via clip or lanyard
	Clip 2				
Mecam (311)	Classic	80 minutes continuous	1.75 x 0.5 inches	1 Oz	Clip or necklace
	Mecam HD	60 mins-120 minutes	2 x 2 inches	2.5 Oz	
Ucorder (312)	Pockito IRDC260-R	up to 75 minutes	2.5 x 1.25 x 0.5 inches		
	Pockito IRDC260-B	up to 75 minutes	2.5 x 1.25 x 0.5 inches		
	Pockito IRDC150	Up to 2 h	1.1 x 0.6 x 3.5 inches		
	Pockito IRDC250	Up to 2 h	1.1 x 0.6 x 3.5 inches		
Parashoot (313)	2.1		45 x 45 x 15 mm	1.5 Oz	Via clip
Spyemporium (314)	Spy hidden camera glasses	1-2 h	160 x 40 x 40 mm		Glasses/ on face
Vievu (315)	Vievu2	2.5 h recording. 1.5 streaming	1.9 x 1.9 x 0.75 inches	2.4 Oz	Via clip
	LE3	Up to 5 h	3 x 2.1 x 0.85 inches	2.8 Oz	Via clip
Panasonic (316)	WV-TW310L	5 h continuous	45 x 75 x 41 mm	210 g	
	WV-TW310S	5 h continuous	45 x 75 x 41 mm	160 g	
Me Mini (317)	N/A	3.5 h			Lanyard
Pivot head (318)	N/A				Glasses/ on face
Fly Nixie (319)					Wrist

Ca7ch (320)	Lightbox		38 x 38 x 10 mm	30 g	Via clip
Elmousa (321)	QBIC-MSI	2 h	2.14 x 2.4 x 1.57 inches	95 g	Lanyard
Vidcie (322)	Lookout QUB	1 h, 8 h with battery pack	4.8 x 4.8 x 1.5 cm	37 g	Via clip

Mm = millimetre; h = hour; g = gram; Oz = ounce; cm = centimetre

Table 2.5 Summary of commercially available RTLS unused in research to date

Manufacturer	Model	Infrastructure/ method	Dimensions	Accuracy
Ekahau (323)	A4	Wi-Fi, RSSI and triangulation	45 x 55 x 19 mm	1 m
	A4+	Wi-Fi, RSSI and triangulation	45 x 55 x 19 mm	1 m
	B4	Wi-Fi, RSSI and triangulation	60 x 90 x 8.5 mm	1 m
	W4	Wi-Fi, RSSI and triangulation	51.5 x 50 x 17.5 mm	1 m
Ubisense (324)	Series 7000 industrial	UWB, TOA, AOA	71 x 64 x 47 mm	15 cm
	Series 7000 compact	UWB, TOA, AOA	38 x 39 x 16.5 mm	15 cm
	Series 700 tool tags (integrated unit)	UWB, TOA, AOA	107 x 39 x 30 mm	15 cm
	Series 7000 slim tag	UWB, TOA, AOA	83 x 42 x 11 mm	15 cm
	Series 700 intrinsically safe tag	UWB, TOA, AOA	38 x 39 x 25.5 mm	15 cm
	Series 9000 compact tag	UWB, TOA, AOA	38 x 39 x 16.5 mm	15 cm
	Series 7000 Trimode tag	UWB, TOA, AOA	71 x 64 x 47 mm	
Aeroscout (325)	T2 tags	Wi-Fi, RSSI, TDOA	62 x 40 x 17 mm	
	T2s	Wi-Fi, RSSI, TDOA	45 x 31 x 18 mm	
	T2-EB	Wi-Fi, RSSI, TDOA	85 x 59 x 19 mm	
	T3	Wi-Fi, RSSI, TDOA	74 x 50 x 10 mm	
	T4b	Wi-Fi, RSSI, TDOA	69 x 48 x 21 mm	
	T4P	Wi-Fi, RRSI, RDOA	180 x 85 x 45 mm	
	T5a	Wi-Fi, RSSI, TDOA	62 x 40 x 17 mm	
	T5b	Wi-Fi, RSSI, TDOA	113 x 59 x 19 mm	
	T5c	Wi-Fi, RSSI, TDOA	113 x 59 x 19 mm	
	T5h	Wi-Fi, RSSI, TDOA	62 x 40 x 17 mm	
	T6	Wi-Fi, GPS, RSSI, TDOA	100 x 80 x 55 mm	
Zebra (326)	Where tag IV	Wi-Fi, TDOA	43.7 x 66 x 21.3 mm	2 m
	Wheretag III	Wi-Fi, TDOA	21 x 66 x 44 mm	
Elpas (327)	Asset tracking tag (healthcare)	RF, IR, LF		Sub room

	Healthcare positioning tag	RF, IR, LF		Sub room
	High risk security bracelet (healthcare)	RF, IR, LF		Sub room
	Infant protection bracelet	RF, IR, LF		Sub room
	Personal safety bracelet	RF, IR, LF		Sub room
	Personnel identity badge (Healthcare)	RF, IR, LF		Sub room
	Asset tracking tag (commercial)	RF, IR, LF		Sub room
	Lone worker transmitter	RF, IR, LF		Sub room
	Low profile asset tag	RF, IR, LF		Sub room
	Personnel identity badge (commercial)	RF, IR, LF		Sub room
Centrak (328)	Asset tags	Wi-Fi		
	Staff tags	Wi-Fi		
	Patient tags	Wi-Fi		
Teletracking (329)	Whole system	IR, RSSI		Bed/bay
Sonitor (330)	Whole system	Wi-Fi, ultrasound, RSSI		I feet
Versustech (331)	Clearview badge	IR,		Up to chair level
Radianse (332)	T-100	RF, IR		Up to bed level
	T-400	RF, IR		Up to bed level
	T-600	RF, IR		Up to bed level
Securecare (333)	EnvisionIT	Wi-Fi		30 cm
Mojix (334)	E-Location	Passive RFID		Within 1 m
Assetworks (335)	Whole system	Tag to tag RFID		
Tempsys (336)	Fetch system	RF and ultrasound, TDOA		½ m
Awarepoint (337)	Asset tags	Zigbee,	1.8 x 1.3 x 0.5 inches	Up to bay level
	Wearable tag	Zigbee,	1.8 x 1.3 x 0.5 inches	

Comita (338)	Whole system	WI-FI		
Trackit (339)	Asset and patient tag	UWB, TDOA		< 1 feet
Nebusens (340)	Sirius Quantum	Zigbee,	22 x 32.72 x 5 mm	1 m
Essensium (341)	Mobile nodes	Wide over narrowband RF, TWR, TOF	19.8 x 8.8 cm	typically 50cm
Pluslocation (342)	R1 badge tag	UWB, TDOA	38 x 78 x 9.6 mm	< 1m
	R1 asset tag	UWB, TDOA	13 x 36 x 33 mm	<1m
	R2 tags	UWB, TDOA	87 x 42 x 10	<1m
Technical life care (343)				
Airista (344)	TDOA 1P66 tag	Wi-Fi, RFID, RSSI, TDOA	180 x 90 x 40 mm	1-2 m
	TDOA tag	Wi-Fi, RFID, RSSI, TDOA	53 x 35 x 15 mm	1-2 m
	AUTP-W tag	Wi-Fi, RFID, RSSI, TDOA	70 x 44 x 16 mm	
	AUTW-W tag	Wi-Fi, RFID, RSSI, TDOA	68 x 42 x 18 mm	
	ATP-W	Wi-Fi, RFID, RSSI, TDOA	86 x 54 x 8 mm	
	ATA-W tag	Wi-Fi, RFID, RSSI, TDOA	53 x 38 x 16 mm	
Conduco (345)				
Luminosity (346)		IR, RF		
Purelink (347)	Personnel tracking tag	RFID	85 x 54 x 4 mm	2 m
	Equipment tracking tag	RFID	85 x 54 x 4.5 mm	2 m
Sanitag (348)	Staff tag	RF, RSSI, TOF	90 x 61 x 5 mm	2.5 m
	Patient tag	RF, RSSI, TOF	43 x 36 x 10 mm	2.5 m
Aidarfid (349)		Wi-Fi, RF		
Openrtls (350)	tag	UWB, TDOA, TWR	66 x 44 x 17 mm	10 cm
Bespoon (351)		UWB, TWR, triangulation		
Ecived (352)	Loulan	RFID, ultrasonic		5 cm
Skytron (353)		Wi-Fi,		Up to chair level
Logi-tag (354)		RFID		
Red point positioning (355)	Tag	UWB,	56 x 32 x 14 mm	< 0.5 m

Bordatech (356)	Wrist tag	RFID,	Sub room
Point RF (357)	Dynamic positioning system	RF, IR, LF	1.5 m

RSSI = Received signal strength indicator; UWB = Ultra wide band; TOA = Time of arrival; AOA = Angle of arrival; TDOA = Time difference of arrival; RF = Radio frequency; IR = Infrared; RFID = Radio frequency identification; TWR = Two way ranging; TOF = Time of flight; LF = Low frequency; m = metre; cm = centimetre; mm = millimetre

Table 2.6 Summary of commercially available GPS unused in research to date

Manufacturer	Model	Battery life of wearable component	Dimensions
Trackstick (358)	Trackstick mini	3-14 days	3 1/2 x 1 1/2 x 3/8 inches
	Trackstick II	16 h-2 days (AAA)	4 1/2 x 1 1/4 x 3/4 inches
	Super trackstick	3 days-3 weeks (AAA)	4 1/2 x 1 1/4 x 3/4 inches
Trackershop-UK (359)	Pro-pod5	14-15 days	6.35 x 4 x 2.5 cm
	Pro pod 4	8-11 days	6.25 x 4 x 2 cm
	The chameleon	24 h	60 x 23 x 12 mm
	Personal GPS tracker		77 x 47 x 20 mm
Gotek 7 (360)	Prime 1.0	10 days normal. Up to 12 months with 1 update per day	
	Prime 2.0	15 days normal up to 14 months (1 per day)	65 x 42 x 25 mm
Carewhere (361)		5-7 days	
Pocketfinder (362)		Up to one week	
BluetrackGPS trackers (363)	Prime lite	100-170 h (5min) 150-220 h (10min)	67.8 x 37 x 20 mm
	Prime 1300	10 days in normal mode	
	Prime 2000	15 days in normal mode	65 x 42 x 25 mm
	Bond 2000	10-15 days normal mode	62 x 34 x 31 mm
	Bond 5800	20-40 days normal mode	70 x 40 x 44 mm
	Bond 11600	40- 60 days normal mode	140 x 35 x 33 mm
	Bond 17400	80 -100 days normal mode	200 x 35 x 30 mm
	The sniper	2 months live mode (2-4 months in battery save)	60 x 10 x 45 mm
	GPS belt		Depends on waist size
	Slim jim	4- 6 days normal use	115 x 35 x 5 mm
Trackinapack (364)	Advanced	Up to 10 days	2.63 x 1.38 x 0.79

			inches
	Advanced plus	Up to 15 days	2.5 x 1.5 x 0.79 inches
Protect my kids (365)		7 days	
Amber alter GPS (366)		Up to 40 h	2.8 x 1.5 x 0.8 inches
Traclogik (367)	Guardian GPS	100-220 h	67.8 x 37 x 20 mm
	Guardian pro GPS	2-14 days	62.5 x 40 x 25 mm
	Covert 2000	10-15 days	61 x 34 x 31
Laipac (368)	s911 lola	up to 5 days in sleep mode	5.4 x 4 x 1.6 cm
	s911 bracelet		5 x 4.4 x 1.5cm
	s911 personal locator		100 x 45 x 25 mm
Loc8tor (369)		Up to 9 months in power save. 3-14 days normally	68 x 36 x 20 mm
Meitrack (370)	MT90	14 h	77 x 47 x 20 mm
SonikGPS (371)	SNK001		
Global tracking group (372)	UBI-5000E	Up to 30 days	67.5 x 40 x 21 mm
GPS intergrated (373)	PGT2		92 x 44 x 18 mm
	PGT3		92 x 44 x 18 mm
Buddi (374)			
Key tracker (375)	Personal tracker		22 x 58 x 38 mm
RM tracking (376)		up to 6 days at 2 h per day	3.9 x 2.3 x 0.9 inches
Landairsea (377)	Silvercloud realtime GPS tracker	5-6 days at 2 h per day	3.9 x 2.26 x 0.9 inches
	Tracking key pro	2 week (4h), 4 week (2h), 6 week (1h per day)	3.01 x 1.95 x 1.4 inches
Dynaspy (378)	World tracker enduro pro	Up to 150 h	64.66 x 43.19 x 27.7 mm
	Ultra accurate real time	Up to 150 h	64.66 x 43.19 x

			27.7 mm
Whereible GPS (379)	Wheritrack		3 1/8 x 1 9/16 x 3/8 inches
Ilotech (380)	Triloc	60+ h	52 x 69.5 x 17 mm
GTX corp (381)	Prime AT	up to 16 days	67 x 37 x 20 mm
	GT200	50-60 h (5min), 70-80 h (10min), 120-150 h (sleep)	74.8 x 42.8 x 17.5 mm
	Smart sole	2-3 days	Depends on shoe size
	VL 2000	54-108 h	72.2 x 38.4 x 18.7 mm
Biosensics (382)	PAMsys		
Reconinstruments (383)	Recon jet	4 h	
Nike (384)	Sportwatch GPS	8 h with average use	1.5 x 10.1 x 0.6 inches
Garmin (385)	Forerunner 620	6 weeks (watch) 10 h (training)	45 x 45 x 12.5 mm
	Forerunner 220	6 weeks (watch) 10 h (training)	45 x 45 x 12.5 mm
	Forerunner 910XT	up to 20 h	54 x 61 x 16 mm
	Forerunner 920XT	24 h	48 x 55 x 12.7 mm
	Forerunner 610	4 weeks (watch), 8h (training)	45.7 x 63.5 x 14.2 cm
	Forerunner 310XT	up to 20 h	54 x 56 x 19 cm
	Forerunner 210	3 weeks (watch), 8 h (training)	45 x 69 x 14 mm
	Forerunner 110	3 weeks (power save), 8h (training)	4.5 x 6.9 x 1.4cm
	Forerunner 10	5 weeks (watch), 5 h (training)	45.5 x 57.2 x 15.7 mm
	Vivoactive	10 h (up to 3 weeks in smart watch mode)	43.8 x 38.5 x 8 mm
	Fenix 3 sapphire	Up to 20 h (6 weeks in watch mode)	51 x 51 x 16 mm
	Fenix 3	Up to 20 h (6 weeks in watch mode)	51 x 51 x 16 mm
	Epix	24 h (16 weeks in watch mode)	50.8 x 53.3 x 17.8

			mm
	Forerunner 15	8 h (5 weeks in watch mode)	45.5 x 57.2 x 15.7 mm
	Tactix	50 h (5 weeks in watch mode)	49 x 49 x 17 mm
	Fenix 2	20 h (5 weeks in watch mode)	49 x 49 x 17 mm
Revolutionary tracker (386)	RT-01		
	RT-02		
Everon (387)	Vega GPS bracelet		
Trax family (388)	Trax	1 day	38 x 55 x 10 mm
Ninja tracking systems (389)	Ninja tracker	300-400 h standby time, 5 minute reporting time, 100 – 170 h, 10 minute reporting:150-220 h	
Personal GPS trackers (390)	Personal GPS tracker	Up to 7 days	65 x 40 x 18 mm
	GPS tracker watch	24-48 h	60 x 45 x 18 mm
	Mini GPS tracker	2-4 days	58 x 22 x 11 mm
Retrievor (391)			28 x 15 mm
Duotraq (392)	DQ 300	140 h	68.5 x 38.5 x 23.5 mm
Mind me (393)	Mind me locate	48 h	65 x 35 x 17 mm
Bubble tracker (394)	Personal GPS tracker		79 x 42 x 18 mm

Cm = centimetre; mm = millimetre; h = hour;

2.4 Discussion

The present systematic review sought to identify tools which have been used or could be modified for use to assess where physical activity and sedentary behaviours occur. The present review identified 188 research papers which used 12 different types of technology. The most widely used technology was GPS with 119 publications; followed by wearable cameras and RFID with 23 and 20 publications respectively. The remaining 9 types of technology each contributed a small number of studies to the total sample. However, it should be noted that a number of these were bespoke or prototype systems; this is particularly true of RFID, Integrated Circuit (IC) tag systems and various communication protocols for wireless localisation.

Systematic grey literature searches identified 21 wearable cameras, 78 RTLS tags and 82 GPS devices. By only including devices which are ‘ready to use’ we sought to address the practicalities of deployment and limit the inclusion of bespoke technologies. Combined with the devices used within research papers to date, we identified a total of 264 devices. The history, principles of use and the applications for GPS, RTLS and wearable cameras will now be discussed in greater detail.

2.4.1 GPS

Originally developed by the United States Department of Defense, the GPS system consists of 24 satellites orbiting Earth. These satellites transmit signals to GPS receivers and are able to determine the location, direction and speed of the receiver based on trilateration between three or more satellites (24). Due to the original military application of GPS, a deliberate error was embedded into the system to reduce the risk of enemy forces using the system. This deliberate error was removed in 2000, thus making the system available to civilian users. The use of GPS has since proliferated into areas such as criminal offender tracking, vehicle tracking and vehicle navigation. Such has been the widespread adoption of GPS, that the European Union is currently investing substantial amounts of money into its own satellite system to ensure it is not reliant on American satellites. Early GPS devices possessed limited battery life and memory capacity and form factors unsuitable for long periods of wear. Thus GPS devices were first used for sports applications before making their way into health research.

The earliest GPS study in a sporting domain was conducted in 1997 (80). It was found from this initial evaluation that GPS could be used to assess human locomotion (80). Following this early study, GPS has been used to assess movement characteristics in sports such as Australian football (81), Orienteering (82), Hockey (83) and Rugby (84). These studies have generally found GPS to be a suitable measure of movement parameters in sport, such as speed and distance. Physiological measures such as heart rate are often included alongside GPS to provide further data on the demands of a particular sport. Two of the more popular GPS devices used in sport (SPI-pro, GPSports and MinimaxX, Catapult innovations) are worn on the back via a custom made vest and are therefore unlikely to be suitable for long term wear. These sports studies therefore provide little insight into the applicability of GPS for assessing free living physical activity.

The earliest study to use GPS to investigate free living physical activity was conducted in 2005 (22). The GPS units were found to provide valid and reliable measures of location when compared to a known geodetic point (22). Following the validation of these units, a small pilot study examined the feasibility of integrating GPS, GIS and accelerometer data. It was found that GPS and accelerometer data could be successfully integrated, with GPS data available for 67% of all MVPA time (22). Accelerometer, GIS and GPS data have since been successfully integrated in further studies to assess active commuting to school (85) and time spent outdoors after school (86).

In reviewing 24 studies which use GPS in physical activity research, (88) GPS data loss was found to be highly correlated with device wear time ($r=0.81$, $p<0.001$). Common reasons for data loss include signal dropout, limited battery power and poor protocol adherence (88). Due to devices requiring a line of sight to the orbiting satellites, signal dropout can occur when this line of sight is broken. The necessity for GPS devices to have a line of sight to at least three orbiting satellites also results in GPS only receiving signal within certain indoor environments such as a single storey building with a wooden roof or high storey building with large windows. Even under these circumstances, GPS is unable to determine room or sub-room level indoor location. Participants are often required to remain stationary outside before commencing a journey to ensure that the GPS device can acquire satellite signal, failure to adhere to this can result in data loss.

Whilst GPS can be used to successfully augment accelerometer measurement of physical activity, several shortcomings need to be addressed. There is currently no established approach to the analysis and interpretation of GPS data (24). Guidelines and common data analysis programs for the capture and analysis of GPS data, such as the PALMS system, are therefore highly useful in standardising approaches. Due to requiring a clear line of sight to orbiting satellites, GPS is most suitable for assessing outdoor location. However, up to 90% of our time is spent indoors (25,26). The ability to assess where physical activity and sedentary time occur in an indoor environment would allow the formation of a more comprehensive behavioural profile which incorporates contextual information alongside accelerometry measured intensity and duration.

2.4.2 Wireless localisation

Wireless localisation technology has been commercialised under the umbrella term RTLS. Used in healthcare (395) and warehouse environments, RTLS systems are able to assess the location of people or assets within an indoor environment. Many RTLS devices are commercially available (see Table 2.5). All function on the principle of determining the location of a mobile component via the known location of fixed components, though the method of determining location and the type of fixed component vary between manufacturers. Interested readers are referred elsewhere for detailed technological reviews of wireless localisation (396-399).

The fixed components of RTLS systems also vary between RTLS manufacturers. Some manufacturers, such as Aeroscout (Stanley Healthcare, Waltham, Massachusetts), require the installation of proprietary fixed reference points. Others, such as the Ekahau system (Ekahau, Reston, Virginia), are able to utilise existing Wi-Fi points within buildings as fixed reference points and therefore do not require the installation of infrastructure. Several manufactures also provide infra-red location beacons for increased location accuracy in areas of poor signal strength. The location of the mobile component of the RTLS system, worn by an individual or placed on equipment, is then relayed back to software supplied with the RTLS system. This software requires a floor plan of the environment being monitored; the location of the mobile component is then viewed on this floor plan or as an x and y coordinate. RTLS systems therefore function in much the same manner as GPS; providing x and y coordinates rather than longitude and latitude. The manufacturers of several RTLS systems suggest that their systems are capable of handling hundreds of mobile tags simultaneously. Manufacturer’s state that RTLS systems are generally accurate to within 2-3 metres.

However, RTLS systems are not without limitations. Due to their predominant use in the tracking of patients and equipment, many RTLS systems are configured for real time monitoring and require slight modification to generate a log of coordinates for any later integration with other data streams. At present, RTLS systems are not being used in physical activity or sedentary behaviour research; therefore, the feasibility of incorporating RTLS data with accelerometry is unknown. The RTLS software requires the manual setting of the scale of the floor plan and therefore introduces possible human error into the system.

Despite this, RTLS could potentially be used within physical activity and sedentary behaviour to answer a number of research questions which are currently assessed via self-report methods. For example, RTLS, alongside accelerometry, could provide location information to assess whether youngsters in a day-care centre are more likely to be active when they are near equipment such as a sandbox or when they are near other active youngsters. Likewise, if researchers are undertaking a standing desk intervention to reduce sitting time, participants are currently often asked to self-report how much time they spend at their desk. The amount of time the participant spends at their desk may impact any possible reduction in sitting time due to the standing desk. With RTLS, researchers would be able to objectively determine the amount of time their participants were at their standing desk and thus determine the success or otherwise of the intervention with greater certainty.

Determining the indoor location of physical activity and sedentary behaviour, via RTLS, may also be an important research finding in itself. For example, within an elderly care home environment, RTLS could be used to assess whether individual residents are more sedentary alone in their bedrooms or when mixing with other residents in communal areas. Depending on the findings, some residents may then be best suited to an individual intervention focussing on bedroom based sedentary behaviour whilst other residents may be more suited to a group intervention focussing on communal area sedentary behaviour.

2.4.3 Wearable cameras

Recent interest has accumulated in the use of wearable cameras in physical activity and sedentary behaviour research, mirroring the growth of the life-logging and quantified-self communities. However, several of the wearable cameras identified in this review appear to have limited public health utility due to very short (e.g. 1.5 hours) battery life. The most popular wearable camera in a research setting is the Microsoft Sensecam. Worn on a lanyard round the neck and containing sensors such as passive infra-red, accelerometer and gyroscope, this device automatically captures a first person picture at a frequency of approximately 20 seconds. The device has a battery life of approximately 16 hours with sufficient memory capacity to store approximately 32,000 images (91). From initial small scale, pilot studies it appears that images generated from wearable cameras are a feasible means of assessing active travel behaviour (91,92). Wearable cameras therefore provide broader contextual information; however, they can also be used to infer location. Commercially available wearable cameras, such as the Autographer (OMG Life Limited, Oxford, UK), also provide GPS coordinates alongside the photograph.

Unlike pure location measurement technologies, such as GPS and RTLS, wearable cameras are able to provide broader contextual information based on the generated images. For example, a succession of images may show a television set. From this, it could be identified that the participant is watching television. Likewise, a succession of images may show a group of people of a similar age to the participant which researchers may be able to classify as time spent with friends; this is important as an individual’s friends may play a role in shaping physical activity behaviours (400).

Despite the encouragement offered by these initial studies, significant ethical, privacy and analytical issues remain. There is a possibility that participants may be wearing the device during situations in which they do not wish to be photographed. To overcome this, the device allows the user to turn off the device for several minutes should they require privacy. There is also the possibility that the device may take pictures of an individual that participant’s encounter who does not wish to be photographed. Linked to this is the possibility that individuals may be wearing the device in situations that are unsuitable for photography, such as dropping off or picking up children from school. In an effort to overcome some of these issues, (93) an ethical framework has been proposed for the use of wearable cameras in research. The framework includes the issues of informed written consent from participants, privacy and confidentiality, non-maleficence and the autonomy of third parties (93).

Alongside these privacy issues is the issue of data analysis. Current data analysis methods are laborious, involving the manual trawling and coding of images. For long term monitoring this may prove to be prohibitive in the adoption of wearable cameras. Pattern recognition algorithms to semi-automate this process are available from computer scientists; however, there is a need for these to be integrated into device software in a manner which is suitable for end users. Despite these issues, wearable cameras can be used to assess where behaviour occurs both indoors and outdoors and may therefore be able to supplement GPS to provide a greater range of contextual information.

The preceding discussion of GPS, RTLS and wearable cameras highlights the principles, limitations and use in physical activity and sedentary behaviour research of each of these three technologies. GPS is the dominant technology used within research to date to assess where physical activity and sedentary time occur. However, the development of RTLS and wearable cameras offers the possibility to incorporate these technologies alongside GPS and accelerometry to provide a more comprehensive behavioural profile which fully elucidates the context, intensity and duration of the behaviour. The present systematic review also identified several other location monitoring technologies, such as RFID and IC tags, that are less 'ready to use' than the three main technologies discussed. Whilst these technologies, particularly RFID, may have a substantial research base behind them, there appears to be no 'off the shelf' complete system which is readily purchasable for location tracking.

The ability to assess where behaviour occurs in an indoor environment may be particularly elucidating for sedentary time. With the ability to assess where sedentary behaviour occurs at work (e.g. in a meeting room or at a desk) and home (e.g. sofa, desk or dining table), behavioural researchers would possess a more comprehensive profile of the context in which sedentary behaviour occurs which could further illuminate the most common modes of sedentary behaviour.

It is also worth briefly considering available technologies which were not included in the present systematic review, largely due to a lack of wearability. One such system (Xetal NV, Belgium) uses no wearable components at all; instead using intelligent temperature sensors placed around a room to measure body heat, using this to track location. However, the system is not able to differentiate between individuals and is therefore unlikely to be suitable for use in research where more than one person may be present in a room.

Bluetooth low energy (BLE) proximity systems have recently gained in popularity in certain applications. Many of these systems are primarily aimed towards retail applications for the purpose of proximity marketing. In this scenario small BLE beacons are placed around a retail environment. The customer, as they are perusing the store with a BLE enabled device such as a smartphone, then receives targeted marketing and discount offers to their phone based on their proximity to the beacons. For example, when the customer is perusing the carbonated drinks aisle in a supermarket, an offer may be sent to their phone for a particular brand of drink. These systems offer the potential to install BLE beacons within an indoor environment and determine location based on proximity to the beacons.

Of particular note, one company (Estimote Inc, New York,) have recently miniaturised their BLE beacons to the size of a sticker, suitably small that it may unobtrusively be attached to items such as chairs, bicycles and sports equipment. This novel 'nearables' equipment offers the potential to assess the location and type of behaviour.

2.5 Conclusion

The present systematic review sought to identify tools which have been used or could be used to asses where physical activity and sedentary time occur. We identified 188 research papers, of which 119 used GPS and 23 used wearable cameras. A total of 76 location tracking devices or systems were used. Systematic internet search engine searchers found 21 wearable cameras models, 78 RTLS tags and 82 GPS devices. This gave a cumulative total of 264 location tracking devices or systems. GPS is the dominant form of location tracking used within physical activity research to date. Whilst GPS is a valid measure of outdoor location, it is unable to be used within an indoor environment.

Recent developments in wearable cameras and RTLS systems have ensured that tools are now available which offer the potential to assess where physical activity and sedentary behaviours occur indoors and thus provide further contextual information, alongside GPS, when used in conjunction with measures of physical activity and sedentary behaviour such as accelerometers. Issues and limitations of each technology were identified, including privacy, data analysis and interpretation and common data processing methodologies. The integration of accelerometry, GPS and a technology capable of assessing indoor location would provide researchers with the ability to assess the indoor and outdoor location of physical activity and sedentary behaviour. Future research should therefore investigate the feasibility of incorporating these technologies, with particular reference to the wear-ability of the devices, the integration of data streams and the generation of meaningful behavioural outcomes.

This chapter has contributed to the overall aim of the thesis through systematically identifying available technologies which can measure the location of physical activity and/or sedentary behaviour. In total 264 location tracking devices or technologies were identified.

This fulfils the first part of the overall aim. The next chapter will further this by evaluating the validity and reliability of one location tracking system.

3 Study Two: investigation of the Actigraph proximity feature

This chapter contributes to the overall aims of the thesis through a validation study of one indoor location tracking system. Previous research has validated several of the systems identified in the previous chapter; including the Ekahau system (Ekahau, Reston, Virginia) (398,401-404), the Aeroscout system (Stanley Healthcare, Waltham, Massachusetts) (405), and the Ubisense system (Ubisense group PLC, UK) (406,407). This study applies similar validation methods to a novel location tracking system: the Actigraph proximity system. This system offers the advantage of assessing physical activity and location within the same device thereby reducing participant burden; however, the validity and reliability of the location tracking must first be determined. This chapter therefore fulfils the overall thesis aim of appraising the validity and reliability of a novel indoor location tracking system.

3.1 Introduction

A number of technologies were identified in Study One which are capable of assessing indoor location. Measures of indoor location have been developed for a number of healthcare, logistical and commercial settings. These include RTLS, used to track patients and equipment in healthcare settings and equipment within warehouse settings, and BLE based technologies such as iBeacons used for proximity based marketing. These technologies have been validated in a number of previous studies; typically, these studies involve placing the receiver part of a system in a known position, often within a gridded area to determine the accuracy of the system (408). Previous RTLS validation studies have broadly corroborated the manufacturers stated accuracy; these include the Wi-Fi based Ekahau system (Ekahau, Reston, Virginia) (≤3m) (398,401-404), Wi-Fi based Aeroscout system (Stanley Healthcare, Waltham, Massachusetts) (≤2.5m) (405), the UWB based Ubisense system (Ubisense group PLC, UK) (≤1m) (406,407).

Despite the promising accuracy of these systems, they require extensive infrastructure making them unsuitable for many environments, are expensive (particularly UWB) and in the case of Wi-Fi based RTLS are, in practice, only sufficiently accurate to determine room level location. Furthermore, BLE technologies such as iBeacon typically communicate with a smart phone and therefore require the participant to continuously carry their phone with them in order to continuously measure their location. Given the limitations associated with RTLS and iBeacon, it seems worthwhile to apply similar validation methodologies to novel technologies which may be able to provide a similar level of accuracy at less expense with lower infrastructure requirements.

The systematic review in Study One had an end date for the database and internet searches; however, searches outside the scope of the systematic review were continued in an ongoing effort to identify technologies suitable for indoor location monitoring as they were released. These searches yielded a particularly promising measure of indoor location. The two newest iterations (GT3X+BT and GT9X) of the most commonly used brand of accelerometer in physical activity research, the Actigraph (Actigraph LLC, Pensacola, Florida), also feature BLE capability allowing the devices to be used for proximity monitoring. Subject to adequate validity and reliability, using the Actigraph proximity feature offers the potential to assess activity and location within one device. Prior to the use of the Actigraph proximity feature in physical activity research it is important to evaluate its validity and reliability, using similar methodologies to those used in previous validation studies of GPS, RTLS and other BLE technologies.

This study investigated the Actigraph proximity feature across three experiments. The aim of Experiment One was to assess the basic characteristics of the Actigraph received signal strength indicator (RSSI) signal across a range of straight line distances. Experiment Two aimed to assess the level of receiver device signal detection in a single room under unobstructed conditions, when various obstructions are introduced and the impacts these obstructions have on the intra and inter unit variability of the RSSI signal. Finally, Experiment Three aimed to assess signal contamination across multiple rooms (i.e. one beacon being detected in multiple rooms).

3.2 Methods

3.2.1 Equipment

Actigraph provide the most widely used accelerometers to measure physical activity and sedentary behaviour. The two latest models from Actigraph (GT3X+BT and GT9X) are also equipped with BLE functionality allowing them to be used for indoor location tracking. Actigraph suggest that their location system should be used as a discrete “in” or “not in” an area. The system is currently only useable as an all-Actigraph system (i.e. other BLE enabled devices cannot be used). Using Actilife, Actigraphs are initialised either as “beacons” or “receivers”. Both beacons and receivers collect acceleration data as they normally would. Although either a beacon or receiver could technically be given to a participant, a receiver is generally preferable, for reasons which will be explained shortly.

To track a participant’s location, the participant is given a receiver Actigraph to wear, generally on their waist or wrist, in the same way in which an Actigraph would normally be deployed for physical activity measurement. Beacon Actigraphs are then placed around the environment(s) in which the participant is to be tracked. Similar to iBeacon deployment, Actigraphs should generally be placed high and unobstructed. As a participant moves around the environment, the receiver Actigraph then records RSSI readings from beacon Actigraphs which are broadcast at a user defined interval (from 10-60 seconds).

At the end of the monitoring period, the receiver Actigraph is then downloaded in Actilife with the location data being exported into a csv format. This CSV file shows the beacon

Actigraph serial numbers as column headers with a time-stamped RSSI then shown for each beacon. This is the reason that it is logistically favourable to wear the receiver Actigraph (i.e. if the receiver were around the environment it would be necessary to download each receiver and then manually join the data). Actigraph suggest that this should then be used as a discreet "in" or "not in" an area with an RSSI, regardless of what it is, indicating "in" and no RSSI indicating "not in".

3.2.2 Experiment One

To assess the basic properties of the Actigraph RSSI signal, two GT9X devices, one initialised as a beacon and one as a receiver, were placed facing each other, directly opposite, on a level floor. The receiver Actigraph was initialised to collect proximity data at 10 second intervals, the highest resolution possible. After one minute of data collection (i.e. 6 RSSI readings) with the receiver directly opposite the beacon, the receiver was moved 10cm away from the beacon for one minute. This process was repeated for one minute under the following conditions: 20cm, 30cm, 40cm, 50cm, 60cm, 70cm, 80cm, 90cm, 1m, 1.1m, 1.2m, 1.3m, 1.4m, 1.5m, 1.6m, 1.7m, 1.8m, 1.9m and 2m. The receiver device was then downloaded using Actilife version 6.11.8 and a data table of RSSI's exported to Microsoft excel 2010 for visualisation and analysis.

3.2.3 Experiment Two

In Experiment Two, the properties of the RSSI signal were examined in a test room under controlled conditions. Testing was completed within a ground floor room within the National Centre for Sport and Exercise Medicine at Loughborough University. The room dimensions measured 4.5 x 4.3 metres. The floor was demarcated into 0.5 x 0.5 m grids. Gridding was completed by two researchers using a 10m tape measure. From the top left of the room, 0.5m across from the left hand wall was marked at the top of the room on the floor using a non-permanent marker. This process was repeated from the bottom left of the wall. Masking tape was then used to join the 0.5m mark at the top of the room with the 0.5m mark at the bottom the room. This process was repeated at 0.5m intervals to complete the vertical gridding in Figure 3.1. To complete the horizontal gridding in Figure 3.1, this process was repeated, again starting from the top left corner of the room. From this top left corner, 0.5m down was marked on the floor using a non-permanent marker. This process was repeated in the top right hand corner of the room. Masking tape was then used to join the 0.5m mark at the top left of the room with the 0.5m mark at the top right of the room. This process was repeated at 0.5m intervals to complete the horizontal gridding. Each of the demarcated grids was then individually measured to ensure correct sizing. The gridded floorplan and beacon deployment is shown in Figures 3.1 and 3.2

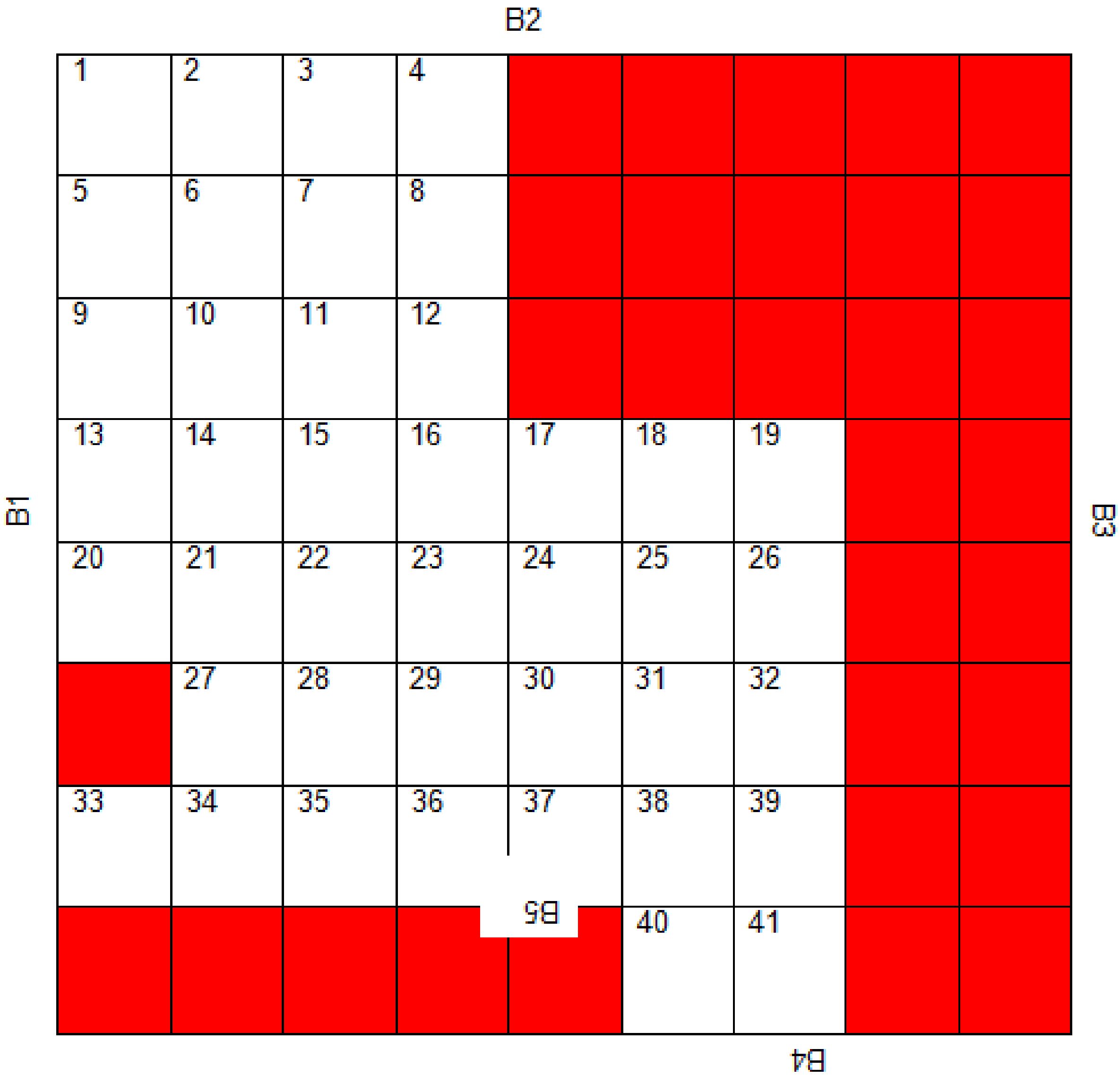

Figure 3.1 Demarcated floorplan used for Experiment Two

Testing for experiment two was completed within ground floor room within the National Centre for Sport and Exercise Medicine at Loughborough University. The room dimensions were 4.5 x 4.3 metres. The room was demarcated into 0.5 x 0.5 metre grids. Five beacons were then placed around the room; one beacon on each wall (four in total) and one beacon placed on cupboards which were high on the wall and may therefore block signal from the wall beacon Red squares indicate that the grid was inaccessible for testing; reasons for this include the presence of furniture and a sink. White grids indicate the grids in which testing was completed.

Figure 3.2 Photograph of the demarcated floorplan used in Experiment Two

Five Actigraph GT9X devices were initialised as beacons and three as receivers. Beacons were placed in the middle of each wall, 30cm from the ceiling. This was based on general principles of deployment obtained from manufacturers and technological review websites (i.e. place beacons centrally and high).

Receivers were initialised to record proximity at 10 second intervals, the highest resolution possible. The three receivers were placed in the centre of each grid for one minute (i.e. 6 measurements) on a cardboard tube one metre from the floor. This height reflects the likely approximate height in a real world setting when standing with arms down by the side or when sitting down. A cardboard tube was used as it does not interfere with BLE signals. At the end of each minute, a transition period of 30 seconds was used to enable the researcher to move the cardboard tube and receivers to the next grid.

When the receivers had been placed in every grid, confounders were then introduced and the protocol repeated for each confounder. These confounders were chosen from Table 3.1 as common interference sources with BLE signals which are likely to be present in a real world setting. Confounders selected were wood, metal and water. Wood and metal confounders consisted of thin sheets which were placed on top of the receivers. The wood confounder was a plywood shelf taken from a storage unit within the test building. The metal confounder was an aluminium sheet taken from a storage unit within the test building. Water confounder consisted of a human hand being placed over the receiver component of each technology with the researcher standing to one side so as to minimise blocking of the BLE signal from one beacon; however, at least three beacons should always have been clearly visible to the receiver. Human tissue was chosen as the water confounder as this was considered more ecological valid and more practical as it reduced the chances of water spillages onto the technology during the protocol. All confounders were of a sufficient size to completely cover the receivers. Each receiver was downloaded using Actilife version 6.11.8 and a data table exported to Microsoft excel 2010 for visualisation and analysis.

Table 3.1 Common sources of BLE interference (409)

Type of Barrier	Interference Potential
Wood	Low
Synthetic material	Low
Glass	Low
Water	Medium
Bricks	Medium
Marble	Medium
Plaster	High
Concrete	High
Bulletproof glass	High
Metal	Very high

3.2.4 Experiment Three

Building upon Experiment Two, Experiment Three assessed the Actigraph proximity feature across multiple rooms in an ecologically valid setting. A test dwelling (a first floor, one bedroom apartment) was used with three GT9X beacons placed around the environment; two beacons in the living room and one in the bedroom. Beacons were again placed high and central, consistent with the manufacturer's recommendations. A floorplan displaying the layout of the dwelling and beacon placement is shown in figure 3.3. One living room beacon faced towards the bedroom and one away from the bedroom. One GT9X receiver was worn by the researcher on their wrist; the researcher was wearing a long sleeved top which allowed the assessment of signal interference caused by clothing. The receiver was initialised to collect proximity data at 10 second intervals, the highest resolution possible.

The researcher completed the following conditions, chosen to reflect real-life scenarios, for 10 minutes each: Sitting on the sofa with the arm on the backrest with the sleeve up, sitting on the sofa with the arm on the backrest with the sleeve down, sitting on the sofa with the arm on the lap with the sleeve rolled up, sitting on the sofa with the arm on the lap with the sleeve rolled down, sitting on the left, middle and right of the dining table with the sleeve down, lying in bed with the arms outside of the duvet and lying in bed with the arms inside the duvet. The receiver device was downloaded using Actilife version 6.11.8 and a data table exported to Microsoft excel 2010 for visualisation and analysis.

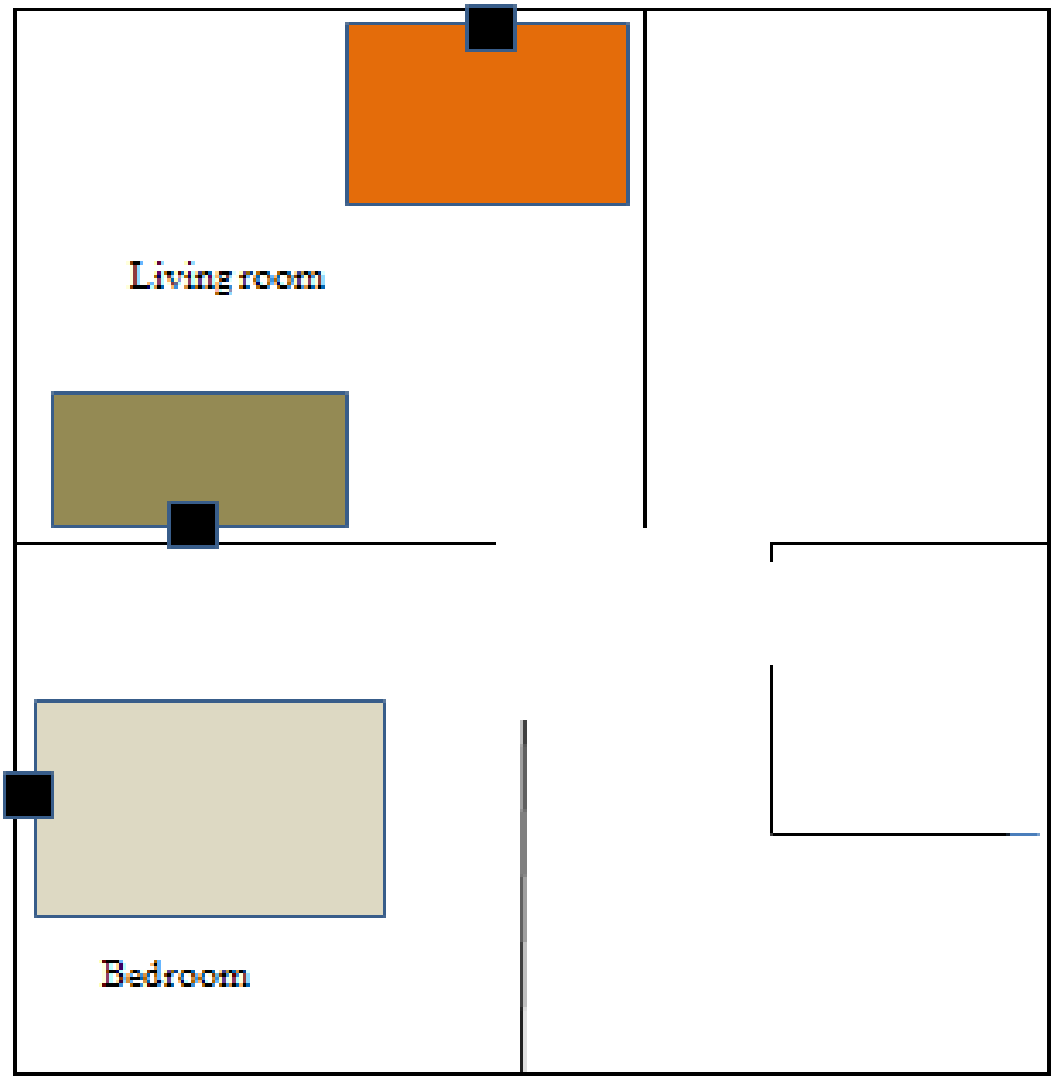

Figure 3.3 Schematic of the test dwelling used in Experiment Three. Three beacons were used; two in the living room and one in the bedroom.

3.2.5 Analysis

3.2.5.1 Experiment One

Within Microsoft 2010, the 6 RSSI readings at each distance was averaged for visualisation. The known distance between the receiver and the beacon and the corresponding average RSSI were graphed to show the linearity of the relationship. The raw RSSI was also processed into a distance estimate using the below formula:

=IF(RSSI/TxPower<1,^10,IF(RSSI/TxPower>1,^7.7095*0.89976+0.111))

This formula (410) was selected as it has been developed by iBeacon users to approximate the algorithm used to convert RSSI to distance estimates in the Apple iBeacon platform;

unfortunately an approximation is required as the exact algorithm used in the iBeacon platform is not publicly available. Given the inherent difficulties in robustly approximating distance from RSSI, the iBeacon platform utilises the distance estimate to categorise distances into immediate (<0.5m), near (<3m) and far (>3m). This categorisation is able to overcome, at least in the iBeacon platform, the difficulties of precise distance estimation from RSSI. The known and calculated distances were plotted to visually show the accuracy of the algorithm and descriptive statistics were calculated to show the accuracy of the immediate, near and far categorisation.

3.2.5.2 Experiment Two

Within Microsoft Excel 2010, descriptive tallies and percentages were calculated for binary BLE signal detection (i.e. signal or no signal) for each beacon and each receiver under each of the four conditions. Mean absolute percent error (MAPE) was then calculated for the total difference between the true and detected BLE signal for each of the four test conditions.

The raw RSSI readings for each of the three receivers across the five beacons under each of the four testing conditions were plotted to visually assess the intra and inter unit variability in RSSI. Intra and inter-unit mean, standard deviation and coefficient of variation were then calculated for each of the four testing conditions.

3.2.5.3 Experiment Three

Within Microsoft Excel 2010, descriptive tallies and percentages were calculated for binary BLE signal detection (i.e. signal or no signal) for each beacon under each test condition. MAPE was then calculated for the total difference between the true and detected BLE signal for each of the beacons.

3.3 Results

3.3.1 Experiment One

A summary of the data from Experiment One is shown in Table 3.2. The relationship between RSSI and distance is non-linear as shown in Figure 3.3. The relationship appears to become more erratic from 1m onwards. Furthermore, data at 0.3m appears to be an outlier amongst the data. Exactly the same RSSI was observed at a number of distances between the receiver and beacon; for example, 0.8m and 1m, 0.7m and 0.9m and 0.4m and 0.5m. This suggests that even if a robust RSSI to distance algorithm could be formulated, the Actigraph RSSI is not suitable for distinguishing precise distances based on RSSI alone; nor is the algorithm used able to adequately determine the zoned distance when using common iBeacon zone classifications

Table 3.2 Descriptive statistics from Experiment One

Distance (m)	RSSI	Calculated distance	Calculated zone	Actual zone
0	-35	0.00	immediate	Immediate
0.1	-45	0.02	immediate	Immediate
0.2	-50	0.05	immediate	Immediate
0.3	-86	2.00	near	Immediate
0.4	-63	0.54	near	Immediate
0.5	-63	0.54	near	Immediate
0.6	-64	0.63	near	Near
0.7	-66	0.86	near	Near
0.8	-67	1.01	near	Near
0.9	-66	0.84	near	Near
1	-67	1.01	near	Near
1.1	-78	3.02	far	Near
1.2	-68	1.12	near	Near
1.3	-83	4.85	far	Near
1.4	-75	2.26	near	Near
1.5	-74	1.98	near	Near
1.6	-79	3.32	far	Near
1.7	-90	1.48	near	Near
1.8	-86	6.02	far	Near
1.9	-82	4.19	far	Near
2	-85	5.93	far	Near

RSSI = Received Signal Strength indicator; Zones are defined as immediate ≤ 0.5m, near >0.5m and ≤ 3m, Far <3m.

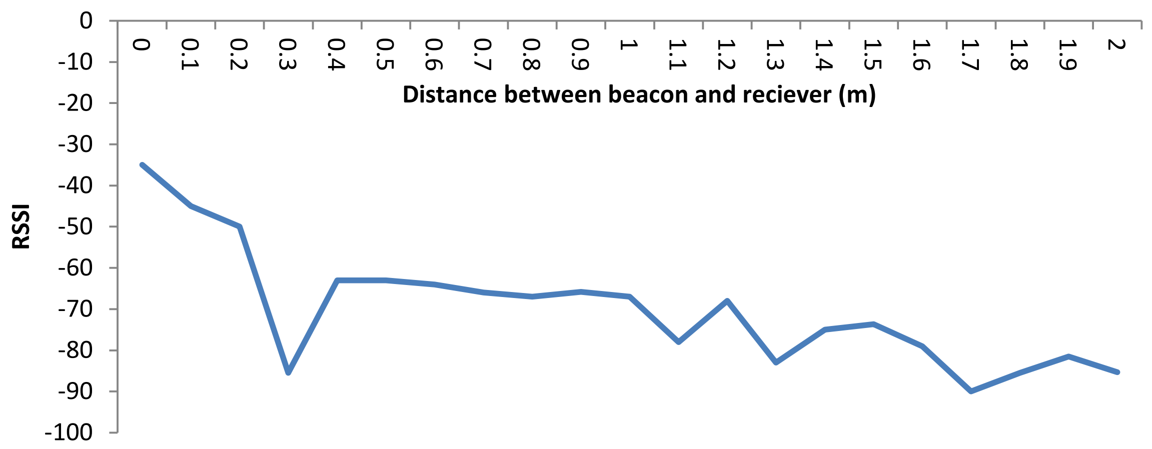

Figure 3.4 Relationship between RSSI and distance in Experiment One

RSSI = Received Signal Strength Indicator. The relationship between RSSI and beacon-receiver distance is non-linear with very similar RSSI's observed at multiple distances (e.g. 0.4-0.9m).

The relationship between the actual distance between receiver and beacon and the calculated distance is shown in Figure 3.4. Similarly to the relationship between RSSI and distance, these results show that, other than at 0.3m, the calculated distance closely approximates the actual distance up to 1m where the relationship becomes much more erratic. Several of the calculated distances are inaccurate by factors of three or more; for example, at actual distances of 1.3m and 1.8m.

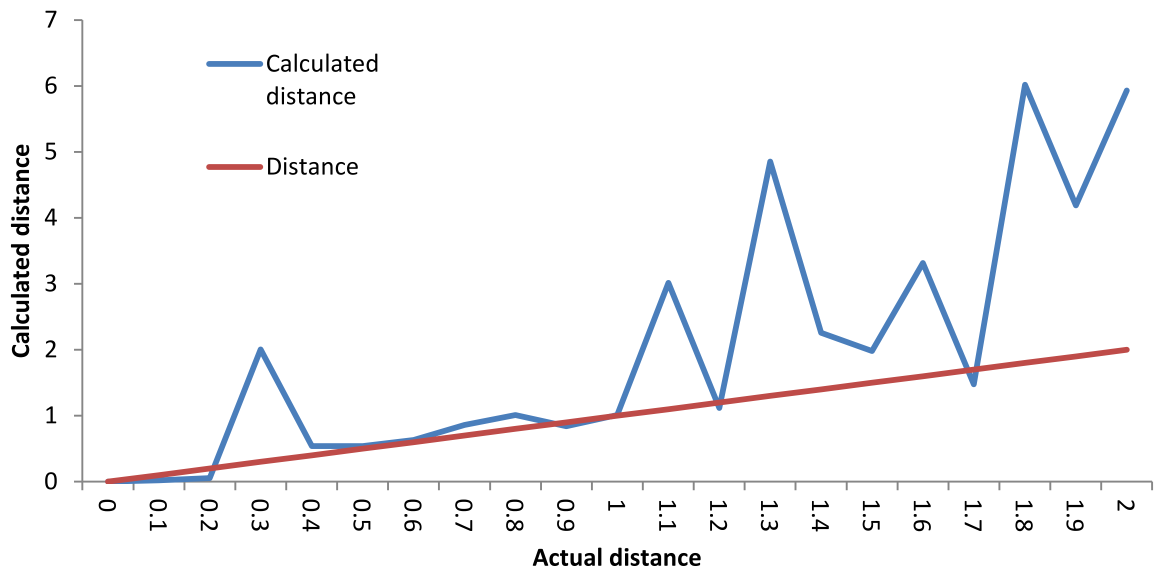

Figure 3.5 Relationship between actual distance and calculated distance

3.3.2 Experiment Two

Table 3.3 shows the total number of epochs and the overall percentage of epochs in which a signal was detected across the three receivers from the five beacons across the four conditions. The normal, wood and metal conditions showed very high signal detection (≥97.5%). Signal detection was attenuated under the human obstruction condition but still showed high detection rates (91.6%). Signal detection is shown per beacon and per receiver in Table 3.4. Overall, each beacon showed approximately the same detection rate, with 1.5% difference in detection between the highest and lowest detected beacons

Table 3.3 Descriptive statistics for binary beacon signal detection across conditions in Experiment Two

	True data points	Measured data points	% signal detection	MAPE
Normal	4095	4048	98.9	1.2
Human	4095	3749	91.6	9.2
Wood	4110	4072	99.1	0.9
Metal	4110	4009	97.5	2.5

MAPE = Mean absolute percent error

Table 3.4 Descriptive statistics per beacon and receiver for binary signal detection across conditions in Experiment Two

Normal	R1	R2	R3	Average
B1	98.9	99.6	99.3	99.3
B2	97.8	100	100	99.3
B3	98.9	99.3	99.6	99.3
B4	98.5	99.6	97.1	98.4
B5	97.1	98.2	98.9	98.0
Human				
B1	86.1	86.4	93.8	88.8
B2	91.9	93.0	87.5	90.8
B3	94.1	94.9	89.7	92.9
B4	93.0	88.6	90.5	90.7
B5	95.2	93.8	94.5	94.5
Wood				
B1	97.8	100	99.3	99.0
B2	98.9	100	98.5	99.1
B3	98.9	100	99.3	99.4
B4	99.6	100	96.0	98.5
B5	98.2	100	99.6	99.3
Metal				
B1	95.6	97.8	98.2	97.2
B2	98.9	97.8	94.5	97.1
B3	99.3	100	96.4	98.5
B4	97.4	95.6	99.3	97.4
B5	95.6	98.9	97.8	97.4
Overall				
B1	94.6	96.0	97.6	96.1
B2	96.9	97.7	95.2	96.6
B3	97.8	98.5	96.2	97.5
B4	97.2	96.0	95.7	96.3
B5	96.5	97.7	97.7	97.3

Figures 3.5 to 3.8 show the variability in RSSI signal detection for each of the three receiver devices for each beacon under normal test conditions. Similar graphs showing the variability in RSSI under human, wood and metal obstruction conditions can be found in appendix a. Under normal test conditions, both intra and inter unit variability is high across all grids. This is further shown in Table 3.5. Overall, inter-unit signal variability was higher than intra-unit under every testing condition. The highest intra-unit variability in RSSI was found during the human obstruction condition (SD = 3.1, CV = 0.04, SEM = 1.31). Counter intuitively the human obstruction condition showed the second lowest inter-unit variability (SD = 4.38, CV

= 0.06, SEM = 2.65) with the highest inter-unit variability found in the metal obstruction condition (SD = 5.12, CV = 0.07, SEM = 2.99).

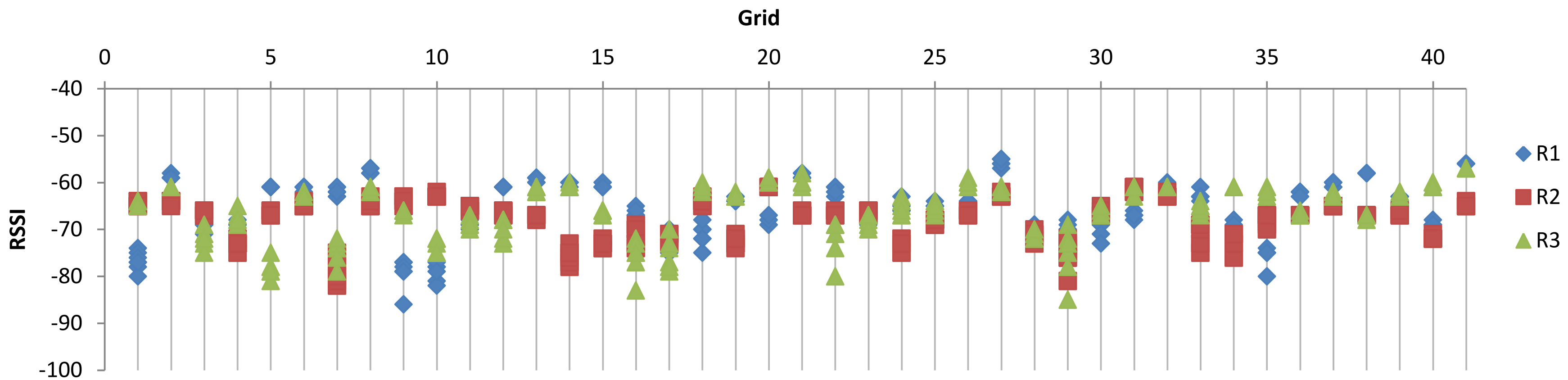

Figure 3.6 Received signal strength indicator (RSSI) distribution for 3 receivers for beacon B1 under normal test conditions

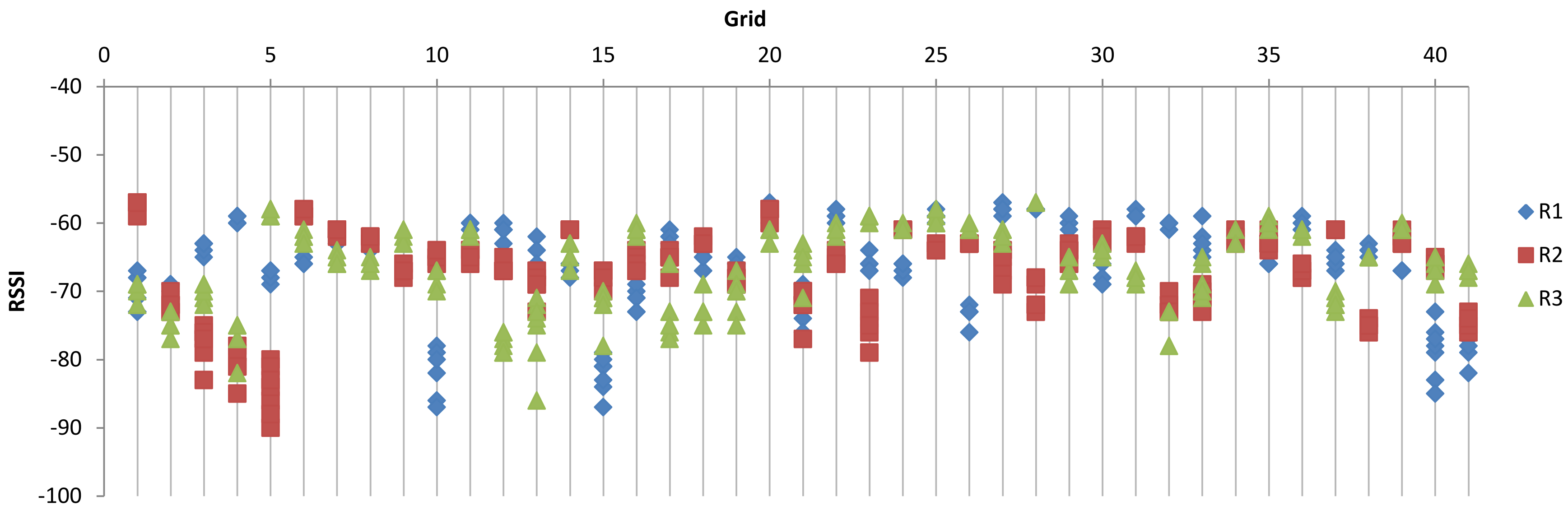

Figure 3.7 Received signal strength indicator (RSSI) distribution across 3 receivers for beacon B2 under normal test conditions

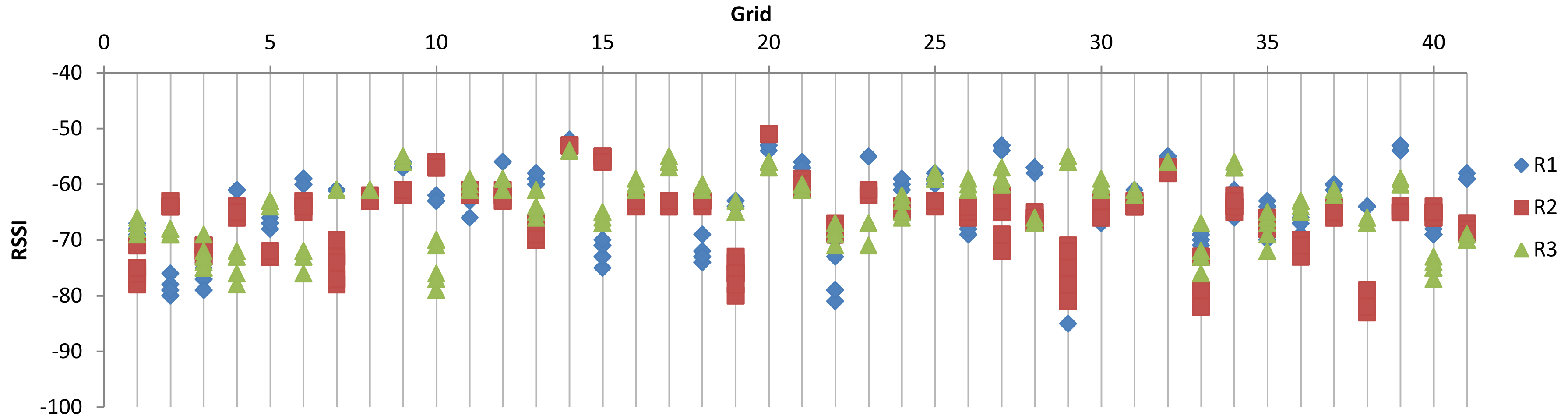

Figure 3.8 Received signal strength indicator (RSSI) distribution across 3 receivers for beacon B3 under normal test conditions

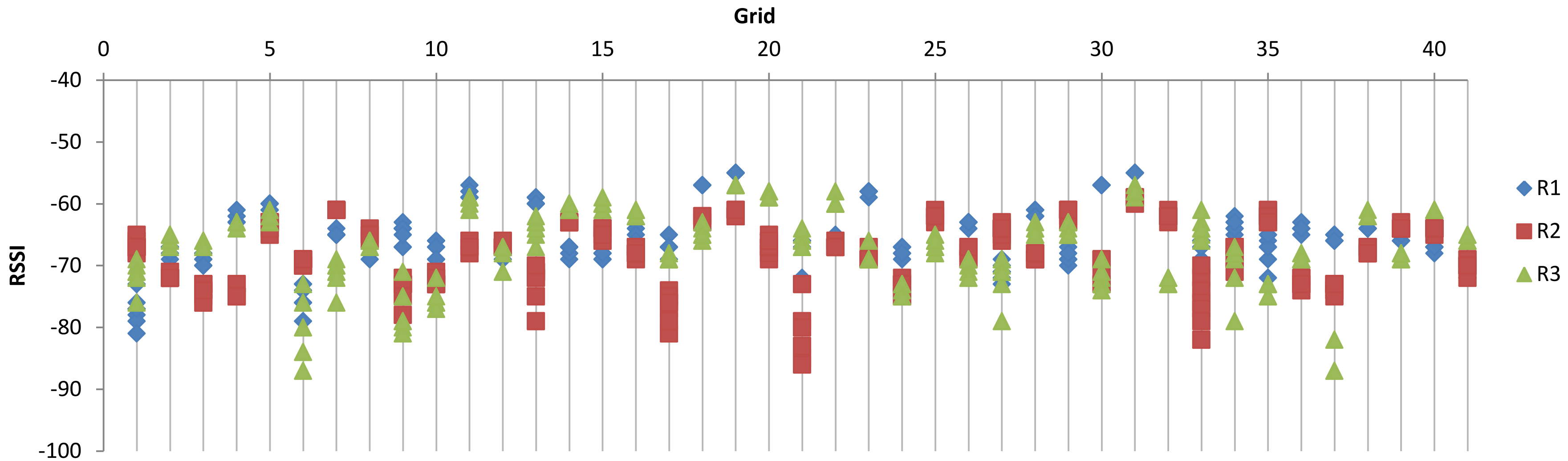

Figure 3.9 Received signal strength indicator (RSSI) distribution across 3 receivers for beacon B4 under normal test conditions

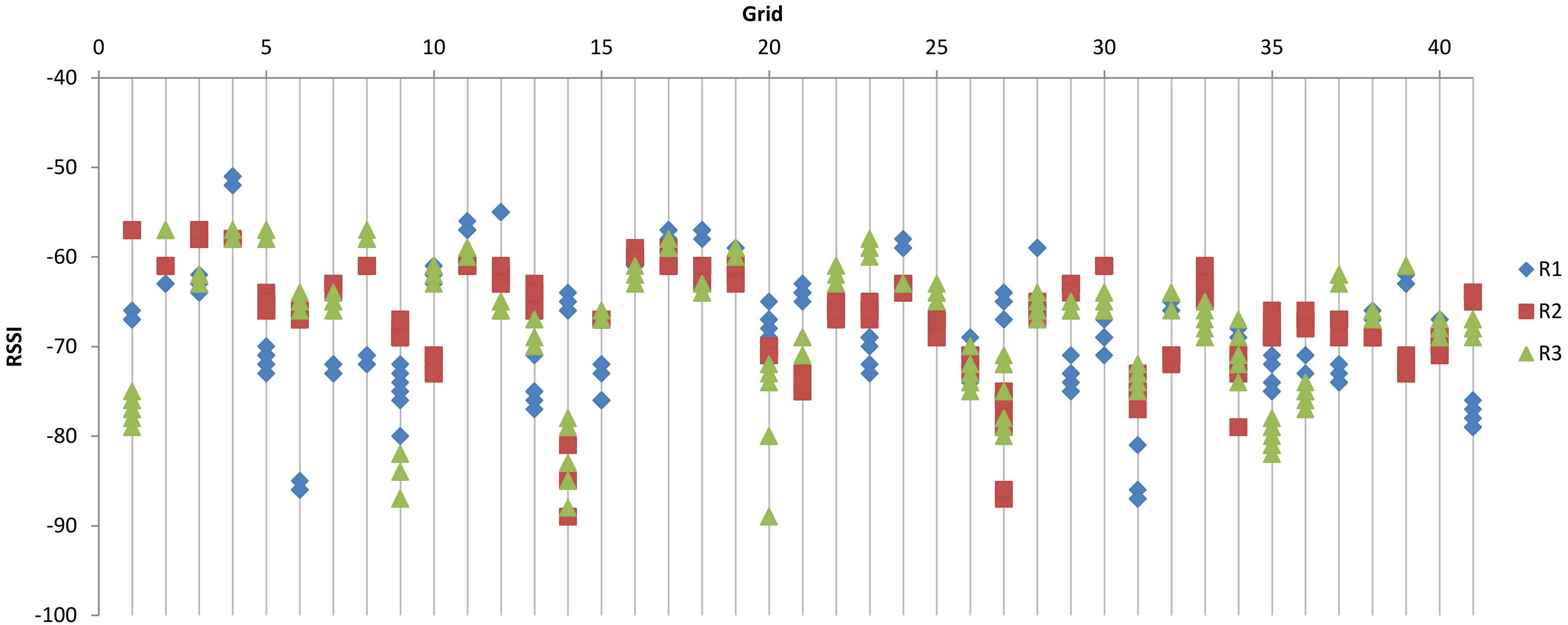

Figure 3.10 Received signal strength indicator (RSSI) distribution across 3 receivers for beacon B5 under normal test conditions

Table 3.5 Intra and inter unit relability statistics in Experiment Two

Condition	Average RSSI	Intra-instrument SD RSSI	CV	SEM	Inter-instrument SD RSSI	CV	SEM
Normal	-65.90	1.04	0.02	0.41	4.59	0.07	2.67
Human	-79.23	3.10	0.04	1.31	4.38	0.06	2.64
Wood	-67.18	1.16	0.02	0.45	4.46	0.07	2.59
Metal	-72.73	0.84	0.01	0.34	5.12	0.07	2.99

RSSI = Received Signal Strength Indicator; SD = Standard deviation; CV = Coefficient of variance; SEM = Standard error of the measurement

3.3.3 Experiment Three

Table 3.6 shows the percentage of epochs where a signal was detected from each beacon under each of the testing conditions. There was a high amount of multi-room signal contamination. This happened most frequently when the participant was lying in bed with the receiver detecting all three beacons 100% of the time. Both living room beacons (sofa and table) were detected 100% of the time that the participant was in the bedroom. Conversely, the bedroom beacon showed variable detection rates when the researcher was in the living room but was detected at least 46% of the time in every condition.

Table 3.6 Summary percentages for signal detection from each beacon in each condition

	Sofa	Table	Bed
Sofa, arm on top, sleeve up	100	100	100
Sofa, arm on top, sleeve down	100	100	100
Sofa, arm on lap, sleeve up	100	100	50
Sofa, arm on lap, sleeve down	53	100	47
Sofa, arm on lap, sleeve up, beacon higher	100	100	100
Table, centre, sleeve down	82	100	88
Table, right, sleeve down	100	100	87
Table, left, sleeve down	100	100	100
Bed, sleeve down, arm free	100	100	100
Bed sleeve down, arm in duvet	100	100	100

3.4 Discussion

This study investigated the Actigraph proximity feature across three experiments. The aim of Experiment One was to assess the basic characteristics of the Actigraph RSSI signal across a range of straight line distances. Experiment Two aimed to assess the level of receiver device signal detection in a single room under unobstructed conditions, when various obstructions are introduced and the impacts these obstructions have on the intra and inter unit variability of the RSSI signal. Finally, Experiment Three aimed to assess signal contamination across multiple rooms (i.e. one beacon being detected in multiple rooms).

In Experiment One, the RSSI signal was found to be non-linearly related to distance, prohibiting distance estimation. In Experiment Two, high signal detection was found in all grids across all beacons even under obstructed conditions. The lowest signal detection was found for the human interference condition (91.6%). In Experiment Three, high multi-room contamination was found for all conditions (≥47%).

The findings of the present study, utilising the novel Actigraph proximity feature, are broadly comparable to previous studies utilising other BLE devices. Previous studies have reported wide variability in raw RSSI readings with a number of statistical approaches used to smooth this variability such as moving average, weighted average and curve fitting; however, these approaches were unsuccessful in producing a reliable RSSI for distance estimation (411-413). Similarly, the results of the present study suggesting RSSI fluctuation increases with distance is similar to previously reported BLE studies (414,415). To determine distance between two devices, RSSI is therefore unsuitable as the only input variable (411). Due to the iBeacon platform using BLE RSSI with a smartphone, the platform is able to utilise other sensors within the phone, such as an accelerometer or magnometer, to facilitate proximity estimation. This is currently not possible in the Actigraph platform; however, this is also not how Actigraph recommend that the system is used. Actigraph instead recommend that the system be used as a binary in/not in an area system via the detection or non-detection of a beacon. The results of the present study indicate that signal detection rates are high ensuring that the system can be used as intended by Actigraph. Processing of multi-beacon signal detection may also allow for room level location.

It is important to assess the findings of the present study in comparison to previous studies of GPS devices. For example, a previous study found GPS units to be accurate to 3.02m (22). In a real world setting this level of accuracy is sufficient to determine that an individual is, for example, in a park but not necessarily which piece of equipment they are using within the park. The analogous indoor version of this suggests that the Actigraph is sufficient to determine that an individual is in a room but not necessarily where within the room. This level of acuity does not appear to have negatively impacted the use of GPS in physical activity research suggesting that it is also unlikely to decisively negatively impact the use of indoor location technologies. Furthermore, GPS may be a useful starting point in considering how Actigraph proximity data should be processed in order to avoid multi-room signal contamination. Using GPS, satellite navigation systems incorporate a “snap to road” feature. This feature ensures that if the raw GPS location places the car in a field to the side of the road then the satellite navigation “snaps” the car back on to the road. It is conceivable that a similar, logically reasoned, feature could be used with Actigraph proximity data when multiple beacons are detected. For example, in an office workplace, a participant is, logically, more likely to be in their own office than in someone else’s; therefore, if two beacons are simultaneously detected it may be possible to “snap” the participant to their own office. Whilst imperfect, this may offer a solution to multi-room signal contamination.

Given the room level detection offered by the Actigraph proximity feature and previous research reporting this level of acuity for other indoor positing systems (396,399), other considerations become more prominent in selecting a technology to use for research assessing indoor location. Wi-Fi based RTLS has the theoretical advantage of using existing infrastructure, which is likely to be present in almost any building, and therefore theoretically has no infrastructure requirements. However, in order for RTLS to function optimally enterprise level Wi-Fi is required which generally contains a density of wireless access points and therefore provides many reference points from which the RTLS can calculate location. This density of access points is likely to be found in large work places and institutions such as hospitals but is unlikely to be found in other settings such as the home.

iBeacons have the advantage of communicating with BLE enabled smart phones which research participants are likely to already possess. This may improve participant compliance if the participant does not have to wear an additional device; however, smart phones and other non-wearable devices may prove problematic in certain circumstances such as the participant not carrying their phone with them all of the time. The researcher would lose the ability to track the participant were this to occur. Furthermore, there are some population groups where the rate of smart phone ownership is likely to be low such as young children or older adults.

The Actigraph proximity systems primary advantage relates to the ability to assess physical activity and location in one device. This is likely to improve participant compliance. Conversely, the main disadvantage of the Actigraph proximity system is its comparatively high cost to other systems, particularly iBeacon. At the time of writing, each Actigraph unit is approximately 10 times the cost of an iBeacon unit, not including the additional cost of Actilife software. There are a number of potential developments, intimated by Actigraph, which may further increase the viability of the Actigraph proximity system (416). Firstly, it may be possible to integrate iBeacon technology into the system whereby Actigraph receivers would detect iBeacons placed around an environment. This would remove the need for Actigraph devices to be used as beacons and therefore greatly reduce the overall cost of a deployment. Secondly and again intimated by Actigraph, it may, in future, be possible to alter the range of the BLE signal (416). This may potentially overcome multi-room signal contamination and may also allow for micro-location binary signal detection; for example, if a beacon were placed above a sofa with a maximum signal range of one metre then researchers would be able to determine sofa time. This would be a significant improvement on the current system.

The preceding discussion highlights the practical considerations in selecting an indoor location technology to use. Currently, there does not appear to be indoor location measurement technology comparable to GPS in terms of accuracy and practicality. The selection of an appropriate tool is therefore likely to depend on the population and setting of a particular study.

The main strengths of this study are the use of a novel indoor location measurement technology and the multitude of conditions it was tested under. This comprehensive testing of the Actigraph proximity feature under a multitude of conditions provides a reliable basis from which to judge the utility of the technology. Conversely, this study also has several limitations. Firstly, although each experiment was conducted in a different environment, only one environment was used per experiment. It is therefore possible that, for example, in Experiment Three there would be more or less cross room signal contamination in a different environment with different building materials and layout. Secondly, in Experiments One and Two the monitoring timeframe per condition was short at one minute per condition. Lastly, Experiments One and three included only one receiver device. Given the inter-unit variability shown in Experiment Two it is possible that other units may have shown different results.

3.5 Conclusion

This study assessed the Actigraph proximity feature and the properties of the RSSI signal across three experiments; a range of straight line distances between receiver and beacon, signal detection and signal variability with multiple obstructions in a single room and, finally, signal contamination across multiple rooms. Overall, the results showed that the relationship between RSSI and distance is non-linear, signal detection is high even when obstructions are introduced but intra and inter unit signal variability is also high and that beacons can be detected across multiple rooms. The non-linear relationship between RSSI and distance and the high intra and inter unit signal variability suggests that it is not worthwhile to attempt distance estimation or location triangulation with this device. Furthermore, multi-room signal contamination suggests that careful beacon deployment or complex post-processing are needed to ensure that only one room is possible per epoch. However, the Actigraph proximity feature also has several distinct advantages. The present study has shown the high signal detection capabilities of the device across multiple obstructions known to influence BLE signals. This suggests that, in line with the manufacturers recommendations, the technology can be used as a binary indicator of room occupancy. Furthermore, the ability to assess physical activity and room occupancy within the same device may reduce participant burden. The necessity for careful beacon deployment or complex processing to avoid multi-room signal detection suggests that piloting of the system across multiple populations and settings is needed to understand where the greatest utility for the system can be found.

This chapter contributes to the overall aims of the thesis through a validation study of one indoor location tracking system. This study found that, consistent with manufacturer’s recommendations, the system can provide a binary indicator of room occupancy. This chapter therefore fulfils the overall thesis aim of appraising the validity and reliability of a novel indoor location tracking system; however, the chapter does not consider how this data could be combined with measures of physical activity and/or sedentary behaviour or the settings in which the system could be deployed. These will be addressed in the next chapter.

4 Study Three: feasibility trialling of the Actigraph proximity feature

Study Three has been published as an original article in a peer reviewed journal (417). With the exception of some minor wording and/or formatting changes that were necessary for the conversion to thesis format, it is presented in its published form.

This chapter contributes to the overall aims of the thesis through a series of small feasibility trials of the indoor location tracking system validated in the previous chapter. These trials build on the work of the previous chapter by combining objectively measured location data with objective measured physical activity and sedentary behaviour. Furthermore, this chapter considers multiple use cases (the home, the workplace and the care home) in order to gain an appreciation of potential research utility. This chapter therefore fulfils the overall thesis aim of extracting behaviourally relevant data through the combination of location, physical activity and sedentary behaviour data.

4.1 Introduction

Despite unequivocal evidence that physical activity is beneficial for health (1,2), public health strategies to date have failed to engage the majority of the population in achieving recommended levels of physical activity. Accelerometer data from national surveillance programmes have shown that only a small minority of adults are meeting physical activity guidelines; for example, in the United States just 5% of adults (3) and in the United Kingdom just 4% of men and 6% of women achieved national guidelines (10).

An emerging body of cross sectional and experimental evidence (4-8) suggests that, independent of physical activity, large amounts of sedentary time may confer an unfavourable cardio-metabolic risk profile. National surveillance programmes show that adults spend the majority of their waking hours sedentary; for example, when using an accelerometer cutpoint of less than 199 CPM adults spend approximately 10 hours sedentary per day in the United Kingdom (10) and, when using a cutpoint of less than 100 CPM, approximately 8 hours sedentary in the United States (11). It should be pointed out that accelerometers assess movement and that a lack of movement (i.e. time spent under 100 or 199 CPM) may not be true sedentary time spent in a seated or reclined posture (12); however, these sedentary time figures are broadly comparable to the sedentary time figures found in a recent study conducted in the Netherlands of ~2500 participants with objectively measured posture via the ActivPAL (8).

This preponderance of sedentary behaviour is set against a background of transitioning from labour intensive occupations to large numbers of people in sedentary occupations (418), leading to a reduction of more than 100 calories per day of occupation related energy expenditure in the US over the past 50 years (419). There is undoubtedly a plethora of contributing factors to this “lack of success” in increasing population levels of physical activity; for example, lack of knowledge of physical activity guidelines (420), the disconnect between immediate effort with future reward (421) and a lack of understanding of the behavioural context (422). One way in which the measurement of context may facilitate successful interventions is by identifying context specific correlates which can then be targeted for intervention. This paper operationally defines context as who, what, where, when and why as suggested by the sedentary behaviour taxonomy (18).

Despite the broadness of context, which encapsulates who, what, where, when and why (18); the measurement of context is an understudied research area. Several questionnaires are available which collect information on the domain, such as work, leisure or travel, in which physical activity or sedentary time is accumulated; for example, the domain specific sitting time questionnaire (19) or the international physical activity questionnaire (IPAQ) (20). From each domain a composite measure is then calculated which provides a crude estimate of the "context" of physical activity or sedentary time. However, a review of sedentary behaviour measurement found all composite questionnaires, when compared to objective measures, to have Spearman's rho of less than 0.49 (21). Interviewer administered 24 hour recalls are able to provide a wealth of contextual information such as the domain and purpose of the behaviour (423); however, they may be unsuitable for long term monitoring studies and can be burdensome for the participant and labour intensive for the researcher.

Similar to the measurement of physical activity and sedentary time, objective monitoring of context may be logically seen to provide a more optimal and richer measurement paradigm. Previous objective monitoring of context, in a physical activity setting, has largely utilised GPS and wearable cameras. Originally developed by the US military, GPS utilises orbiting satellites to calculate longitude and latitude coordinates to provide objective quantification of outdoor location (24). In a physical activity setting GPS has been combined with accelerometry to quantify physical activity accumulated in outdoor locations such as in green space (170,228,243) or during active travel (85,165,256). However, the average individual spends 85% of their day indoors (424) where, due to the loss of satellite signal, GPS does not function.

This paper discusses the objective measurement of context, using feasibility trial data from three ongoing studies to illustrate the utility of quantifying context. Trial One assesses wearable cameras and electrical energy monitoring as measures of television viewing. Trials Two and Three utilise proximity sensors to assess indoor locations of older adult care home residents and workplace intervention exposure respectively. Data generated from these specific technologies are discussed; however, there are a host of alternate technologies available with many other possible applications. These exemplar trials, and the technologies used within them, should be viewed as illustrative of the utility of measuring specific aspects of context, but not the entire behavioural context, to add important information to current measurement paradigms.

4.2 Concurrent validity of electrical energy monitoring and wearable cameras as measures of television viewing

4.2.1 Background

Television viewing is perhaps the predominate form of leisure time sedentary behaviour (41,425). Self-report data from the 2012 Health Survey for England show that, on average, individuals engage in 2.8 hours of television viewing on a weekday and 3.1 hours on a weekend day (426). Meta-analytic reviews suggest that each 1 hour per day increment in television viewing time, may be related to a 13% increased risk of childhood obesity (427). Meta-analytic evidence in adults suggest that the relative risk of all-cause mortality is 1.33 between those in high and low television viewing categories (428), whilst the relative risk per 2 hour increment in television viewing is 1.2 for type 2 diabetes and 1.15 for cardiovascular disease (131). Furthermore, television viewing is associated with unhealthy dietary behaviours in children, adolescents and adults (429). The prevalence of television viewing, alongside its direct relationships with health outcomes and other unfavourable behaviours suggests that television viewing is a key domain of total sedentary time.

4.2.2 Usual measurement practice

Television viewing time has been assessed almost exclusively using self-reported measures which may be subject to recall and social desirability biases (114,430). Test-retest reliability of self-reported television viewing is predominantly moderate-to-high; however, validity is rarely assessed and can vary substantially depending on the reference measure used (41).

4.2.3 Novel measurement practice and exemplar data

A great deal of interest has accrued in recent years in the use of wearable cameras to assess the context of physical activity and sedentary time. The most mature and widely used wearable camera in a research setting is the Sensecam (123). This device is worn via a lanyard or clip on the back of the device and automatically captures a first-person point of view image approximately every 20 seconds (431). Given the potential privacy concerns of image capture, an ethical framework has been proposed to guide researchers and participants in their use of wearable cameras (93). Wearable cameras have previously been used to assess active travel and to augment accelerometer measured time spent sedentary and in physical activity (91,92,123,160,432,433). Given the wide range of information that can be extracted from an image, wearable cameras offer the potential to simultaneously assess a number of contextual factors; however, image coding can be laborious on the researcher. The images generated by wearable cameras may therefore be suitable for assessing television viewing.

Energy monitors are small units which are plugged into electrical power sockets and collect energy usage data when the plug from an appliance is inserted into the energy monitor. Interested readers are referred elsewhere (434) for more detailed discussion and example devices used in energy monitoring. Energy monitoring therefore offers the potential to measure when a television is switched on or off.

Both wearable cameras and energy monitoring may be able to provide a more objective measure of television viewing than self-report measures. Energy monitors provide an objective measure of when the television is switched on and the wearable camera permits objective information on whether the person is watching the television (i.e. within close proximity and facing the screen). The aim of this feasibility trial is to determine the concurrent validity of these technologies as measures of television viewing.

A convenience sample of participants (n=6, 50% female, mean age 27 ± 2) were recruited from the National Centre for Sport and Exercise Medicine at Loughborough University with the only exclusion criteria being non-ownership of a television. The researcher visited the participants home to fit their main television set with a small energy meter (Plogg, Energy Optimisers, UK) which measured the electrical energy consumed in Watts per minute. This was used to determine if the television was switched on. Participants wore an Autographer (OMG Life Limited, Oxford, UK) wearable camera attached, via a clip on the back of the camera, to the neckline of their top. The Autographer was set to medium image capture rate (up to 240 images per hour). Participants also wore a waist-worn Actigraph GT3X+-BT (Actigraph LLC, Pensacola, Florida) on their right hip collecting data at 100Hz. Participants were monitored for 24 hours but only wore the wearable camera when they were at home; this was felt necessary as this study looked specifically at television viewing time and the limited battery life of the camera may have been depleted if the camera were used outside of the home. Participants were therefore shown how to operate the camera to ensure that it could be switched on when at home and off when the participants left their home.

Ethical approval was obtained from Loughborough University ethics committee and all participants provided written informed consent to participate in the study. Informed consent was obtained from participants whilst they were working and before the researcher visited the participant's home. Camera images were coded to show whether the television was visible and the location of the participant (i.e. which room they were in). Figure 4.1 shows examples of images that were coded as a) watching television b) television not seen but in the living room c) not in the living room and d) un-codeable. The category "no TV but in the living room" was determined by comparison with images coded as "TV watching". If there was consistency in the features (e.g. curtains, coffee tables etc.) with the "TV watching" images but no television actually present in the image then the image was coded as "no TV but in the living room". If there were no identifiable features (such as Figure 4.1d) then the image was deemed to be un-codeable. Actigraph vertical axis data were processed using a cutpoint of 100 CPM for sedentary time. This cutpoint was used as it is the most widely used cutpoint to determine sedentary time (12); however, the accuracy of this cutpoint has been questioned (48,160).

Results are shown in Table 4.1. Energy monitors showed the television was switched on for an average of 202 (± 14) minutes per day; however, wearable camera images showed an average of just 90 (± 43) minutes of television viewing and a further 52 (± 24) minutes with the participant in their living room but a television not seen in the image. The remaining camera images were un-codeable due to a lack of identifying features (e.g. a picture of a ceiling). Of the 202 minutes, 163 (± 11) were spent in < 100 CPM whilst 39 (± 13) were spent in light activity.

In this very small sample, 32% of daily sedentary time was accumulated when the television was turned on; conversely, if wearable camera images are used as the measure of television viewing then 17% of daily sedentary time is accumulated whilst watching television. Wearable camera television viewing in this study is in broad agreement with previous studies using wearable cameras which have found 11% of total sedentary time is spent watching television (160). It is possible that energy monitoring overestimates the amount of time spent watching television rather than when the television is switched on. However, it is also possible that wearable cameras may underestimate television viewing through the participant turning their neck rather than their body depending on the position of their sofa, or slouching or lying, all of which may leave the camera pointed away from the television. Self-reported television viewing time was not collected in this study; however, previous self-report data from the 2012 Health Survey for England show that, on average, individuals engage in 2.8 hours (168 minutes) of television viewing on a weekday and 3.1 hours on a weekend day

(186 minutes) (426). This may further suggest that energy monitoring overestimates television viewing.

Table 4.1 Summary statistics of energy monitoring and wearable cameras as measure of television viewing

	Participant						Mean ±SD
	1	2	3	4	5	6	
Actigraph wear time	758	760	808	800	809	834	795 ± 30
Autographer wear time	204	206	276	390	182	216	246 ± 77
Total daily sedentary time (<100 CPM)	477	579	429	416	589	599	514± 84
TV on time	185	185	215	215	208	208	202 ± 14
Camera TV shown time	73	103	16	127	136	86	90 ± 43
Camera in living room but TV not shown	95	59	47	36	24	51	52 ± 24
TV turned on but camera shows another room	7	12	120	11	41	44	39 ± 43
TV turned on but image un-codeable	10	11	32	41	7	27	21 ± 14
TV on and < 100 CPM	157	155	159	170	184	156	163 ± 11
TV on and >100 CPM	28	30	56	45	24	52	39 ± 13
Percentage of total daily sedentary time with TV switched on	33	27	37	41	31	26	32 ± 6
Percentage of total daily sedentary time with TV switched on and shown in camera images	15	18	4	31	23	14	17 ± 9

All figures are minutes unless otherwise stated; TV = Television; CPM = Counts per minute

Figure 4.1 Wearable camera images showing (a) TV, (b) no TV but in the living room, (c) not in living room,(d) un-codeable image

The high number of un-codeable images suggests that this form factor of wearable cameras (deployed on a lanyard or fixed to clothing) may be a poor measurement tool when the individual is slouching. The field of view for the camera is compromised by the camera pointing upwards rather outwards. Therefore wearable cameras may not be suitable for identifying some recreational sedentary behaviours where slouching may occur such as television viewing. This is particularly noteworthy as previous research using self-report questionnaires has found television viewing to be the most prevalent leisure time sedentary behaviour (19). Wearable gaze cameras, often in the form of eye glasses, may be able to overcome this limitation. The added benefit of gaze cameras is that they are likely to allow for better quantification of multiple screen use.

4.3 Measurement of indoor location of sedentary time accumulation

4.3.1 Background

GPS have previously been used to assess the outdoor location of time spent sedentary or in physical activity (22,23); however, the majority of individuals spend the vast majority, approximately 85%, of their day indoors (424) where GPS cannot provide location information (24,88). Furthermore, features and equipment within the indoor environment may influence physical activity and sedentary time (114,116). Several technologies, such as BLE iBeacons, RFID and RTLS, are available which are able to measure indoor location (130); however, their use in physical activity research to date has been very limited. These technologies, particularly RFID, have been more widely evaluated in healthcare and warehousing for purposes such as asset tracking (435) or detecting when a patient is in or out of their hospital bed (436).

4.3.2 Usual practice

Domain specific questionnaires are commonly used to assess behaviour performed across workplace/school, travel and home; however, these questionnaires are not able to assess important sub-domain behaviour; for example, which rooms within the workplace, school or home the behaviour occurred (122). Wearable cameras have also been used to assess the type and context of objectively measured physical activity (123) and could provide a measure of indoor location if the captured image contains an identifying feature; however, this identifying feature may not always be present in the image and requires an extensive knowledge of the participants environment on the part of the image coder. Sociometers are novel devices which incorporate an accelerometer, Bluetooth proximity sensor and audio recorder to collect data on an individual's interactions and communications (124). The validity of these devices has previously been assessed under simulated conditions within environments such as hospital emergency departments with the devices able to distinguish body movement and proximity between individuals but showing poor validity at detecting face-to-face interactions (125). Furthermore, in free living conditions the continuous recording of audio may be off putting to participants and may create an artificial environment in which participants are highly mindful of what they say. Indoor location and sedentary time within a workplace have been measured using a RFID system in conjunction with a posture sensor; however, practical and technical challenges meant that the use of analogous system of indoor location monitoring cannot yet be recommended (126).

There appears to be an age related increase in sedentary time with older adults the most sedentary segment of the population (10,437). Logistical considerations mean that indoor location measurement technologies are currently best suited to environments in which people congregate. By using areas in which people congregate, the researcher is able to use fewer beacons than would otherwise be needed. The combination of older adults being the most sedentary part of the population and the logistical considerations in deploying the technology make older adult care home residents the ideal population for this research.

4.3.3 Novel measurement practice and exemplar data

The following is a description of the deployment protocol used in a feasibility trial of the locations in which older adults in care homes accumulate their sedentary time. Ethical approval was obtained from Loughborough university ethics committee (project number R14-P160) and all participants provided written informed consent to participate in the study. Written informed consent was obtained when the researcher visited the care home to install the measurement system. Based on a systematic review of location measurement technologies (130) a number of options were considered for use in this study. A Wi-Fi based RTLS has the advantage of leveraging existing wireless infrastructure but was deemed unsuitable for this particular study due to a lack of enterprise level Wi-Fi, necessary for RTLS to function optimally, in the care homes. Further information on RTLS can be obtained elsewhere (130). BLE iBeacons have the advantage of being relatively inexpensive and were also considered but were deemed unsuitable as they would have necessitated providing each participant with a mobile phone for the beacon to communicate with. Therefore a different BLE system was used in this particular study and is described in more detail below.

The Actigraph GT9X was used in the present feasibility trial to measure location and the LumoBack device (Lumo Bodytech, Mountain View, California) was used to measure lying, sitting, standing and stepping time. Participants were drawn from a care home in Leicestershire, UK and required to be free of diagnosed dementia and non-bedbound. Contact with the care home was initiated by an existing contact within local government. The researcher then met directly with the care home owner and care home staff and provided information about the study. Both the care home owner and care home staff agreed to support the study. Care home staff then provided information on the study to the care home residents and used their knowledge of the residents and their professional judgement to approach participants which met the inclusion criteria (free of diagnosed dementia and non-bed bound). In total, 32 Actigraph beacons were deployed around the care home with 5 in resident's rooms (i.e. 1 in each room) on the wall where the door was situated facing inwards to the room and therefore away from the corridor, 12 in communal rooms with 1 beacon on each wall across 3 communal rooms (i.e. 4 beacons per communal room) and 15 in corridors with 1 beacon at each change of direction in the corridor in order to ensure that the whole corridor was covered. Beacons were placed in the centre of the wall at a height of 2.5m and unobstructed to ensure adequate BLE coverage. If an obstacle was present (e.g. a clock) then beacons were placed slightly lower to avoid the obstacle (i.e. the obstacle was not moved). The Actigraph receiver was worn by care home residents (n=5, 100% female, mean age 87 ± 5) on their non-dominant wrist. Actigraph receivers were initialised to collect proximity data at 10 second intervals and raw acceleration at 100Hz. These are the highest resolutions possible for proximity and raw acceleration respectively. Receivers were removed overnight, placed on charge by the care home staff and given back to the participants when they woke up in the morning. This was to ensure that the receiver Actigraph did not deplete its battery.

Residents also wore the LumoBack posture sensor. The LumoBack (4.15 x 10 x 0.8cm, 25g) is a small posture sensor which is worn on the small of the lower back via an elasticated belt and continuously tracks the amount of time spent lying, sitting, standing and stepping via inertial sensors collecting data at a constant 25Hz (54). The LumoBack has shown strong correlations in free living conditions against the activPAL in total time spent standing (R^2 = 0.86) and sitting (R^2 = 0.89) (55) with a MAPE of 9.5% when assessing total sitting time (56). Furthermore, the LumoBack has shown excellent agreement in step counting under controlled laboratory conditions against the Optogait treadmill test (MAPE 0.2%, Intraclass correlation coefficient (ICC = 0.99) and under free living conditions against the activPAL (MAPE 0.4%, ICC = 0.99) (57).

Actigraph data were downloaded using Actilife version 6.11.8. Proximity data were then exported in CSV format into Microsoft Excel 2010. This CSV file shows the beacon serial numbers as column headers with the RSSI between the receiver and beacon shown per epoch. In accordance with manufacturers recommendations, the presence of an RSSI indicates that a resident was in proximity to that beacon with the absence of an RSSI indicating that the resident was not in proximity to that beacon. Using the known beacon locations, each 10 second epoch of proximity data were then coded as "residents room", "communal area" or “corridors” depending on the presence or absence of an RSSI for each beacon in that epoch. The coded data were then averaged and plotted to show the average time spent in each location per hour of the day.

LumoBack devices were synced with their mobile phone application at the conclusion of the study by the researcher. This syncing sends the data to the LumoBack data storage platform which was developed by a fee for service data aggregation company who were able to use the LumoBack application programming interface (API) to obtain data, format this data in a user defined format and to then make this data exportable. This online platform was primarily developed for use in the study of another PhD student with the present study utilising the platform to obtain useable data. Data were downloaded from this platform as a CSV file. This file was then imported into Microsoft Excel 2010 where the data were averaged to show average time spent in each posture during each hour of the day.

Following preliminary analyses, example proximity and posture data from five care home residents are presented. Residents wore both devices for one week with data presented as average values per day. These data are taken from a larger study and used for illustrative purposes to highlight the utility of the measurement technology. Descriptive statistics of time spent in each posture, measured via the LumoBack, and each location, measured via Actigraph GT9X Bluetooth proximity, per hour are presented in Figures 4.2 and 4.3 respectively.

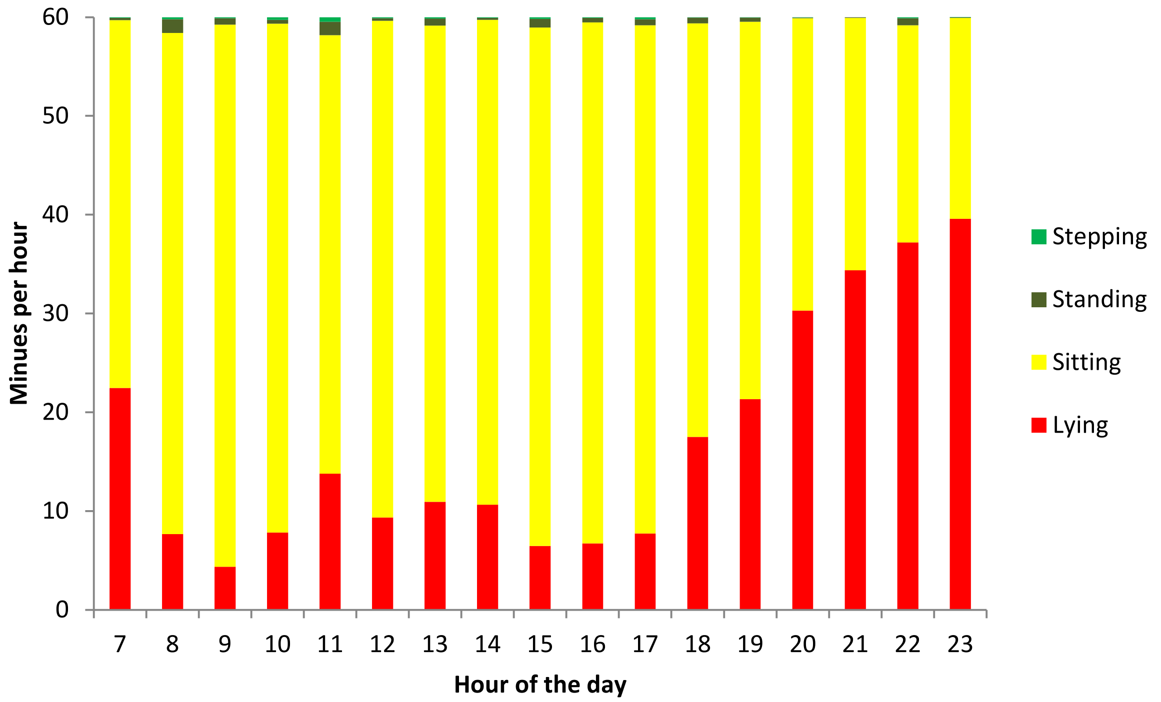

Figure 4.2 Hour by hour plot of LumoBack measured average behaviours of the care home residents.

Figure 4.2 shows that participants spent the vast majority of their day sedentary. Conversely, participants engaged in very small amounts of standing or stepping.

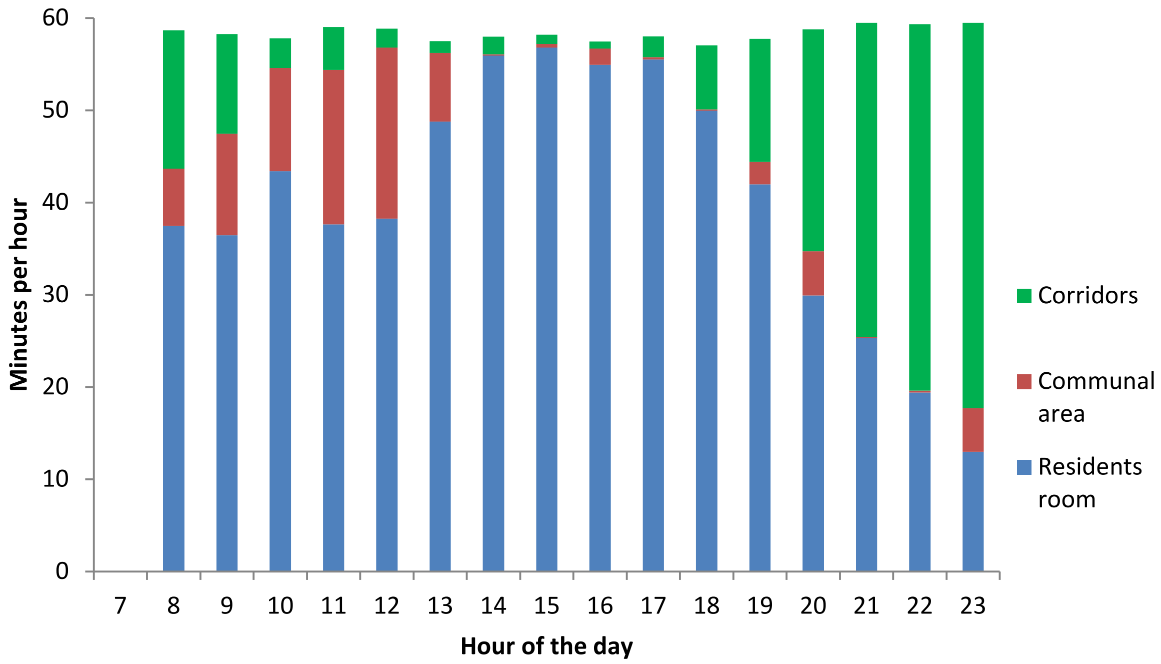

Figure 4.3 Hour by hour plot of resident's average location within the care home

Processed location data (Figure 4.3) showed that participants spent the majority of their waking day in their own room and more time in communal areas in the morning than in the afternoon. The large amount of time spent in corridors in the later evening reflects the fact that during the overnight period the devices were taken off so they could be charged (in the corridor charging station) rather than actual resident's location.

These data provide preliminary suggestions that older adult care home residents accumulate very large (98% of time 7am-11pm) amounts of sedentary time with the majority of this time occurring in their own room within the care home. Time spent in communal areas may be important to facilitate social contact between residents. Furthermore, residents may be more likely to engage in activities (e.g. bingo) within communal areas than within their own room which, although sedentary, may convey psychological well-being benefits in this population. The very high amount of sedentary time may reflect the functional status of care home residents as opposed to older adults who reside in their own home or an assisted living facility. Given the limited location possibilities available to care home residents, it seems worthwhile to investigate the utility of this technology in settings which may offer more location possibilities and populations which are likely to spend their time in more varied locations.

4.4 Quantifying workplace intervention exposure

4.4.1 Background

Adults typically accumulate their sitting in three domains: the workplace, during leisure time and for transport (133). Many adults are now employed in sedentary occupations, such as office work (418). Desk-based office workers spend the majority of their working hour's sedentary (438,439); it has therefore been suggested that workplaces may be an ideal setting to introduce interventions to decrease sedentary time. Interest has grown in recent years around the provision of activity permissive office equipment such as height adjustable desks and treadmill workstations, to displace sedentary time with standing or light ambulation (440).

4.4.2 Current practice

A number of studies are beginning to emerge investigating the use of height adjustable desks with objective measures of physical activity and/or sedentary time (441). The installation of height adjustable desks has been found, one week after installation, to reduce activPAL measured sedentary behaviour by 143 minutes per day at the workplace and 97 minutes per day overall with these effects maintained at 3 month follow up (442). Similar findings have been reported elsewhere with an activPAL measured 73 minute reduction in workday sitting and a 65 minute increase in workday standing (443). Conversely, other height adjustable desk studies have reported non-significant reductions in workplace sitting time unless part of a multi-component intervention (441).

In order to obtain a more robust quantification of the effect these interventions have in reducing sedentary time, it is important to quantify intervention exposure (e.g. the amount of time spent using the height adjustable desk). Current methods rely on self-reported work hours to quantify this effect; however, this does not take account of working time spent away from the height adjustable desk (e.g. in meetings, at lunch, time spent accessing communal resources such as supply stores or copiers/printers).

4.4.3 Novel measurement practice

Objectively quantifying time spent at the height adjustable desk or treadmill workstation offers the potential to better evaluate the effects of these interventions. This quantification could be achieved via proximity monitoring between the participant and the desk, for example using small BLE stickers (e.g. Estimote Inc, New York). This technology currently requires the participant to carry a mobile phone which may be potentially unsuitable for some applications. In future, it is likely that this technology will be able to communicate with a smart watch or other BLE enabled device. Quantification of time spent at the height adjustable desk or treadmill workstation could also be achieved using sensors affixed under the desk. However these systems generally assess whether any individual is at the height adjustable desk or treadmill workstation and may be unable to differentiate when a specific individual is there. This is clearly problematic when assessing a specific participant’s intervention exposure. Given the limitations of these systems to assess height adjustable desk exposure it was deemed more worthwhile and feasible to focus on objectively assessing office dwell time (i.e. the amount of time spent in the office) as a proxy of height adjustable desk exposure in the present feasibility trial. Although imperfect, objectively assessing office dwell time to quantify intervention exposure may present a considerable improvement on the current method of self-reported work hours.

This study presents initial feasibility trial data collected as a precursor to a recently initiated cluster randomised controlled trial (RCT) incorporating height adjustable desks and proximity based location measurement; for brevity, the main trial is described in general terms with a focus on the features most pertinent to the initial pilot data and the present paper. A detailed protocol of the main cluster RCT is available elsewhere (444). Briefly, the cluster RCT (Trial ID ISRCTN10967042) aims to develop and evaluate an intervention to reduce workplace sitting time over 12 months within office based UK National Health Service (NHS) employees. Guided by the behaviour change wheel (445), the intervention incorporates environmental, organisational and individual strategies including height adjustable workstations, self-monitoring tools and other behaviour change techniques. Data will be collected at four time points; baseline, 3, 6, and 12 months. The main outcome of the study is a reduction in activPAL measured sitting time at 12 months with objectively measured physical activity and a variety of work-related health and psycho-social measures as secondary outcomes. Work related measures include presenteeism, occupational fatigue and job satisfaction. Particularly relevant to the present paper, participant's office dwell time will be measured using the Actigraph proximity feature, allowing the quantification of intervention exposure (i.e. time spent neat the height adjustable desk) in an unobtrusive manner. To the author's knowledge, this will be the first height adjustable desk intervention to include an objective measure of office dwell time as a mechanism for better quantification of intervention efficacy in reducing workplace sitting.

Summary descriptive statistics of five participants (20% female, mean age 26 ± 4), measured for one day each, from preliminary feasibility trialling of the system are presented here to illustrate the utility of this new measurement approach. All participants were drawn from a convenience sample of Loughborough university employees with no exclusion criteria. All participants already used a height adjustable desk in their office. Ethical approval was obtained from Loughborough university ethics committee and all participants provided written informed consent to participate in the study. Informed consent was obtained from participants within their workplace.

Office dwell time was measured via Actigraph Bluetooth proximity with each participant wearing a GT9X on their non-dominant wrist. Proximity data were recorded at 15 second intervals and acceleration data were collected at 100hz. A proximity epoch of 15 seconds was used to facilitate combining this data with 15 second activPAL data. Actigraph GT9X beacons were placed high and unobstructed in the centre of the same wall where the door was situated with beacons placed facing inwards to the office. This high and unobstructed placement is consistent with manufacturer's recommendations. The range of the Actigraph

BLE signal is dependent on the environment in which they're deployed but is approximately 10-20 metres; however, BLE is obstructed by, among other things, concrete, plaster and brick which should ensure that erroneous signals received from beacons in other rooms is minimal. Time spent sedentary and upright were measured via the activPAL attached to the participant's thigh collecting data at the default rate of 20Hz. These data were then summarised into time spent in each posture per 15 second epoch and exported to Microsoft Excel. Participants self-reported their working hours. Data presented only include time during these self-reported working hours.

Actigraph data were downloaded using Actilife version 6.11.8. Proximity data were then exported in CSV format into Microsoft Excel 2010. This CSV file shows the beacon serial numbers as column headers with the RSSI between the receiver and beacon shown per epoch. In accordance with manufacturers recommendations, the presence of an RSSI indicate that a participant was in proximity to that beacon with the absence of an RSSI indicating that the participant was not in proximity to that beacon. Using the known beacon locations, each 15 second epoch of proximity data were then coded as "in office" or "out of office". Proximity data were then combined with posture data in Microsoft Excel 2010 using the respective timestamps from both data streams. Total time spent in each posture whilst "in office" or "out of office" during self-reported working hours were then calculated. All data are presented in Table 4.2.

Table 4.2 Summary statistics of sedentary and upright time (minutes) accuulated inside and outside the office during self reported working hours

	Participant					Mean ± SD
	1	2	3	4	5	
Sedentary time during self-reported working hours	235	290	247	119	108	200 ± 73
Sedentary time in the office during self-reported working hours	196	273	236	11	98	163 ± 96
Sedentary time outside the office during self-reported working hours	39	27	11	107	10	39 ± 36
Upright time during self-reported working hours	208	90	79	375	154	181 ±108
Upright time in the office during self-reported working hours	55	49	26	176	134	88 ± 57
Upright time outside the office during self-reported working hours	139	40	53	200	19	93 ± 70

These analyses showed that using the current practice of self-reported working hours, participants accumulated 200 minutes of sedentary time at work; however, using the novel measurement practice of office dwell time, only 163 minutes of this time occurred in their office. Sedentary time during self-reported working hours in the present feasibility trial is towards the lower end of previous research investigating sedentary behaviour in office workers with previous research finding office workers spend 50-75% of their working hours sedentary (127). Nonetheless, the purpose of this feasibility trial was to show that office workers do not spend all of their working hours, or indeed accumulate all of their occupational sedentary time, at their desk and the ensuring implications for assessing height adjustable desk efficacy.

These data provide preliminary indications that office workers may spend a proportion of working hours outside of their office. This has clear implications for assessing the efficacy of office based environmental interventions such as height adjustable desks. Using office dwell time as the sedentary time denominator may therefore provide a more robust means of assessing intervention efficacy than self-reported working hours.

4.5 Discussion

This paper has briefly outlined and provided sample data for three studies, each involving contextual monitoring in conjunction with objective measurement of physical activity and/or sedentary behaviour. These feasibility trials included the use of energy monitoring and wearable cameras to quantify television viewing, the use of indoor location monitoring to assess the locations in which sedentary time occurs and the use of a proximity system to quantify office dwell time as a surrogate of exposure to a height adjustable desk

Using energy monitoring and wearable cameras to measure television viewing it was found that wearable cameras may not be suitable for measuring television viewing due to a large number of pictures being un-codeable due to a lack of distinguishing features likely brought about by the mal-aligned field-of-view of the camera due to slouching postures. That being said, wearable cameras have successfully been used to assess a wide range of contextual information beyond television viewing and, as such, are a valuable measurement tool (123,160,422,433). Energy monitoring is a feasible means of identifying when the television is switched on but not necessarily when it is being watched. For example, the participant may not be looking at the television or may be in an entirely different room.

The second feasibility trial highlights indoor location monitoring in conjunction with the LumoBack to elucidate the locations in which sedentary behaviour occurs in older adult care home residents. This feasibility trial found that older adult care home residents spend the vast majority of their waking day sedentary, on average, accumulating 720 minutes of sitting. Although previous literature using objective assessment of care home residents is scarce (446), this figure appears to be considerably higher than previous estimates of sedentary time among this group. For example, an accelerometer study in the UK found an average of 607 minutes per day of sedentary time among care home residents (446). This may be due, at least in part, to differences in measurement with the use of a posture sensor in the current study rather than an accelerometer to quantify sedentary time. Location monitoring showed that on average older adult care home residents spend the majority of their day in their own rooms and more time in communal areas in the morning than in the afternoon. Time spent in communal areas may be important to facilitate social contact between residents. Furthermore, residents may be more likely to engage in activities (e.g. bingo) within communal areas than within their own room. This has important implications for intervention design.

Lastly, proximity monitoring was highlighted as a means of quantifying office dwell time as a measure of exposure to a height adjustable desk installed in the office. This is important as the success or failure of an intervention to reduce sedentary behaviour can only truly be judged by quantifying exposure to the intervention; in other words, when it is actually possible for the participant to use the desk. This is not to say that a height adjustable desk intervention with low exposure cannot be successful; for example, an individual who spends the entire working day at their desk may achieve a greater absolute reduction in sitting but an individual who spends less time at their desk could still achieve a greater relative reduction during the time that they do spend at the desk. In essence, quantifying exposure is important to more fully elucidate the intervention effect. This technology has been implemented into an ongoing study which, to the author's knowledge, will be the first to quantify the amount of time the participant spends at their desk before and after the installation of a height adjustable desk.

The three feasibility trials outlined in the present paper provide a flavour of the value of measuring context within physical activity and sedentary behaviour research. These feasibility trials should be viewed as examples with many other possible applications of the measurement technologies. For example, energy monitoring could be used to differentiate when exercise equipment such as treadmills are switched off at the wall socket, on at the wall socket but off at the treadmill or on at the wall socket and on at the treadmill. This may allow inference, using the time that the treadmill is on at the wall socket and treadmill, of the type of physical activity. Similarly, indoor location can be as readily measured and equally useful in a variety of settings and populations such as childcare centres, fitness centres or individual homes. For example, the presence of a television in a young person's bedroom may be a correlate of higher screen time (139); however, the strength of this correlate may be affected by the amount of time the young person spends in their bedroom. Indoor location monitoring allows for this quantification.

Similarly to measurement tools for quantifying physical activity and sedentary time, the measurement tools available to assess the context in which these behaviours occur are evolving rapidly with many tools likely to have been complemented or supplanted by newer models or tools before the research studies in which they are used reach publication. This should not discourage researchers from using contextual measurement tools; as the tools will retain their functionality in providing important contextual information. For example, one noteworthy innovation in proximity sensing is the recent miniaturisation of this technology to a smaller form factor into a "nearable" sensor (e.g. Estimote Inc, New York). This technology can therefore now be affixed to smaller objects such as chairs, exercise equipment or small screen equipment. This offers the tantalising possibility of quantifying the type of behaviour being performed in an inexpensive and unobtrusive manner.

Although the measurement of context can provide important behavioural information, it is not without limitations. Currently, depending on which piece of context the research seeks to assess, the participant may be required to wear an additional device(s). Wearing more than one device may have implications for participant burden (24); however, GPS and accelerometry have successfully been used in a number of studies (85,233,237) suggesting that an additional wearable, though not ideal, is not an insurmountable obstacle. Images generated from wearable cameras have been used to assess a wide range of contextual information (123,160,433); however, the labour intensive nature of image coding (93) and potential data loss due to a relatively short battery life and lack of participant recharging among some groups, such as older adults, (422) suggest that wearable cameras are no more or less suited to assess context than other technologies. The selection of the appropriate technology is therefore likely to be research question and study population specific. For example, despite the limitations of wearable cameras, they may be the best currently available technology to concurrently assess a number of contextual factors. Conversely, if a study has a more focused requirement, for example assessing indoor location of older adults, then other technologies, such as proximity sensors, may be more suited.

The ideal tool to measure the context of physical activity and/or sedentary time is likely to possess the following features: the ability to measure the whole context, to be integrated into tools which measure physical activity and/or sedentary time so that participants are only required to wear one device, medium to long term battery life and collecting data in a manner which does not compromise participant privacy. Such a device does not currently exist and is unlikely to in the foreseeable future. Nonetheless, measuring the context in which physical activity and/or sedentary time occur can provide valuable information alongside objective measures of activity intensity and posture.

4.6 Conclusion

Wearable technologies, such as accelerometers and posture sensors, are commonly used to quantify physical activity and/or sedentary behaviour. These sensors are able to measure the volume, duration and frequency of the behaviour; however, they are unable to provide contextual information such as where the behaviour is performed, what specific behaviour is being performed and with whom. This contextual information is vital to providing greater specificity of correlates of physical activity and/or sedentary time and, thereby, allowing greater refinement of intervention strategies. Fortunately, novel technologies are emerging with the potential to provide this information. These technologies include measures of indoor location, energy monitoring of electrical appliances such as televisions and BLE based “nearable” sensors allowing measurement of interactions between participants and objects. This list is not exhaustive with newer technologies complementing or supplanting existing technologies at a rapid pace. The adoption of these technologies for research use will provide the behavioural researcher with a more complete picture of the behaviour than has previously been available.

This chapter contributes to the overall aims of the thesis through a series of small feasibility trials of the indoor location tracking system validated in the previous chapter. The feasibility trials in this chapter demonstrate the utility of the system to provide more refined and behaviourally relevant data than has previous been possible through objective measures of physical activity and sedentary behaviour alone. This chapter therefore fulfils the overall thesis aim of extracting behaviourally relevant data through the combination of location, physical activity and sedentary behaviour data; however, the very small sample sizes used in these trials show utility in principle but prohibit detailed examination of levels, patterns and potential behavioural levers to alter the behaviour. These will be addressed in the next chapter.

5 Study Four: objectively measuring the context of sitting in older adults

This chapter contributes to the overall aims of the thesis through a use case of the tracking system validated and trialled earlier in the thesis. This use case is older adult care homes. Older adults are shown by national surveillance programmes to be the most sedentary segment of the population. Furthermore, the congregation of multiple individuals within the same living space increases the deploy-ability of the system as fewer beacons are needed. This chapter builds on the work undertaken in the previous chapter by using a larger sample size enabling an identification of levels, patterns and potential behavioural levers to favourably alter behaviour. This chapter therefore fulfils the overall thesis aim of extracting behaviourally relevant data through the combination of location, physical activity and sedentary behaviour data.

5.1 Introduction

Given the deleterious effects of excessive sedentary time on health (6,447) and the high amount of time spent sedentary (8); interventions to reduce sedentary time are sorely needed (448). Although on average all age groups spend the majority of their day sedentary, there appears to be an age related increase in sedentary time with older adults the most sedentary segment of the population (10,437). Furthermore, older adults typically have more discretionary time than working age adults and may therefore be more amenable to reducing their sedentary time. Assessing the context of current sedentary time may provide a wealth of information which can lead to improved specificity and, ultimately, more efficacious interventions (449-451). For example, in an older adult care home environment, determining time spent sedentary in communal areas and in residents rooms may inform whether a group intervention, for high sedentary time in communal areas, or individual intervention, for high sedentary time in the resident's room, is required.

Existing indoor positioning systems are currently more conducive to assessing indoor location within rooms or institutions where multiple people are likely to congregate for large periods of time, largely due to the infrastructure needed for any system to function (130). The constellation of older adults being the most sedentary segment of the population (437) and the measurement technology being most favourable under multi-occupancy conditions make older adult care home residents the optimal scenario in which to apply this novel measurement paradigm. Furthermore, care homes are an advantageous setting over other possible settings, such as workplaces or schools, as residents also live within the care home ensuring that as much data as possible is captured. The presence of a large number of older adults living in the same property also allows the quantification of when multiple occupants are in the same room simultaneously. This is particularly important in older adults as loneliness may increase an individual's risk of being sedentary (422). For example, in a care home environment, this loneliness effect may possibly manifest in residents being more sedentary in their own rooms than in communal areas of the care home. Conversely, simultaneous room occupancy of multiple residents may facilitate incidental movement such as passing items to other residents or moving seats to be next to a friend. There is therefore a need to quantify simultaneous room occupancy to quantify these possible effects.

The purpose of this feasibility study was therefore to apply a novel measurement paradigm to profile the locations in which older adult care home residents spend their sedentary time and the effect of residents simultaneously being in the same location on movement levels. Feasibility studies are concerned with whether something can be done, should we proceed with it and if so, how (452). In this study, this will cover whether the measurement system can be deployed and whether it can provide novel information. The primary hypothesis was that residents would spend the majority of their day sedentary. The secondary hypothesis was that residents would spend more time sedentary in their own room than in communal areas. The tertiary hypothesis was that residents would show less movement when simultaneously in communal areas of the care homes with other residents.

5.2 Methods

5.2.1 Care home and participant recruitment

The process of care home recruitment was initiated through an existing contact, a physical activity and health co-ordinator, in local government within Leicestershire, UK. The local government representative was provided with study materials to distribute to care homes where, in the representatives judgement, a number of residents were likely to meet the study inclusion criteria (at least 65 years old, free of dementia and non-bed bound) and the care home staff would be willing to facilitate the study; two care homes agreed to take part in this study out of the four that were approached. The researchers then met with the activities co-ordinator at each care home. The activities co-ordinator was asked to identify residents which, in their judgement, would be able and willing to take part in the study. It was agreed with each activities co-ordinator that they would be provided with all study materials and begin recruitment of care home residents for participation in the study. This approach was taken as the activities co-ordinator has a much greater appreciation and understanding of the residents capabilities with residents also likely to feel more comfortable being approached by someone they are familiar with. In total, 26 residents agreed to participate in the study with each care home providing 13 residents. Additionally, 16 care home workers agreed to take part in the study with Care Home One providing six staff members and Care Home Two providing 10 staff members. Ethical approval was obtained from Loughborough university ethics committee and all participants provided written informed consent to participate in the study. Written informed consent was obtained when the researcher visited the care home to install the measurement system.

5.2.2 Equipment

5.2.2.1 Actigraph

Actigraph (Actigraph LLC, Pensacola, Florida) provide the most widely used accelerometers to measure physical activity and sedentary behaviour. The two latest models from Actigraph (GT3X+BT and GT9X) are also equipped with BLE functionality allowing them to be used for proximity based applications. Actigraph suggest that their location system should be used as a discrete “in” or “not in” an area. The system is currently only useable as an all-Actigraph system (i.e. other BLE enabled devices cannot be used). Using Actilife, Actigraphs are initialised either as “beacons” or “receivers” with both beacons and receivers collecting acceleration data as they normally would. Although either a beacon or receiver could technically be given to a participant, a receiver is generally preferable as the receiver stores data on the beacons it encounters.

To track a participant’s location, the participant is given a receiver Actigraph to wear, generally on their waist or wrist, in the same way in which an Actigraph would normally be deployed for physical activity measurement. Beacon Actigraphs are then placed around the environment(s) in which the participant is to be tracked with a high and unobstructed placement preferable. As a participant moves around the environment, the receiver Actigraph then records RSSI readings from beacon Actigraphs which are broadcast at a user defined interval (from 10-60 seconds).

5.2.2.2 LumoBack

The LumoBack (LumoBody Tech, Mountain View, California), worn on the lower back, measures an individual’s posture, through which machine learning algorithms calculate the amount of time spent lying sitting, standing and stepping (39). The monitor connects wirelessly via low energy Bluetooth to a mobile phone application where data can be visualised and synced to the cloud. Data is not exportable from the phone.

LumoBack, on request, are then able to provide the synced data to the researcher; unfortunately, this data is in a format which requires extensive manipulation to be useable. To overcome this obstacle, a fee for service data aggregation company were commissioned to develop an online platform which was able to use the LumoBack application programming interface (API) to obtain data, format this data in a user defined format and to then make this data exportable. This online platform was primarily developed for use in the study of another PhD student with the present study utilising the platform to obtain useable data.

5.2.3 Deployment procedure

5.2.3.1 Participant deployment of Actigraph receiver and LumoBack

All participants wore both devices, an Actigraph on the non-dominant wrist and LumoBack around the lower back, for one week with all participants from Care Home One participating simultaneously and all participants from Care Home Two participating simultaneously. The Actigraph was initialised to collect proximity data every 10 seconds as this was the highest possible proximity resolution; however, collecting proximity data at this resolution significantly reduced device battery life. Actigraph charging hubs were therefore placed in each care home with staff asked to remove the Actigraphs from the residents overnight, place them in the charging hub overnight and then place them back on the resident the following morning. Staff were asked to remove their own devices when they left the care home (i.e. at the end of their shift), place them on charge and then put the device back on when they re-entered the care home (i.e. at the start of their next shift).

Participants were asked to wear the LumoBack during waking hours and to place the device lying flat when taken off so that this time could be recorded as non-wear. Following the one week measurement period, all devices were collected from the care homes and the data downloaded.

5.2.3.2 Care home deployment of Actigraph beacons

The floorplans for Care Homes One and Two are available in Figures 5.1 and 5.2 respectively. Beacons were placed high and unobstructed to ensure adequate BLE coverage. Each beacon was placed using eyesight to judge the correct placement, with each beacon at approximately the same height and approximately in the centre of the wall. A laser distance measurer was used to obtain precise measures of this; however, beacons were not moved from their original placement unless drastically off centre or drastically different in height to previous beacons.

On occasion, obstacles to beacon placement were encountered such as clocks, curtain rails and pictures. In these instances the resident or care home were not asked to move obstacles, beacons were instead placed as close as possible to the desired spot.

Resident’s rooms within both care homes were relatively small; therefore one Actigraph beacon was sufficient to cover the whole room and provide a discrete (in/not in) room occupancy measure. This is in accordance with Actigraph recommendations, whereby the presence of a Bluetooth signal (regardless of the RSSI) is deemed as “in proximity”. Communal areas in the care homes were of a sufficient size that more than one beacon was necessary to ensure whole room coverage. In these rooms a beacon was placed on each wall of each communal room. Corridor beacons were placed in such a way that one beacon was used to cover a straight passage of a corridor with a second beacon then placed when the corridor changed direction.

Figure 5.1 Floorplan and beacon deployment in Care Home One

Figure 5.2 Floorplan and beacon deployment for Care Home Two

5.2.4 Demographic and anthropometric measures

Basic demographic data including gender, age and ethnicity were self-reported by the residents. In cases where the participant had difficulty in reading the questionnaire or difficulty in writing down their responses, the participant’s responses were noted by the activities coordinator in each care home in consultation with the participant. Demographic and anthropometric data were not collected on care home staff. Height and weight of each participant were provided by the care homes. Each care home maintained a schedule of weekly height and weight measures to ensure that any changes could be monitored. It was therefore deemed unnecessary to measure the participant’s height and weight again. Each care home used WeightCheck chair scales (WeightCheck, East Sussex, UK) to measure their resident’s weight. These medical grade scales are commonly used to measure the weight of participants who experience difficulty in standing on a standard set of scales. Whilst, the participants of this study did not require chair scales (i.e. they could have stood on a standard set of scales), the chair scale was commonly used in both care homes. In relation to height, Care Home One used a portable Seca 213 stadiometer (Seca Ltd, Birmingham, UK) to measure their residents height whilst Care Home Two used a portable Seca 206 measuring tape (Seca Ltd, Birmingham, UK) which was attached to the wall. Height and weight measurements in both care homes were conducted by trained personnel. Demographic, height and weight data were entered into Microsoft Excel 2010 and descriptive statistics (mean and SD) were calculated for each care home.

Grip strength was measured using a Takei analogue 5001 hand dynamometer (Takei Scientific Instruments, Japan). Prior to the test, each participant was asked to remove hand or wrist jewellery to ensure it was not damaged during testing. The dynamometer was then adjusted with the participant’s dominant hand to ensure that the second joint of the index finger was at a 90 degree angle on the handle. The researcher first demonstrated the correct performance of the test to each participant. Following this demonstration, each participant was then asked to stand to perform the test with their feet hip width apart and their toes pointing forwards. Each participant was instructed to grasp the dynamometer between their fingers and the palm at the base of their thumb and hold the dynamometer at thigh level, in line with the forearm and not touching their body with their elbow straight. When participants were comfortable in this posture, they were instructed to take a deep breath in and then exhale whilst squeezing the dynamometer as hard as they could. Each participant performed one grip strength test on their dominant and non-dominant hand. The results of these tests were then noted down on data collection forms designed for this study. The data were entered into Microsoft excel 2010 and descriptive statistics (mean and SD) were calculated for each care home. Participants were encouraged to take as much rest as they needed before commencing the next test.

Next, participants completed the 30 second chair stand test. For this test, a chair was provided by each care home. The researcher demonstrated to each participant how to perform the test. Participants were then instructed to sit in the middle of the chair with their hands on the shoulder crossed at the wrist with their feet flat on the floor. When each participant was comfortable in this position, the researcher started the stopwatch and the participant began to stand. The researcher then counted the number of times each participant was able to stand within the 30 seconds. The results of these tests were then noted down on data collection forms designed for this study. One test was performed per participant. The data were entered into Microsoft excel 2010 and descriptive statistics were calculated (mean and SD) for each care home. Participants were encouraged to take as much rest as they required before starting the next test.

The 8 feet up and go test was also conducted. The same chair used in the 30 second chair stand test was also used for this test with a tape measure marking 8 feet on the floor. This was kept to the side of the room to ensure that no participants tripped. The researcher demonstrated to each participant how to perform the test. Each participant was then instructed to sit on the chair with the hands on their lap. A cone was then placed 8 feet away to show the participant where they had to walk to. When the participant was comfortable, the researcher started and timed the test with the participant standing up from the chair, walking to and around the cone at their normal pace and then walking back to the chair to sit down again. Participants were permitted to use a walking aid if required. The results of these tests were then noted down on data collection forms designed for this study. One test was performed per participant. The data were entered into Microsoft Excel 2010 and descriptive statistics were calculated (mean and SD) for each care home.

5.2.5 Data treatment and analysis

5.2.5.1 Actigraph

Using Actilife version 6.11.8, a proximity data table was generated using a 10 second epoch displaying the RSSI received from every beacon within range during that epoch. Displaying the RSSI received from every beacon within range led to some instances in which beacons from more than one location were recorded as "in proximity"; for example, simultaneous readings from a beacon within the residents room and from a nearby beacon in the corridor creating uncertainty about the true location. Therefore, the following process was used to establish one location per epoch:

1. If the residents room beacon had an RSSI then they are in their room
2. If the residents room beacon does not have an RSSI and any communal beacon has an RSSI then they are in the communal area
3. If both the residents room and communal areas have no RSSI but there is an RSSI from a beacon in the room of another resident then they are in that's residents room
4. If there is no RSSI from the residents room, the communal area or another residents room but there is an RSSI from a corridor beacon then they are in the corridor

This one location per 10 second epoch was then aggregated up to time spent in each location per 5 minute epoch so that it could be combined with LumoBack data. Wrist acceleration data, collected at 100Hz, was summarised into 10 second epochs and combined with 10 second location data. The average count per epoch (CPE) was then calculated in each location. The term "movement" is used to refer to average CPE throughout the rest of this thesis.

5.2.5.2 LumoBack

LumoBack data for each participant were downloaded from the online platform developed for data aggregation. LumoBack data showed the amount of lying, sitting, standing and stepping occurring in each 5 minute epoch; a 5 minute epoch was used as this is the epoch in which data is synced from a device to the mobile application. LumoBack data is only available in a resolution of 5 minutes. This shows the amount of lying, sitting, standing and stepping occurring over each 5 minute period but not where this happened with the 5 minutes. It is therefore not possible to analyse LumoBack data, or to combine LumoBack data with other data streams, in an epoch lower than 5 minutes.

5.2.5.3 Combined proximity and posture data

Using the timestamps from both data streams, the five minute epoch data from Actigraph and LumoBack were aligned in Microsoft Excel 2010 to show the time spent in each posture in each location. Due to limitations in the LumoBack data (i.e. the inability to determine where postures happen within each 5 minute epoch) it is not possible to ascribe a posture to a location if there are multiple locations and multiple postures within the same 5 minute epoch (i.e. if there are 2.5 minutes in the residents room with 2.5 minutes in the communal areas and 2.5 minutes sitting with 2.5 minutes standing it is not possible to ascribe sitting to the residents room or the communal area). Time spent in each posture in each location per 5 minute epoch was therefore calculated using Excel formulas in the following process:

1. If there are 5 minutes of LumoBack non-wear then this means that it is not possible to combine the two data streams and there is therefore no time in any posture in any location
2. If all 5 minutes are spent in one posture (e.g. sitting) then this means that the time in each location (i.e. the resident’s room, communal areas and corridors) must have been spent in that one posture. Therefore return the time spent in each location for that 5 minute epoch.
3. If all 5 minutes are spent in one location then this means that the time in each posture (i.e. lying, sitting and standing) must have been spent in that one location (e.g. the residents room). Therefore return the time spent in each posture for that 5 minute epoch.
4. In instances where a full 5 minute epoch is not available for both data streams, but there is some data, if the sum of time in each posture is equal to the time spent in one location then this must mean that all postures happened in one location. Therefore return the time spent in each posture.
5. In instances where a full 5 minute epoch is not available for both data streams and the sum of time in each posture is **not** equal to the time spent in one location or there are multiple postures and multiple locations in the same 5 minute epoch then this epoch of data cannot be combined. This is due to the inability to attribute postures to locations if there are multiple postures and multiple locations (i.e. if there are 2.5 minutes in the residents room with 2.5 minutes in the communal areas and 2.5 minutes sitting with 2.5 minutes

standing it is not possible to ascribe sitting to the residents room or the communal area).

5.2.5.4 Statistical analysis

Data were imported into the Statistical Package for the Social Sciences (SPSS) version 23. Preliminary data inspection revealed that the parametric assumptions of normal distribution and homogeneity of variance were violated. The Kolmogorov-Smirnov test showed the data were non-normally distributed for some variables ($D\ (5,9) = \leq 0.473$, $p<0.05$). Furthermore, the Levene's test showed that the assumption for homogeneity of variance was also violated for some variables ($F\ (1,12) = \leq 11.25$, $p<0.05$). Mann-Whitney tests with exact significance were therefore used to test for differences between Care Home One and Care Home Two residents. No statistical analyses were conducted on care home staff. Statistical significance was set at 0.05.

5.3 Results

Descriptive statistics for care home residents are shown in Table 5.1. Participants taking part in the study in both care homes were, on average, similarly aged (87 ± 10 years old and 86 ± 7 years old in Care Homes One and Two, respectively) and predominantly female (77% and 69% in Care Homes One and Two, respectively). The vast majority of residents taking part in the study were white British (100% in Care Home One and 92% in Care Home Two). The remaining resident in Care Home Two was White Irish. There were no significant differences in grip strength, the 30 second chair stand or the 8 feet up and go test between the two care homes ($U = \geq 16$, $p \geq 0.059$)

Table 5.1 Descriptive demographic and anthropometric characteristics for Care Home One and Care HomeTwo residents (Mean ± SD unless otherwise stated)

	Care Home One	Care Home Two	P Value
Residents			
Total number of residents	38	39	
Number of residents in the study	13(34%)	13(± 33%)	
Age	87 ± 10	86 ± 7	
Gender (% female)	77 %	69 %	
Height (cm)	159 ± 16.59	161 ± 0.09	
Weight (Kg)	58 ± 11	61 ± 14	
Ethnicity (% white British)	100 %	92 %	
Grip strength left (Kg)[1]	13 (10)	10 (9)	0.68
Grip strength right (Kg)[1]	18 (14)	12 (6)	0.633
30 second chair stand (reps)[1]	7 (3)	3(3)	0.183
8 feet up and go (seconds)[1]	11 (9)	46 (63)	0.059
Staff			
Number of staff in the study	6	10	

[1]Indicates that the median and interquartile range are presented

Average minutes spent sitting of residents in each area of Care Home One and Care Home Two are shown in Figures 5.3 and 5.4 respectively. These figures show that, on average, residents make at least hourly transitions between their own room and communal areas of the care home throughout the day.

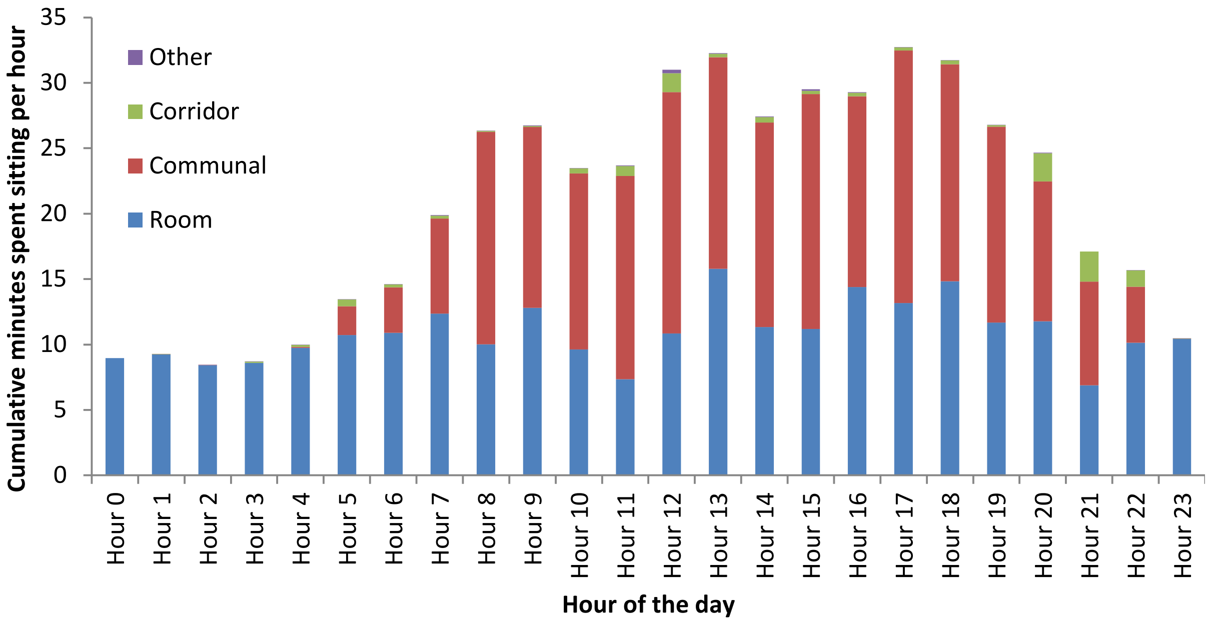

Figure 5.3 Average sitting time in each location per hour from Care Home One

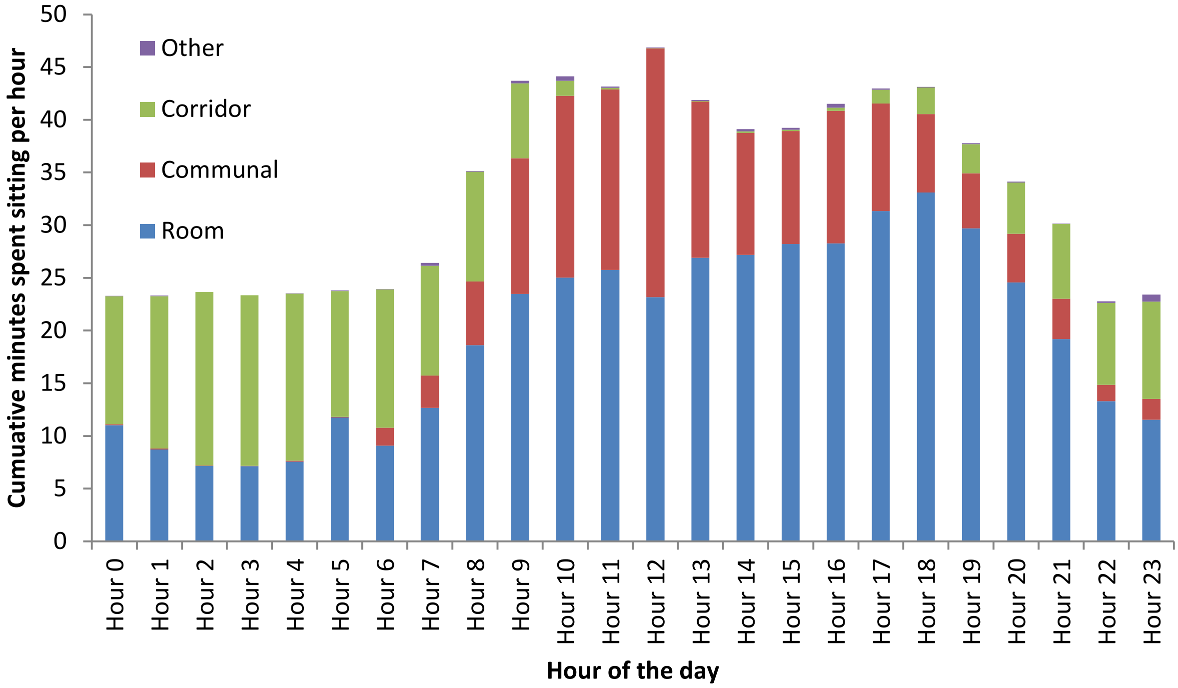

Figure 5.4 Average sitting time in each location per hour from Care Home Two

Table 5.2 shows the descriptive and statistical results for residents from the two care homes. No significant differences were found between Care Home One and Care Home Two in the amount of time spent sitting in communal areas of the care home (301 minutes per day and 39 minutes per day respectively, U=23, p=0.057) or in the amount of time residents spent sitting in their own room (215 minutes per day and 337 minutes per day in Care Home One and Two respectively, U=32, p=0.238). Significant differences were found in the amount of time spent standing in the residents room (7 minutes per day in Care Home One and 2 minutes per day in Care Home Two, U=7, p = 0.001) and standing in communal areas (4 minutes per day and 0 minutes per day in Care Home One and Two respectively, U=8, P=0.001).Further differences were found in the amount of time spent stepping in the residents room (1 minute per day and 0 minutes per day in Care Home One and Two respectively, U=8, p=0.001) and stepping in communal areas (1 minute per day in Care Home One and 0 minutes per day in Care Home Two, U=17, p=0.006).

Table 5.2 Summary of time (minutes) spent in each posture in each location by care home residents (Median and Interquartile range)

	Care home One residents	Care home Two residents	P Value
Own room laying down	227 (255)	48 (112)	0.003*
Own room sitting	215 (342)	337 (185)	0.238
Own room standing	7 (7)	2 (2)	0.001*
Own room stepping	1 (1)	0 (0)	0.001*
Communal room laying down	0 (14)	0 (38)	0.553
Communal room sitting	301 (359)	39 (245)	0.057
Communal room standing	4 (5)	0 (0)	0.001*
Communal room stepping	1 (2)	0 (0)	0.006*
Corridor laying down	1 (83)	97 (191)	0.156
Corridor sitting	13 (17)	104 (180)	0.057
Corridor standing	0 (0)	0 (1)	0.591
Corridor stepping	0 (0)	0 (0)	0.418
Other residents room laying down	0 (0)	0 (1)	1
Other residents room sitting	1 (1)	2 (5)	0.438
Other residents room standing	0 (0)	0 (0)	0.4
Other residents room stepping	0 (0)	0 (0)	1

*indicates statistical significance

Average movement (defined as 100Hz wrist acceleration data summarised into counts per 10 second epoch) for a given number of residents simultaneously in the communal areas is shown in Figures 5.5 and 5.7 for Care Home One and Care Home Two, respectively. To achieve this, the average count per 10 second epoch was calculated for the time in which a given number of residents were simultaneously in the communal area (e.g. average count per 10 seconds was calculated for the time in which any 2 residents were in the communal area). In both care homes, average movement increases with the number of residents in the communal area. Furthermore, in both care homes, there is a tendency towards there being six or fewer residents in the communal area simultaneously. Individual residents data showing average movement per room are highlighted in Figures 5.6 and 5.8 for Care Homes One and Two respectively. In both care homes, residents showed wide variability in both the cumulative movement and movement distribution across rooms. For example, resident 3 accumulated approximately four times more movement, on average, than resident 4 (751 counts and 179 counts respectively). Similarly, resident 3 achieved their highest movement in their own room whilst resident 10 achieved their highest level of movement in the corridors of the care home.

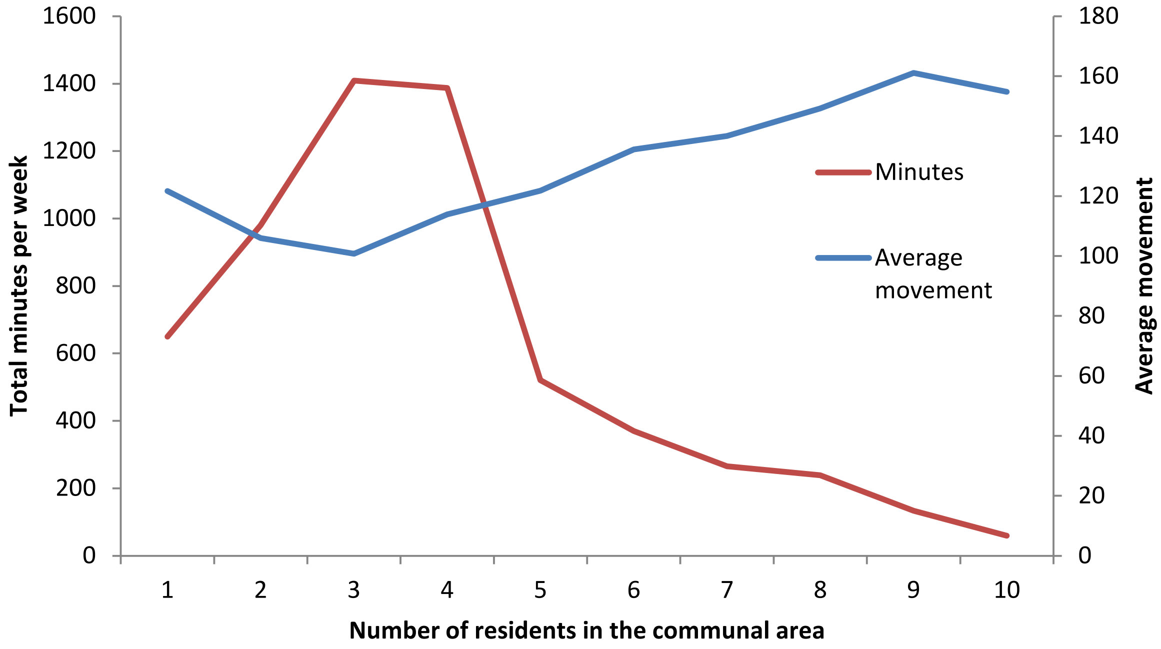

Figure 5.5 Average movement[1] and total minutes per week for the number of residents simultaneously in the communal area of Care Home One

[1]Movement was defined as 100Hz wrist acceleration data summarised into counts per 10 second epoch. The average count per 10 second epoch was then calculated for the time in which a given number of residents were simultaneously in the communal area (e.g. average count per 10 seconds was calculated for the time in which any 2 residents were in the communal area).

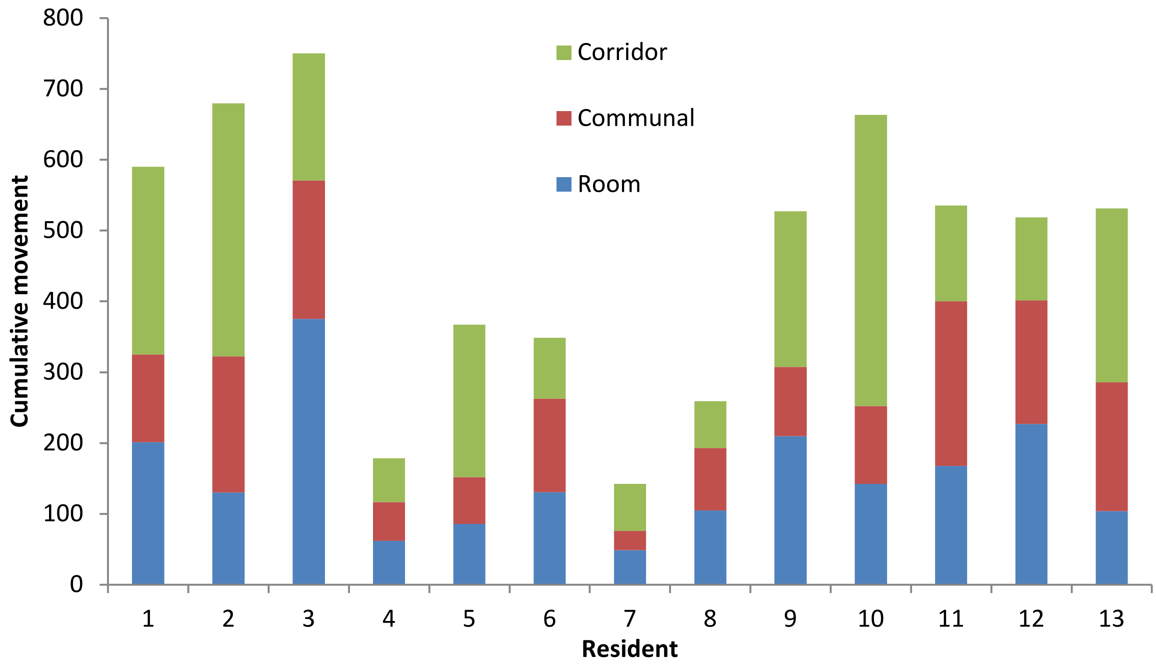

Figure 5.6 Cumulative average movement[1] per resident per location in Care Home One

[1]Movement was defined as 100Hz wrist acceleration data summarised into counts per 10 second epoch.

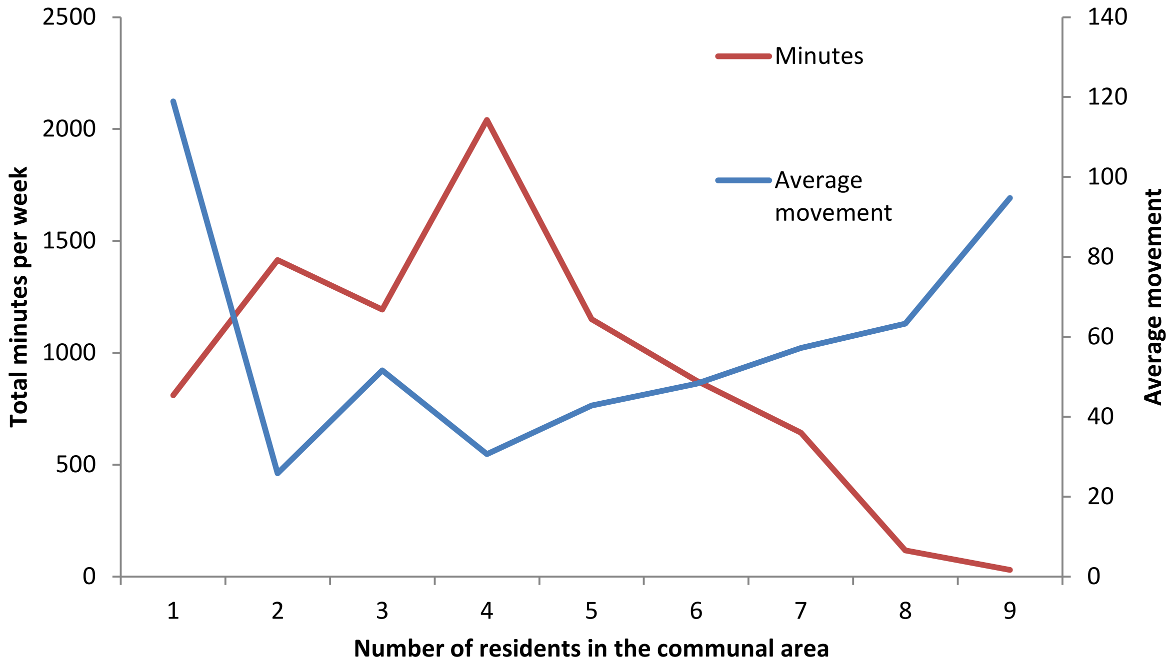

Figure 5.7 Average movement[1] and total minutes per week for the number of residents simultaneously in the communal area of Care Home Two

[1]Movement was defined as 100Hz wrist acceleration data summarised into counts per 10 second epoch. The average count per 10 second epoch was then calculated for the time in which a given number of residents were simultaneously in the communal area (e.g. average count per 10 seconds was calculated for the time in which any 2 residents were in the communal area).

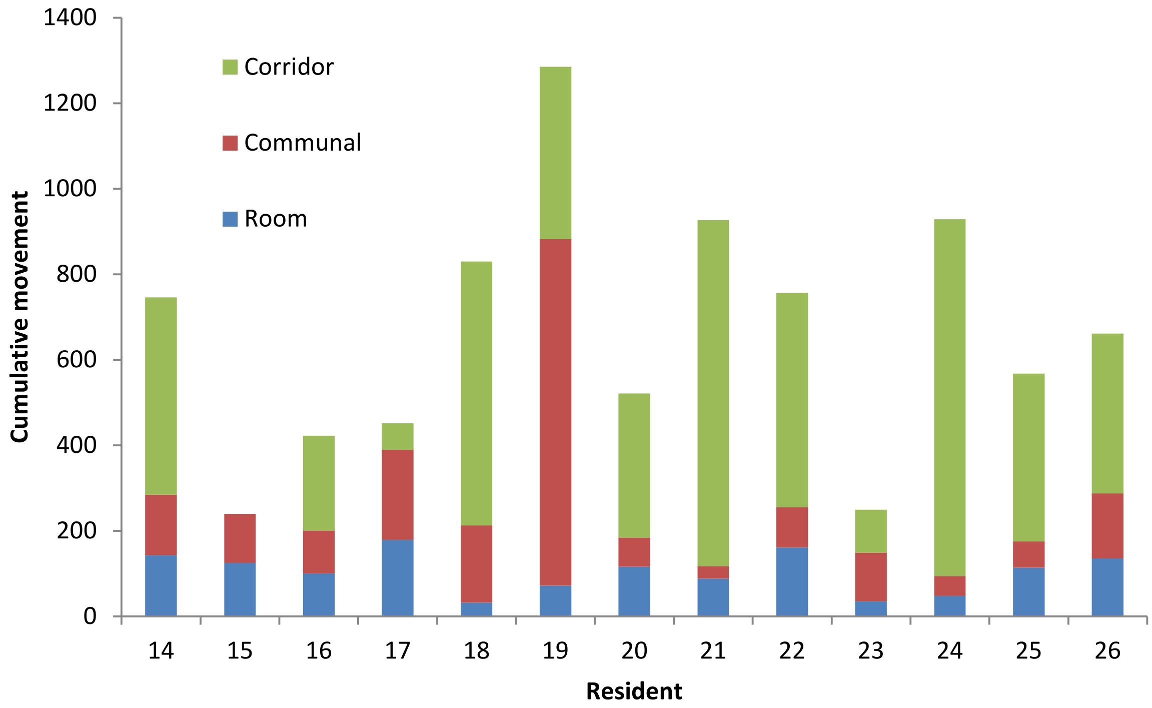

Figure 5.8 Cumulative average movement[1] per resident per location in Care Home Two

[1]Movement was defined as 100Hz wrist acceleration data summarised into counts per 10 second epoch.

Table 5.3 shows the descriptive staff results from Care Home One and Care Home Two. In total data were available for 250 minutes per day on average in Care Home One and 736 minutes per day on average in Care Home Two; however, corridor lying and corridor sitting time in Care Home Two appeared to be implausibly high. When corridor lying and corridor sitting time were removed from Care Home Two, data were then available for 293 minutes per day on average. Given the paucity of available staff data (250 minutes per day in Care Home One and 293 Minutes per day in Care Home Two), no further analyses were conducted.

Table 5.3 Summary of average time (minutes) spent in each posture in each location by care home staff (Mean ± SD) per day

	Care Home One	Care Home Two
Room lying	107 (±166)	130 (±197)
Room sitting	22 (±25)	112 (±171)
Room standing	7 (±7)	5 (±8)
Room stepping	3 (±3)	2 (±2)
Communal lying	25 (±45)	15 (±23)
Communal sitting	60 (±38)	11 (±10)
Communal standing	12 (±9)	1 (±2)
Communal stepping	5 (±4)	0 (±1)
Corridor lying	5 (±8)	195 (±217)
Corridor sitting	4 (±3)	248 (±170)
Corridor standing	0 (±0)	16 (±37)
Corridor stepping	0 (±0)	1 (±1)

5.4 Discussion

The purpose of this study was to apply a novel measurement paradigm to generate new information around the context of sitting. In an attempt to maximise utility, this novel measurement paradigm was applied to a group which are known to be highly sedentary and to a setting which was conducive to the current state of the proximity technology. These cross-sectional data corroborate previous findings (422,446) that older adults are highly sedentary and suggest that a large amount of sedentary time is accumulated in the residents own rooms and in communal areas of the care home.

In Care Home One, residents spent more time sitting in communal areas of the care home than in their own rooms (301 minutes per day and 215 minutes per day, respectively). However, Figure 5.3 shows that on average, in each hour of the day, residents spent time sitting in both their own rooms and communal areas. This suggests that residents make relatively frequent transitions (i.e. at least once an hour) between areas of the care home. Despite this, residents accumulated very small amounts of standing and stepping. This may reflect the small building size of the care homes ensuring that residents can navigate the care home in a relatively short space of time.

In Care Home Two, residents spent more time sitting in their own room than in communal areas (337 minutes per day and 39 minutes per day respectively). This is an area which should be addressed in this care home as it may reflect a lack of social interaction in the care home. Similar to Care Home One, residents in Care Home Two spent their time sitting in both their own rooms and communal areas of the care home during most hours of the day, as shown in Figure 5.4. This again suggests that residents make relatively frequent (i.e. at least hourly) transitions between areas of the care home.

Residents in both care homes spent a very small amount of time standing and stepping on average. It is likely that this reflects the functional limitations of care home residents. These functional limitations also likely largely explain some of the more peculiar findings of the study; for example, residents in Care Home Two spending 97 minutes lying in the corridor. These findings are likely due to the resident's functional limitations necessitating at least some travel between rooms being completed in a wheelchair and this being monitored as lying by the LumoBack (453).

There was a tendency in both care homes towards increased movement, as measured by wrist accelerometer, when more residents were simultaneously in the communal areas of the home. In Care Home One, average movement was 122 counts when one resident was in the room, rising to 154 counts when 10 residents were simultaneously in the communal areas. Furthermore, over the course of one week, just 59 minutes in total were spent with 10 residents simultaneously in the communal area. This suggests that there is considerable scope for more time to be spent in the communal areas by more residents. In Care Home Two, movement was highest, 119 counts, when only one resident was present in the communal areas; however, movement rose from a low of 26 counts when 2 residents were simultaneously in the communal area to 95 counts when 9 residents were simultaneously in the communal area.

There was a paucity of available data for staff in both care homes (250 minutes per day and 293 minutes per day in Care Home One and Care Home Two respectively). This dearth of data prohibited further analysis. A contributing factor to this paucity of data is likely to be the merging of LumoBack posture data and Actigraph location data. The merging process detailed in section 5.2.5.3 required either 5 complete minutes in one location, 5 complete minutes in one posture or, if a complete 5 minutes of data was not available, an equivalent amount of posture and location data available in a 5 minute epoch. This was necessary due to the LumoBack data only being available in summary 5 minute epochs with an inability to look at the temporality within those 5 minutes. This results in an inability to ascribe multiple locations to multiple postures within a 5 minute epoch (i.e. if there are 2.5 minutes in the residents room with 2.5 minutes in the communal areas and 2.5 minutes sitting with 2.5 minutes standing it is not possible to ascribe sitting to the residents room or the communal area). For care home staff, it is highly likely that there are many instances where they do not spend a full 5 minutes in one location or in one posture. These instances would not have passed through the merging process. Future studies may therefore benefit from a sedentary behaviour sensor with greater resolution to allow subsequent merging with other data streams. The spurious findings for corridor lying and corridor sitting in Care Home Two may reflect staff being instructed to place their Actigraph on charge when they left work and to then put the monitor back on at the start of their next shift. Chargers were placed in or near corridors and it is therefore possible that staff did not put their monitor back on and thereby left the devices in the corridor.

The finding that residents in both care homes spent a large amount of time sitting alone in their own rooms suggests that interventions should either encourage residents to be less sedentary in their rooms or to leave their rooms for communal areas more often. Furthermore, in both care homes there is a tendency towards higher average movement per resident when more residents are simultaneously in the communal areas; however, there is also currently a tendency towards less total time being spent in the communal areas by higher numbers of simultaneous residents (e.g. very little time spent with 8 or 9 residents simultaneously in the communal area). This shows that there is considerable time available in which more residents could occupy the communal areas. When considered collectively, these findings suggest that the greatest benefit to residents could be gained through getting more residents into the communal areas more often. Encouraging residents to leave their rooms for communal areas more frequently may serve a dual benefit in facilitating social interaction and lower isolation.

These findings complement those of a previous study using wearable cameras to assess the context of sedentary behaviour among community dwelling older adults (422); identifying household, leisure and transport as key domains where prolonged bouts of sedentary time are likely to occur. In particular older adults were found to be sedentary in their own home for 70.1% of the time. This finding is similar to the finding in the present study that older adult care home residents spend a large proportion of their time sedentary in their own room. The study by Leask and Colleagues (422) used a wearable camera as their measurement tool which has the advantage of assessing a wider range of contextual variables than is possible with the proximity monitoring system used in the present study. However, wearable cameras also have significant privacy and analytical challenges including the possibility of capturing unwanted people or events in images, laborious data coding (93) and the possibility that a large number of images may be un-codeable (such as in Feasibility Trial One of Study Three).

The novel measurement paradigm applied to older adult care home residents in this study could equally be applied to other groups and settings to generate new data around the context of behaviour (417). The technology used to measure indoor location is currently more conducive to settings where people are likely to congregate such as schools, workplaces or childcare centres; however, care homes were ideal for this study as residents live in the care home ensuring that location could be measured for the entire day. This would not have been the case if the system used in this study was deployed to an alternative setting. It is certainly possible to deploy the system to, for example, a workplace setting and to also place beacons in other settings of interest for that population such as in a vehicle or at their home. However, this would greatly reduce the scalability of the system as placing a beacon in the vehicle and home of 20 participants would require an additional 40 beacons and present logistical challenges. Indoor location technology is therefore currently best suited to assessing particular settings or addressing research questions which require an event monitor providing data in a particular location rather than a life logger providing data across a number of locations. Such an example can be found in Feasibility Trial Three of Study Three.

The strengths of this study include the use of novel measurement technology to generate more refined and objective data around the context of sitting. These data are able to provide unique insights into the context of sitting which can be used to refine intervention strategies aimed at reducing sitting time. Furthermore, the proximity system used in this study provides similar acuity of indoor location to other available systems (i.e. room level) but is advantageous due to its wearability and potential to capture simultaneously wrist accelerometry data. However, the unit cost per device is much higher than alternatives such as iBeacons and this may therefore limit the scalability of the system.

Potential limitations of the study include the use of the LumoBack for measuring sedentary behaviour. This device is only able to provide data in summary 5 minute epochs which show the time spent lying, sitting, standing and stepping across each 5 minute epoch but not the temporality within the 5 minute epoch. This lack of temporality then presents challenges when aligning this 5 minute data with higher resolution data such as the 10 second proximity data used in this study. This device has not been validated in older adults; however, it has been validated in working age adults (55,56) and shows validity and reliability comparable to that of the ActivPAL (PAL technologies Ltd, Glasgow, UK). Furthermore, although waist worn, this device may be more wearable than the ActivPAL in an older population due to potential skin irritation and skin flaking caused by the ActivPAL stickers (50). Another limitation was that selection bias could not be ruled out due to the non-random nature of the sample. Additionally, there were some staff and residents at both care homes who did not consent to take part in the study and did therefore not provide any demographic data. It is therefore possible that the sample is not representative of the wider care home; this was anecdotally confirmed by the activities coordinator at each care home who recruited residents for the study suggesting that reasons for non-consent among residents included memory impairment (e.g. dementia), severe physical limitations such as being bed bound and some residents simply not wishing to take part. In each case, approximately one third of residents from each care home took part in the study.

5.5 Conclusion

The novel measurement paradigm developed throughout preceding studies and applied, in this study, to profiling the locations in which older adult care home residents spend their sedentary time is able to generate new and important insights into the context of behaviour. Care home residents were found to accumulate most of their sedentary time within communal areas of the care home in Care Home One and their own rooms in Care Home Two. Average movement per resident was also higher when more residents were simultaneously in the communal area. These findings suggest that interventions should encourage more residents to leave their rooms and go to the communal areas more often. Although applied, in this study, to older adult care home residents the technology used within this study could equally provide new and important insights across a number of populations and settings.

This chapter contributes to the overall aims of the thesis through a use case, in older adult care homes, of the tracking system validated and trialled earlier in the thesis. Through the use of this system, in combination with an objective measure of sedentary behaviour, the chapter was able to identify that care home residents accumulate most of their sedentary time within their own rooms. Furthermore, average movement per resident, as assessed via wrist accelerometer, was higher when more residents were simultaneously in the communal areas. This is information that was not previously available when a measure of physical activity or sedentary behaviour was used in isolation. This chapter therefore fulfils the overall thesis aim of extracting behaviourally relevant data through the combination of indoor location, physical activity and sedentary behaviour data.

6 General discussion

The overall purpose of this four study thesis was to develop, refine and apply a novel measurement paradigm able to generate new insights into the context of physical activity and sedentary time. The purpose of Study One was to identify technologies which are able to measure, or could be modified to measure, indoor location. The purpose of Study Two was to assess the validity and reliability of the Actigraph proximity feature. The purpose of Study Three was to feasibility trial the most promising technology across a number of settings and populations to ascertain where the technology could provide the most novel insights. The purpose of Study Four was to apply a novel measurement paradigm to profile the locations in which older adult care home residents spend their sedentary time and the effect of residents simultaneously being in the same location on movement levels. The primary hypothesis was that residents would spend the majority of their day sedentary. The secondary hypothesis was that residents would spend more time sedentary in their own room than in communal areas. The tertiary hypothesis was that residents would show less movement when simultaneously in communal areas of the care homes with other residents.

6.1 Summary of main findings

In Study One, a systemic review identified 188 published research papers using a variety of technologies to measure location. GPS was the most widely used technology, comprising 119 of the identified papers. Systematic searching of internet search engines identified a further 21 wearable cameras, 35 RTLS and 82 GPS devices which are commercially available but have not been used in published research to date. Studies to date have primarily used GPS to assess outdoor location, often combining this with accelerometry to determine the contribution of outdoor environments, such as green space, to MVPA (170,228,243); however, the average individual spends the majority of their day indoors (424), where GPS cannot assess location. To date no indoor equivalent of GPS has emerged; however, several technologies show promise. Wearable cameras capture automated, point of view images and have been used to assess various aspects of the context of physical activity, such as who is present or the specific behaviour being performed (91,92,123,160,432,433); however, this technology has significant privacy concerns and data analysis can be laborious on the researcher. Primarily used within health care and warehouse settings, RTLS is able to track the indoor location of people or equipment with an accuracy of approximately 3 metres (396,399). Although each manufacturer differs, generally speaking, this technology uses a variety of techniques, such as triangulation, trilateration or fingerprinting to calculate the location of a wearable tag relative to the locations of fixed reference nodes through a variety of communication protocols such as Wi-Fi, Ultra-wide band or Zigbee. Previous reviews of location measurement technology have focused either on the technological components and electrical engineering relevance of the technologies (396-399) or have focused on the utility of applying the technologies to enhance understanding of a particular behaviour (88). This is the first systematic review to comprehensively assess both the characteristics of the available technology and to identify areas in which this technology has been or could be used to further understanding of a physical activity and sedentary behaviour.

In Study Two a series of three experiments investigated the Actigraph proximity feature. Experiment One assessed the basic characteristics of the Actigraph RSSI signal across a range of straight line distances. Experiment Two assessed the level of receiver device signal detection in a single room under unobstructed conditions, when various obstructions are introduced and the impacts these obstructions have on the intra and inter unit variability of the RSSI signal. Finally, Experiment Three assessed signal contamination across multiple rooms (i.e. one beacon being detected in multiple rooms). In Experiment One, the relationship between RSSI and distance was found to be non-linear and unsuitable for distance estimation due to the same RSSI being observed at a number of distances (e.g. 0.8m and 1m). This therefore results in an inability to calculate distance from RSSI alone. This is consistent with previous research using other BLE devices that RSSI in isolation is unsuitable for distance estimation (411-413). In Experiment Two, similar methodologies were followed to those used in previous validation studies of GPS (22) and RTLS (398,401-404) in which the tested technology is placed in a known location. The location calculated by the technology is then compared to the known location. High signal detection (≥91.6%) was achieved in all conditions; however, there was a large degree of intra and inter-unit variability in RSSI with inter-unit variability higher than intra-unit variability under all test conditions. The human obstruction condition showed the highest level of intra-unit variability (SD = 3.1, CV = 0.04, SEM = 1.31) whilst the highest level of inter-unit variability was shown in the metal obstruction condition (SD = 5.12, CV = 0.07, SEM = 2.99). In Experiment Three, there was a large degree of multi-room signal contamination (≥47%). The highest level of multi-room signal contamination occurred in the bedroom with all beacons (including those from the living room) being detected 100% of the time. Collectively, these results show that the Actigraph proximity feature is unsuitable for distance estimation given the non-linear relationship between RSSI and distance and the high inter-unit variability in RSSI; however, given the high signal detection rates, even when obstructions were introduced, the system is suitable as a binary means of determining proximity. This corroborates the advice given by Actigraph as to how the system should be utilised. The findings of this study should also be seen as comparable to those of previous validation studies. For example, a previous study found GPS units to be accurate to 3.02m (22). In a real world setting this level of accuracy is sufficient to determine that an individual is, for example, in a park but not necessarily which piece of equipment they are using within the park. The analogous indoor version of this suggests that the Actigraph is sufficient to determine that an individual is in a room but not necessarily where within the room. Similarly, Wi-Fi based RTLS units are accurate to approximately 3m which is, in practice, sufficient for room level accuracy in many settings. However, high multi-room signal detection was also observed in Experiment Three. This suggests that either careful deployment of the system is needed to avoid multi-room contamination or post-deployment processing to avoid multi-room contamination. This study is the first to investigate the Actigraph proximity feature using similar methodologies to those used for other location measurement technologies.

In Study Three, three small feasibility trials were undertaken to assess the setting and population in which this technology could demonstrate the greatest utility. Feasibility Trial One assessed the concurrent validity of wearable cameras and energy monitoring equipment as measures of television viewing in a small convenience sample (N=6, 50% female, mean age 27 ± 2). Energy monitoring was able to determine when the television was turned on (average 202 ± 14 minutes per day) or off but not necessarily when it was being watched. Wearable camera images were able to capture when the participant was in the same room as the television and therefore corroborate that the television was being watched (average 90 ± 43 minutes per day); however, a large number of images showed the living room but not the television (52 ± 24 minutes per day) or were un-codeable due to a lack of identifying features. This suggests that wearable cameras may be a poor measure of behaviours where slouching may occur, leaving the camera pointing upwards. Self-reported Health Survey for England data show that, on average, individuals engage in 168 minutes of television viewing on a weekday (426). This may suggest that energy monitoring overestimates television viewing by including time in which the television is turned on but the participants may not be in the room. In Feasibility Trial Two, a proximity monitoring system was used in an older adult care home environment in conjunction with the LumoBack posture sensor. This feasibility trial showed that residents (N=5, 100% female, Mean age 87 ± 5) were highly sedentary (98% of time between 7am-11pm) and spent the majority of their waking day in their own room and more time in communal areas in the morning than in the afternoon. These data corroborate previous findings (422,446) that older adults are highly sedentary. It is therefore important to develop interventions to reduce this sedentary time. The measurement technology applied in this feasibility trial shows utility in elucidating where this sedentary time is spent and therefore offers insight into how it could be reduced. For example, residents who spent the majority of their sedentary time within their own room may benefit from an individualised intervention whilst residents who spent the majority of their sedentary time in communal areas may benefit from a group based intervention. Feasibility Trial Three assessed the use of proximity sensors in quantifying office dwell time to provide a better denominator against which the success of height adjustable desk interventions may be quantified. This feasibility trial found that a convenience sample of office workers (N= 5, 20% female, mean age 26 ± 4) spend a considerable amount of their working day away from their office, both in a sedentary (average 39 ± 36 minutes per day) and upright posture (average 93 ± 70 minutes per day), and thus away from their height adjustable desk. In contrast, office workers, on average spent 163 ± 96 minutes per day sedentary in their office and 88 ± 57 minutes upright in their office. A number of studies are emerging investigating the use of height adjustable desks with objective measures of physical activity and/or sedentary time (441). These studies typically ask participants to self-report their working hours to obtain a measure of intervention exposure (441). These findings suggest that the effects of height adjustable desk interventions may currently be exaggerated or diluted by including time which is spent at work but not in the office. Objectively assessing office dwell time may therefore provide a more robust quantification of intervention efficacy in future intervention trials.

Study Four of this thesis applies the novel measurement paradigm, developed throughout the thesis, to an older adult care home environment. The Actigraph proximity feature was used to assess the locations in which residents from two care homes (N=13, 77% female, mean age 87 ± 10 in Care Home One and N=13, 69% female, mean age 86 ± 7 in Care Home Two) spent their LumoBack measured sitting time and the impact of resident’s simultaneous room occupancy on average accelerometer assessed movement levels. No significant differences were found between Care Home One and Care Home Two in the amount of time spent sitting in communal areas of the care home (301 minutes per day in Care Home One and 39 minutes per day in Care Home Two, U=23, p=0.057) or in the amount of time residents spent sitting in their own room (215 minutes per day and 337 minutes per day in Care Home One and Two respectively, U=32, p=0.238). Significant differences were found in the amount of time spent standing in the residents room (7 minutes per day in Care Home One and 2 minutes per day in Care Home Two, U=7, p = 0.001) and standing in communal areas (4 minutes per day and 0 minutes per day in Care Home One and Two respectively, U=8, P=0.001).Further differences were found in the amount of time spent stepping in the residents room (1 minute per day and 0 minutes per day in Care Home One and Two respectively, U=8, p=0.001) and stepping in communal areas (1 minute per day in Care Home One and 0 minutes per day in Care Home Two, U=17, p=0.006). In both care homes, average movement per resident, assessed via wrist accelerometry, was higher when more residents were simultaneously in the communal area. These findings suggest that interventions should encourage more residents to leave their rooms and go to the communal areas more often. This will serve the dual-benefit of encouraging social interaction amongst residents. These findings complement those of an earlier study which used a wearable camera to assess the context of sedentary behaviour in community dwelling older adults (422). This study identifying household, leisure and transport as key domains where prolonged bouts of sedentary time are likely to occur (422). In particular older adults were found to be sedentary in their own home for 70.1% of the time (422). The current study complements these findings by focusing on care home residents rather than community dwelling older adults. Previous research, using accelerometer assessed sedentary time, has identified that older adult care home residents spend the majority (79%) of their day sedentary (446). The current study expands these previous findings by quantifying where within the care home this sedentary time occurs. This novel information can then be used to provide tailored intervention strategies to residents who spend their sedentary time in different locations. Although applied, in this study, to older adult care home residents the technology used within this study could equally provide new and important insights across a number of populations and settings.

6.2 Why measure context

It is worth, briefly, reiterating the added value of measuring the context of physical activity and sedentary time. Despite incontrovertible evidence that engagement in MVPA reduces the likelihood of developing a plethora of chronic diseases, objectively measured data show that population levels of MVPA are very low (2,10). Conversely, emerging evidence suggests that excessive sedentary time may be independently associated with increased risk of developing chronic disease yet objective data show that the average individual spends the majority of their day sedentary (7,9). Undoubtedly, there are a number of reasons for this disconnect; however, a contributing factor may be that researchers and public health professionals simply do not possess enough specificity about current behaviour; what behaviours are occurring, when they occur, who they occur with and where they occur (18). This lack of specific knowledge may inhibit intervention efforts to favourably alter behaviour. Measuring the context of existing behaviour may therefore provide the specificity to increase the efficacy of interventions (18). Measuring this context, particularly location, should be seen within the overall context of the relationships between the environments individuals share and their behaviour and health. This relationship and the process of encouraging individuals and communities to collaboratively shape their environments is known as Place Making (454). This process could be aided if individuals and communities were provided with objective data on their environment.

Alongside increasing the efficacy of interventions, measuring context could also make an important contribution to a number of active research areas. An emerging body of research has investigated the use of height adjustable desks to reduce sitting time with studies often using self-reported working hours as the timeframe to assess a reduction in workplace sitting (444); however, it is likely that some time spent at work is spent outside the office and thus away from the desk. It would seem unfair to include time spent at work but outside the office when evaluating the efficacy of height adjustable desks; measuring office occupancy could therefore provide a better denominator of efficacy. Similarly, there is great interest in applying pattern recognitions to the raw signal provided by accelerometers to identify the type of activity being performed such as walking, using a hoover or stair climbing (38). Utilising context data could also aid this as, presumably, the likelihood of stair climbing or using a hoover is much higher when the individual is near a stair case or hoover.

Objectively assessing the context of physical activity and sedentary behaviour is therefore highly worthwhile. Objective assessment is able to provide detailed data on current levels and patterns of behaviour which can then be used to aid the development of more refined interventions. These objective data can also benefit complementary areas to intervention development such as Place Making (454). Despite, the worthwhileness of objectively assessing context there is a need to critically balance this with the practical difficulties of objective measurement.

6.3 Worthwhileness vs practicality

Is the added researcher burden of measuring context outweighed by the utility of the data? This is a finely balanced judgement. There are several general limitations of context measurement such as the possibility of the participant wearing multiple devices, the expense of many of the available systems and the loss of data when merging multiple data streams. These general limitations equally apply to existing measurement practices such as the combination of accelerometry and posture sensor or accelerometry and GPS; these existing practices do not appear to have been detrimentally affected by these limitations. This is, presumably, due to researchers perceiving that the value added by the combination of accelerometry and posture sensor or accelerometry and GPS outweighs these limitations. The onus is therefore to demonstrate that objectively measuring a broader suite of context in conjunction with accelerometry or a posture sensor also outweighs these limitations.

The novel measurement paradigm developed throughout this thesis is a starting point for demonstrating that objectively measuring context outweighs these limitations. Alongside the work in this thesis there are a number of theoretical indications that objectively measuring context is highly worthwhile to a large number of research areas (e.g. pattern recognition of raw accelerometry) and specific research questions (e.g. location specific correlates); however, this will ultimately need to transition from theoretical to research tested. Undertaking this transition can be greatly aided by drawing, where appropriate, parallels with the more mature area of physical activity GPS research (24). This begins with a strong theoretical underpinning. It is perhaps, on first glance, easy to dismiss assessing context as providing obvious data; for example, observing that care home residents sit in both their own rooms and in communal areas. Making an axiomatic but thought provoking observation of physical activity GPS research, Kerr (129) states "…learning that people swim in swimming pools will not advance the science". This applies equally to an indoor environment where learning that people sit in chairs will not advance the science; however, the science will be advanced by learning which chairs people sit in, for how long, how often and who is in nearby chairs.

The natural follow on question to this is "can this be measured". Currently available technology is unable to assess which chair an individual is sitting in; although, emerging technology, such as BLE stickers (marketed by some as 'nearables') may soon render this achievable (130). The work in this thesis does demonstrate that it is possible to assess these variables at a room occupancy level. This is similar to the resolution found in GPS research with GPS able to assess that an individual is in a park but not necessarily where within the park. This level of resolution does not appear to have decisively held back physical activity and GPS research and therefore seems unlikely to decisively hold back other context measurement research. Nevertheless, it is worth considering if the current resolution offered by objectively indoor location technologies (i.e. room level data) could be improved upon in the near future or if this resolution is tethered to inherent, and therefore very difficult to solve, limitations of measuring indoor location.

6.4 Technological limitations of context measurement

Although able to generate important data, the current suite of context measurement technology has several important limitations. The main limitation is that all available technology is currently best suited to "event marking" rather than "life logging"; in other words, there is not an available technology which is easy to use across multiple locations (130). Each type of location measurement technology has unique advantages or disadvantages; however, there are a number of common issues across platforms. Although it is technically possible to use the technology across multiple locations, this would pose several potential issues; particularly the need to either visit the participant in multiple locations to place beacons or rely on the participant to place beacons. In measuring outdoor location, GPS devices are able to utilise a system of orbiting satellites which provide, broadly speaking, coverage across much of the world enabling GPS devices to function as "life loggers". These satellites inhabit known locations and therefore provide reference points from which to calculate the unknown location of a GPS device (24). No comparable system is available for indoor location with the researcher required to setup the equivalent of GPS satellites in each environment under investigation.

There are two possible solutions to this problem. Solution one would involve the technology no longer requiring reference points to measure indoor location. It is difficult to see how this is achievable for RTLS or BLE based systems. Solution two would involve the reference points already being in place; for example, Ekahau RTLS utilises existing Wi-Fi infrastructure but is also unsuitable for life logging given the necessity for enterprise level Wi-Fi. Furthermore, a number of settings, such as retail venues, are installing BLE infrastructure for marketing purposes which researchers may be able to use to assess participant location in this setting; however, this would not apply across every setting (e.g.

the home setting). It is therefore difficult to see how researchers can establish or utilise a sufficient number of indoor reference points to move indoor location technology from an "event marker" to a "life logger". This suggests that, for the foreseeable future, context measurement technology is best used to answer research questions in one particular setting where the researchers can install the required reference points.

6.5 Overall strengths and weaknesses of the thesis

The following section identifies some of the limitations in the work that constitutes this thesis whilst also acknowledging some of the strengths. A major limitation of the work presented in this thesis is that the work either includes no participants (Studies One and Two) or a small sample of participants (Studies Three and Four). This lack of participants may limit the direct and conclusive behavioural implications which can be drawn from the work presented. Despite the small overall sample used in this thesis, the work presented is highly relevant as it presents a methodology and preliminary data which can be utilised to further understanding in subsequent trials with larger sample sizes such the SMArT Work study which utilises Actigraph proximity monitoring to quantify office dwell time in approximately 150 office workers (444).

A further limitation of the work presented in this thesis relates to the assessment of a limited number of components which make up the overall behavioural context. Context is defined as including the who, what, where, when and why of behaviour (18). The contents of this thesis are primarily concerned with where behaviour occurs (i.e. location) although who (Study Four), what (Feasibility Trial One of Study Three) and when (Study Four) are also investigated in specific parts of the thesis. Studies which assess multiple parts of the behavioural context may provide a better elucidation of participant behaviour; however, there are currently a limited number of technologies available which offer this possibility. Previous studies have used the images generated from wearable cameras to assess multiple components of contexts (422); however, image coding can be laborious and may therefore limit the scalability of wearable cameras in large samples (93). The technology and methodology used throughout this thesis is less laborious than image coding and may therefore be more scalable in larger samples.

Lastly, a major limitation of the work presented in this thesis relates to the acuity of the measurement tools. The Actigraph proximity system is able to assess which room a participant is in but not where they are within that room. The ability to assess where a participant is within a room would elevate this area of research significantly. For example, measuring within room location in Study Four would have allowed an identification of time spent in bed or in an armchair within the resident's rooms or time spent in the television area or the dining area within communal areas of the care homes. This level of acuity would provide greater behavioural insight. Technological developments, such as the ability to alter the range of the BLE signal, may make this possible in future.

In addition to the identified limitations, the thesis also has several key strengths. Firstly, the thesis provides a comprehensive and logical progression through the area, incorporating; an identification of available technologies (Study One), an assessment of the validity and reliability of a particularly promising technology (Study Two), a series of trials to understand the potential applications of the technology (Study Three) and, lastly, an application of the technology to understand the behaviours of older adult care home residents (Study Four). This step-by-step, comprehensive and logical flow is a key strength of the thesis.

Secondly, the technologies and methodologies developed throughout the thesis have applications to a number of settings and populations. These range from young children in day care centres or schools, to adults in workplaces through to older adults in care homes. The technologies used in the thesis, particularly the Actigraph proximity system, are currently best suited to areas in which individuals congregate as this limits the number of beacons which are required; however, given sufficient resources the system could also be used in individuals homes. Across these populations and settings, there are areas in which profiling the amount of time spent in a location would be a valuable data stream in and of itself (such as profiling where toddlers spend their time in day care centres) and areas in which profiling location would be a valuable adjunct to an existing research question (such as quantifying office dwell time in height adjustable desk interventions). The transferability of the work which constitutes the thesis is therefore another key strength.

Lastly, the culmination of the thesis in Study Four uses the work conducted throughout the thesis and applies it to the most sedentary segment of the population (10,437). The use of older adults as the population of interest ensures that the study is able to identify levers for behaviour change in the population which is most in need of behaviour change given the deleterious effects of sedentary time on health (4-8). This is another key strength of the thesis.

Future studies should therefore seek to extend this work in older adults by developing intervention strategies to decrease sedentary time.

6.6 Future directions

Several research priorities are evident to build upon the work in this thesis related to the technology used to assess context, data processing and analysis and the settings in which the technology is applied.

6.6.1 Technology related research priorities:

- Advocate and work with device manufacturers to integrate context measurement technology into existing physical activity measurement devices. Ultimately, the long term adoption of context measurement would be greatly facilitated if participants were able to only wear one device to assess multiple features of context.
- Utilise a wider cadre of technology to modify proximity technology from a system which is best used in one location which participants visit (i.e. an event marker) to one which can easily be used across multiple locations participants are likely to visit (i.e. a life logger). For example, the advent of the internet of things raises the possibility that BLE equipped household items may be able to function as a proximity beacon for the home which communicates with a participant worn receiver and, thereby, provide an indication of when the participant is in their home without the need for a dedicated beacon.

6.6.2 Data processing and analysis related research priorities

- Develop analogous data analysis programs to those previously developed for physical activity GPS research such as the physical activity location measurement system (PALMS). These programs should include features such as the merging of context and physical activity data and the ability to generate meaningful outcome variables from this merged data.
- Develop and validate analogous data processing methods to those found in accelerometry. For example, identifying valid day criteria or identifying non-wear criteria.

6.6.3 Application related research priorities

- Identify the settings in which profiling of time spent in a location would be a valuable data stream in and of itself. For example, the older adult care home setting used in this thesis
- Identify existing behavioural research questions which could be improved by objectively assessing context. For example, height adjustable desk interventions with office dwell time quantification used in this thesis.

6.7 Overall conclusion

Objectively assessing the context of physical activity and sedentary behaviour allows the profiling of current levels and patterns of behaviour. This, in turn, allows the identification of behavioural levers to increase physical activity and/or decrease sedentary time. The vast majority of the average individual's day is spent indoors, making indoor location a particularly important component of context. There are a large number of technologies available with the potential to measure the indoor location of physical activity or sedentary time. The Actigraph proximity feature is one such technology. This technology is able to provide a binary measure of proximity via the detection or non-detection of Bluetooth signal: however, the inter-unit variability of the signal prohibits distance estimation. The Actigraph proximity feature, in combination with a posture sensor, is able to elucidate the context of current physical activity and sedentary time and establish behavioural levers for favourable behaviour change. Anticipated future developments, such as the ability to tune the range of the signal, could further increase the utility, practicality and scalability of the system. The Actigraph proximity feature used in this thesis is just one device of many, each with their own advantages and disadvantages in different settings. These systems may be further developed in the coming years and complemented by the emergence of new, and potentially more refined, technologies.

7 References

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8 Appendix A – additional graphs for Study Two

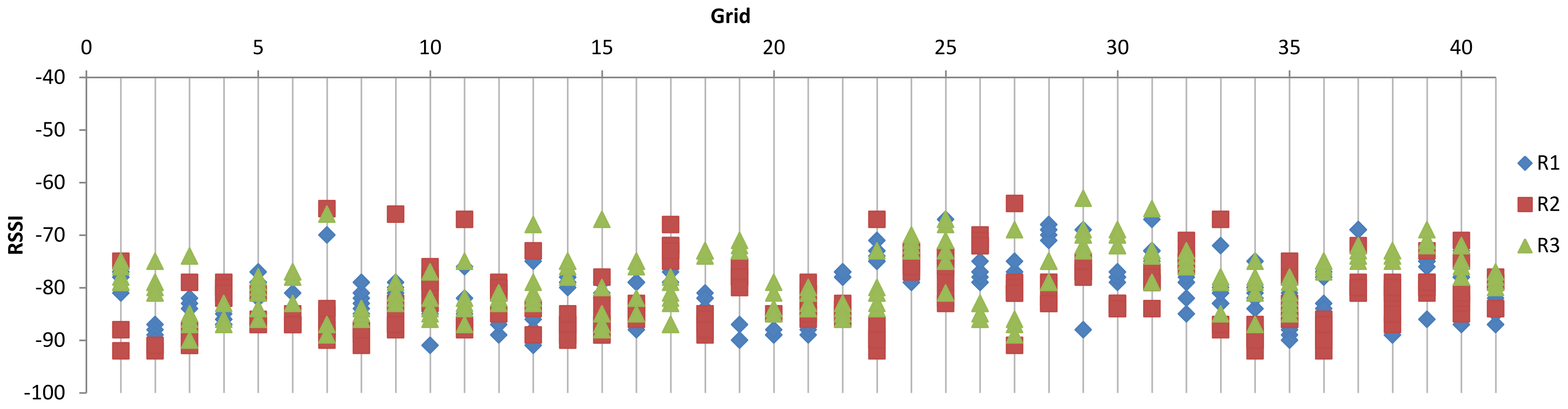

Figure 8.1 Received signal strength indicator (RSSI) for 3 receivers for beacon B1 under human obstruction conditions

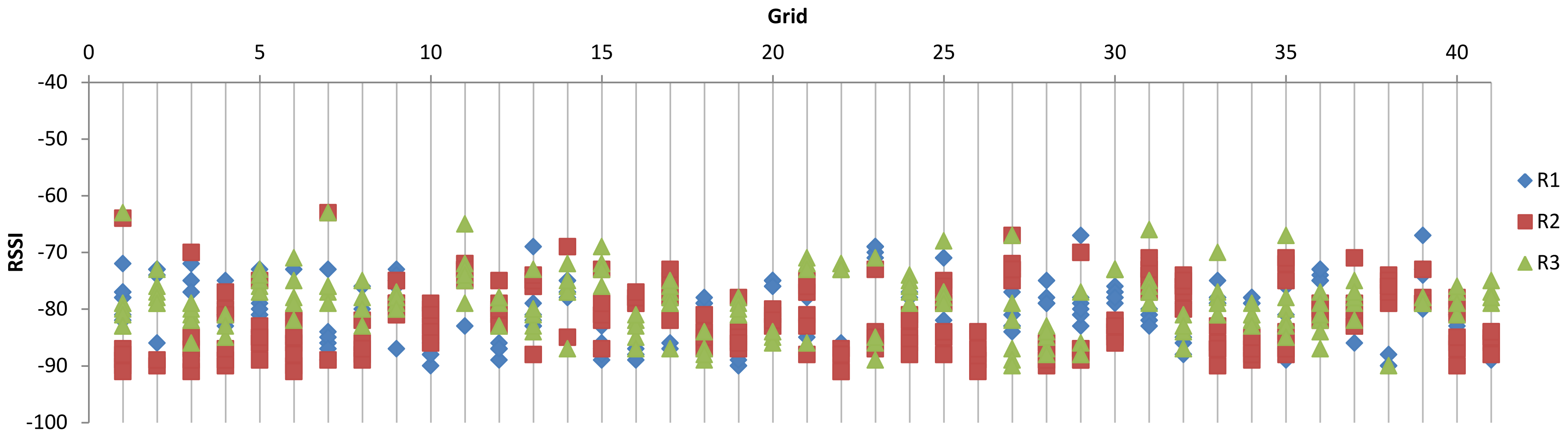

Figure 8.2 Received signal strength indicator (RSSI) for 3 receivers for beacon B2 under human obstruction conditions

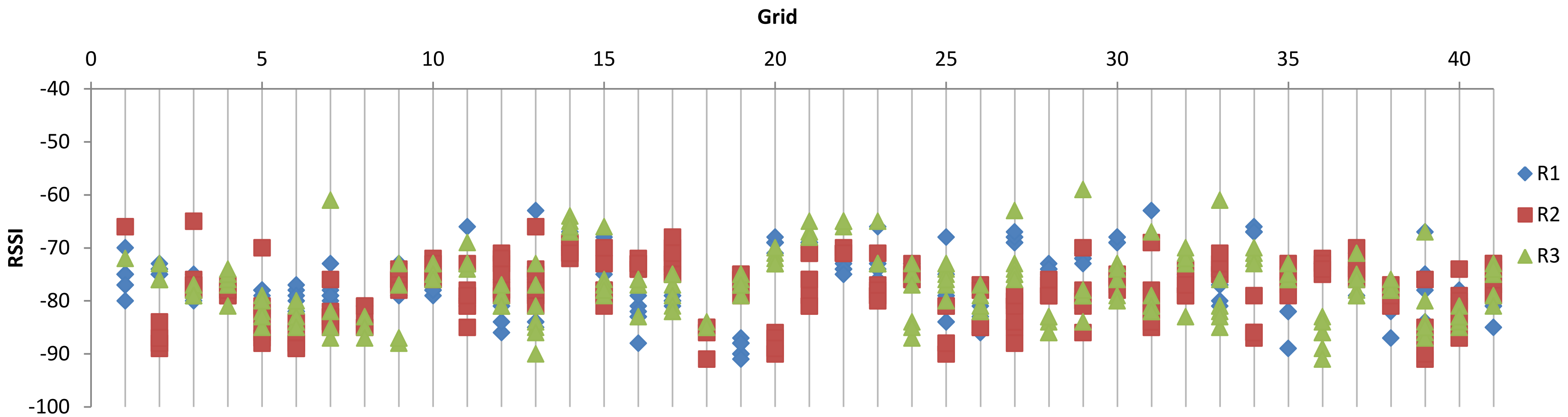

Figure 8.3 Received signal strength indicator (RSSI) for 3 receivers for beacon B3 under human obstruction conditions

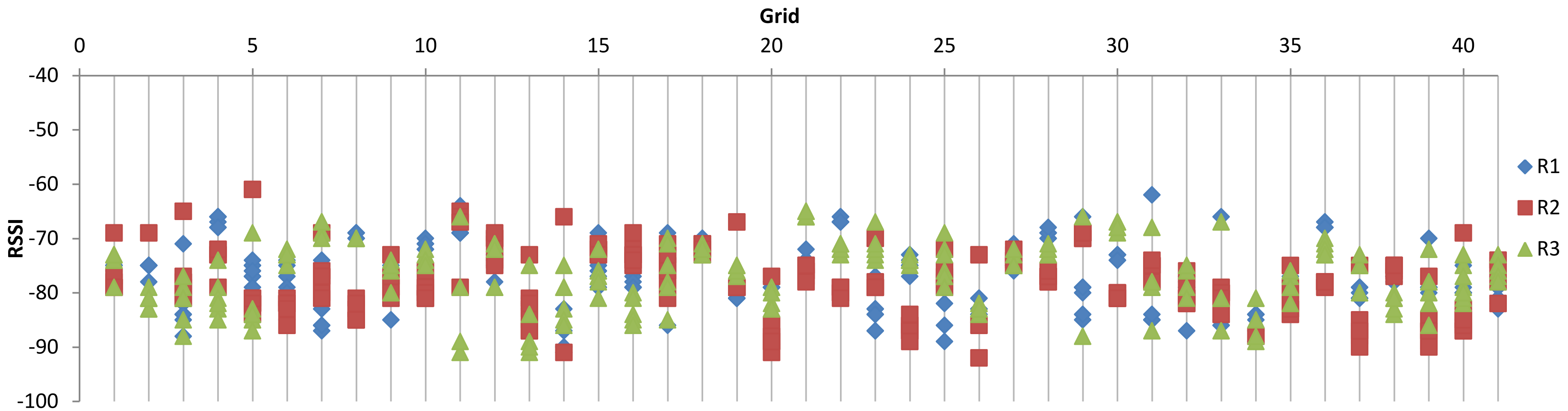

Figure 8.4 Received signal strength indicator (RSSI) for 3 receivers for beacon B5 under human obstruction conditions

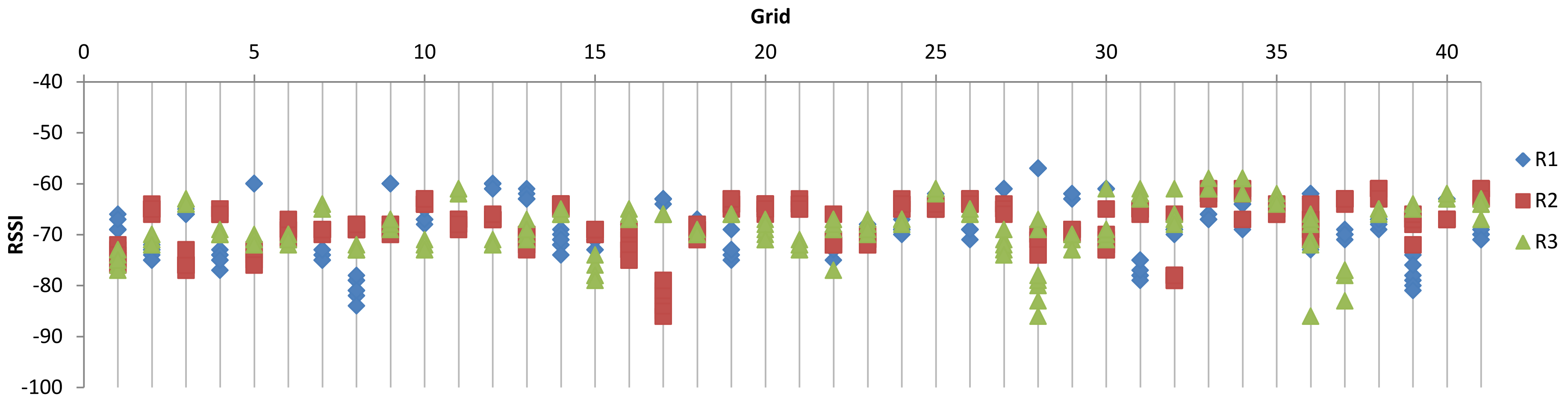

Figure 8.5 Received signal strength indicator (RSSI) for 3 receivers for beacon B1 under wood obstruction conditions

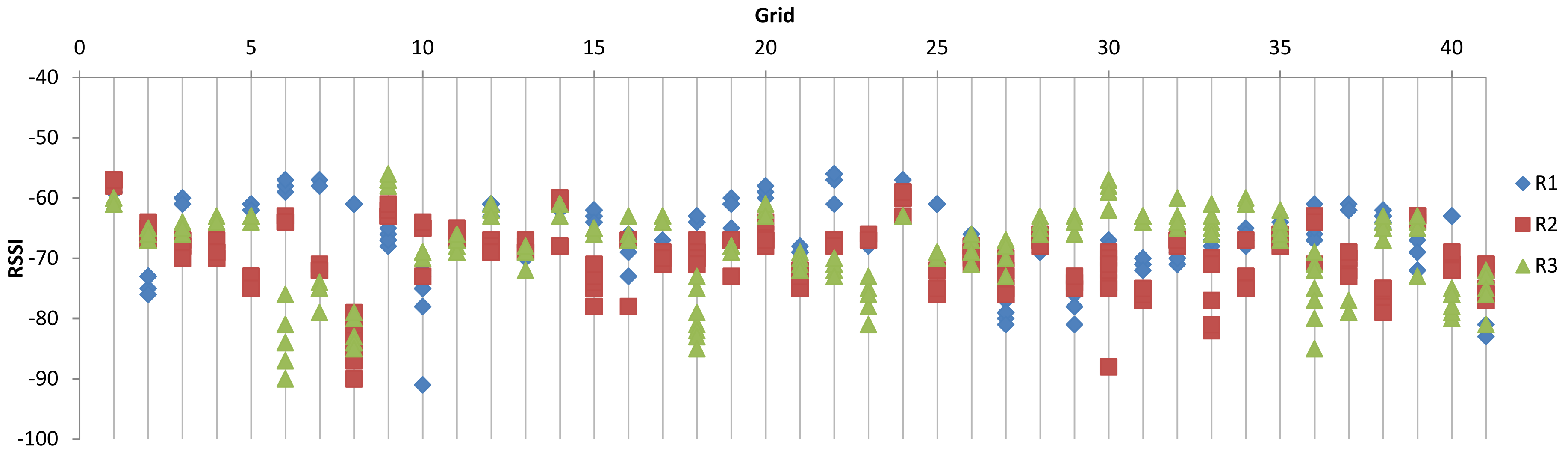

Figure 8.6 Received signal strength indicator (RSSI) for 3 receivers for beacon B2 under wood obstruction conditions

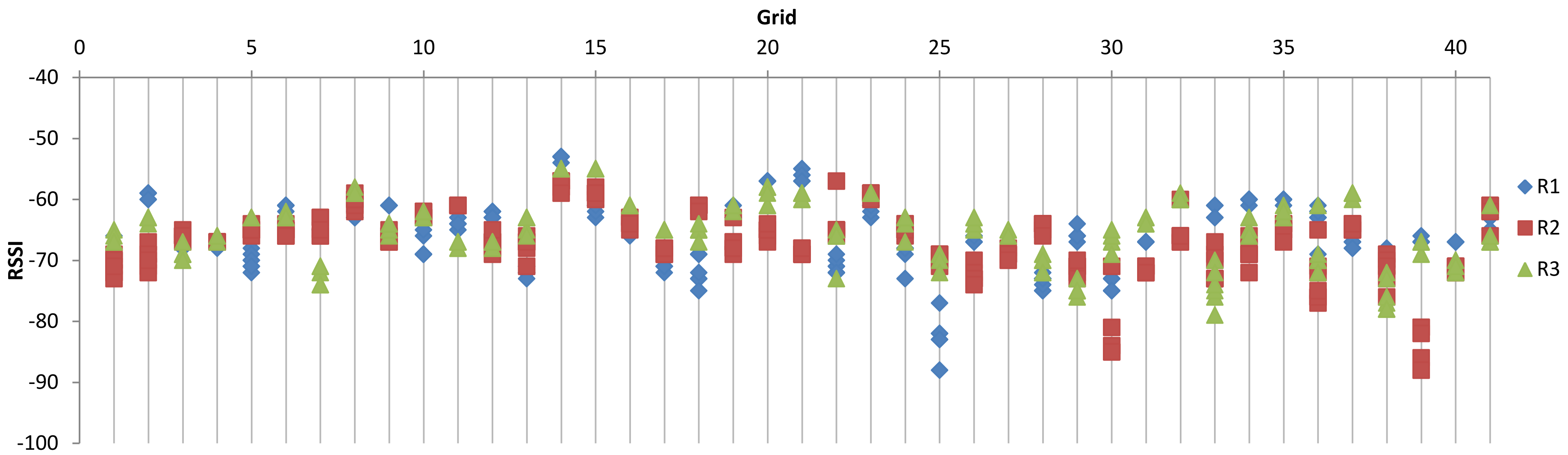

Figure 8.7 Received signal strength indicator (RSSI) for 3 receivers for beacon B3 under wood obstruction conditions

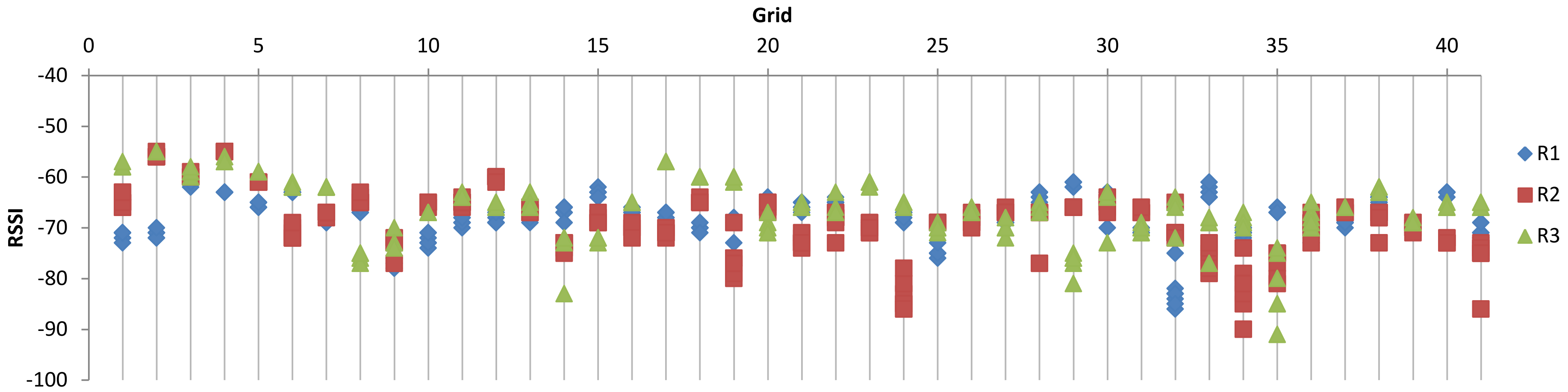

Figure 8.8 Received signal strength indicator (RSSI) for 3 receivers for beacon B5 under wood obstruction conditions

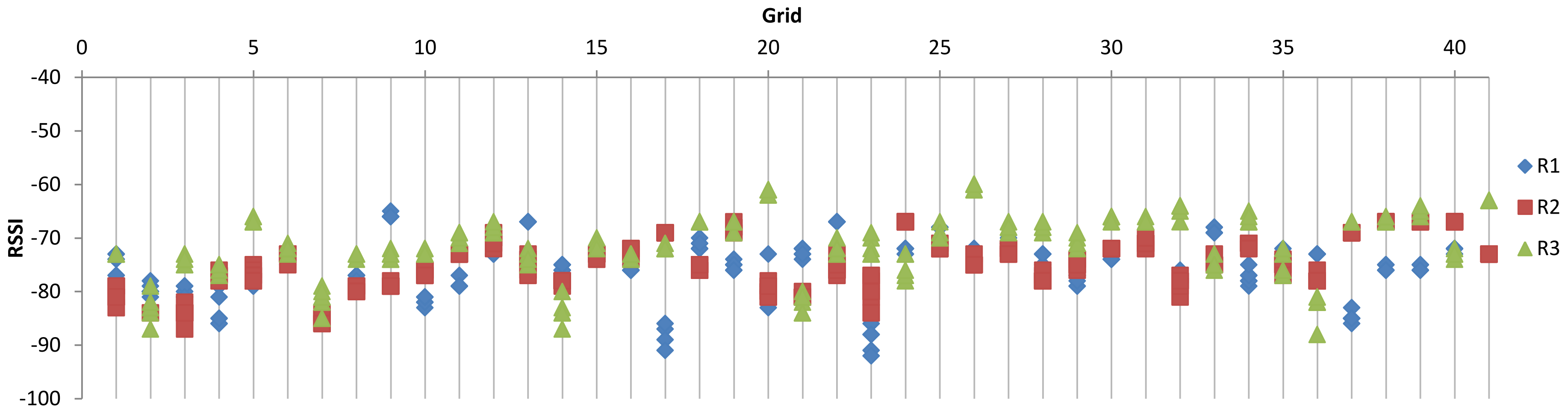

Figure 8.9 Received signal strength indicator (RSSI) for 3 receivers for beacon B1 under metal obstruction conditions

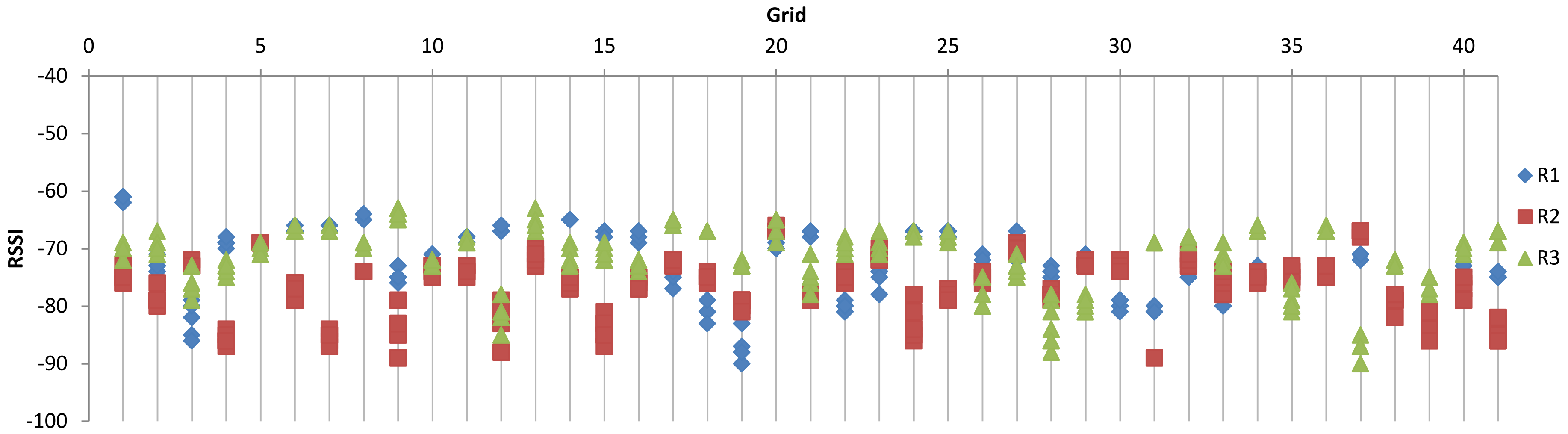

Figure 8.10 Received signal strength indicator (RSSI) for 3 receivers for beacon B2 under metal obstruction conditions

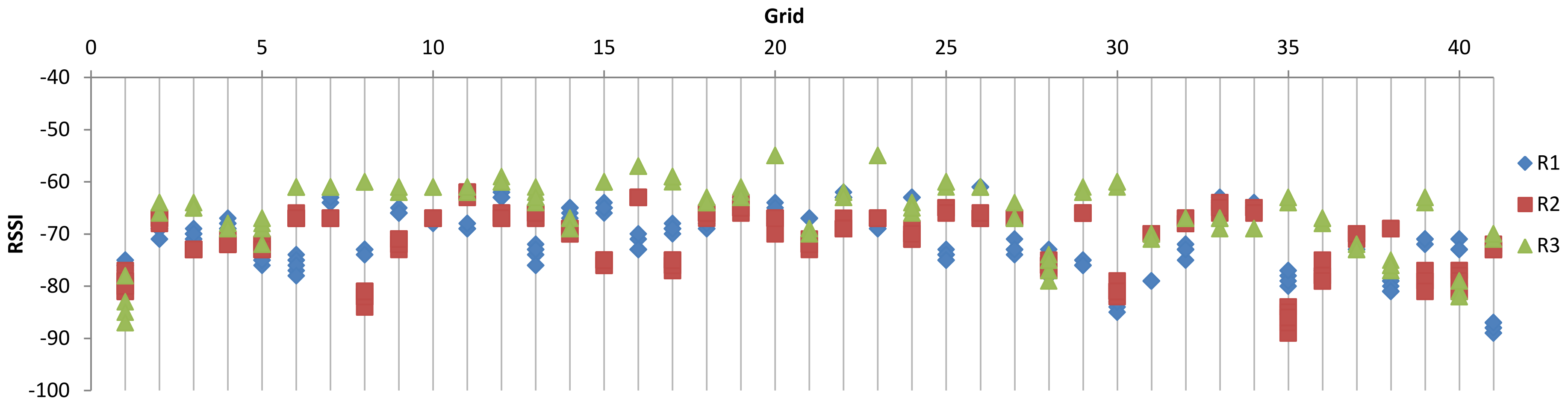

Figure 8.11 Received signal strength indicator (RSSI) for 3 receivers for beacon B3 under metal obstruction conditions

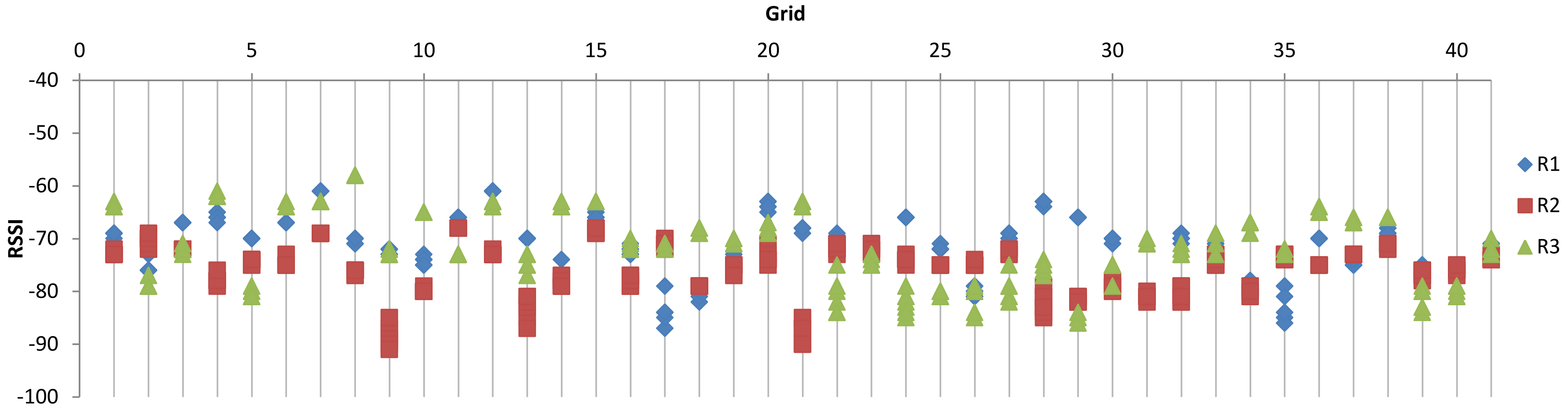

Figure 8.12 Received signal strength indicator (RSSI) for 3 receivers for beacon B5 under metal obstruction conditions

9 Appendix B – Consent form used in Study Three

Loughborough University

Contextual sedentary behaviours sensing

What is the purpose of the study?

This study is seeking to assess whether a novel array of sensors can be used to collect dense and detailed information about you activity and sitting behaviours. Details of each device and the data it collects are provided elsewhere in this pack.

Who is doing this research and why?

This research is being conducted by Adam Loveday, a PhD student at Loughborough University. This research will form part of Adam's PhD thesis. Adam is supervised by Dr Dale Esliger and Dr Lauren Sherar. The researchers are receiving no external funding for this study. This study is part of a Student research project supported by Loughborough University.

What will I be asked to do?

You will be asked to wear a number of devices for a period of 1 week. Details of each device are provided elsewhere in this pack. You will be advised on where to wear each device. You will also be given an opportunity to ask any questions you may have about the devices during your first meeting with the research team.

Once I take part, can I change my mind?

Yes! After you have read this information and asked any questions you may have we will ask you to complete an Informed Consent Form, however if at any time, before, during or after the sessions you wish to withdraw from the study please just contact the main investigator. You can withdraw at any time, for any reason and you will not be asked to explain your reasons for withdrawing.

How long will it take?

We expect the initial home visit, where the equipment will be set-up, to last around 4 hours. You will then be asked to wear the devices for 1 week.

What personal information will be required from me?

We will take some basic measurements, such as height and weight, during the initial laboratory visit. You will also be asked to provide basic demographic information such as gender and age via a questionnaire. We appreciate that your location and activity data is also personal. This data will be anonymised; you will not be identifiable from your data.

Are there any risks in participating?

We don't anticipate any risks to your participation in this study. We would like you to maintain your normal routine. The only downside to you will be a small loss of time for the initial home visit.

Will my taking part in this study be kept confidential?

All of your data will be anonymised; you will not be identifiable from your data. You will be given a participant number which will be associated with all data collected. This number will be confidential to the research team

I have some more questions; who should I contact?

Please contact Adam Loveday. Adam can be reached at A.Loveday@lboro.ac.uk

What will happen to the results of the study?

The results of this study will form part of Adams PhD thesis. The results of this study are also intended for use in conference presentations and submission to an academic journal.

What if I am not happy with how the research was conducted?

If you are not happy with how the research was conducted, please contact Mrs Zoe Stockdale, the Secretary for the University's Ethics Approvals (Human Participants) Sub-Committee:

Mrs Z Stockdale, Research Office, Rutland Building, Loughborough University, Epinal Way, Loughborough, LE11 3TU. Tel: 01509 222423. Email: Z.C.Stockdale@lboro.ac.uk

The University also has a policy relating to Research Misconduct and Whistle Blowing which is available online at http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm

What do I get for participating?

After completing the study you will be provided with detailed feedback on your activity levels. By participating in this study you will also be contributing to research and knowledge.

Physical Activity Monitor Information

What is an activity monitor?

The activity monitors are worn on the wrist and waist to record information about physical activity levels and time spent sitting. The monitors are battery powered and safe, and are comfortable to wear. Most people forget that they are wearing the monitors because of the lightweight and small design. Many studies in children, adults and among patient groups have routinely used activity monitors without any major problems.

What are you supposed to do with the activity monitor?

You will be given 5 red activity monitors; 2 of which should be worn. These will be distinguishable by their straps. You will be shown the correct device placement when you meet the research team. We ask that you please wear one activity monitor on the wrist of your **non-writing hand**. We ask that you wear the other activity monitor on your waist, just above the pointy part of your hip.

We ask that you wear both of the monitors 24 hours a day for 7 days. You will likely find that the wrist worn monitor is easier to wear overnight. If you find the waist worn monitor uncomfortable to wear overnight then you can remove it. If you remove the waist worn monitor overnight, please remove it shortly before bed and put it back on as soon as you wake up.

Both monitors will need to be removed when you are engaging in water-based activities such as showering, bathing and swimming because it is not water-proof (although it is splash- and rain-proof). When you do remove the monitors during water-based activities, we ask that you remove them before entering the water and then put them back on after exiting the water. This will ensure that we are getting as much of your activity measured as possible. The activity monitors are well built so you do not have to worry about them getting bumped or broken during your normal activity and/or work.

Global Positioning System (GPS) information

What is a GPS device?

GPS uses satellites in space to determine where you are on Earth. The GPS device needs to 'see' the satellites; because of this it only gives outdoor location. You may be familiar with some of the uses of GPS such as satellite navigation systems used in cars and smartphones.

How do I use the GPS?

The GPS device will automatically keep a record of your location. You do not need to touch the device. The device has an on/off switch; please ensure that the switch is kept to the right. The device should be placed on the dashboard of your car. If you find that this is unsuitable for your vehicle, you can use the magnetic clip to secure the device within your vehicle.

What will happen to my information?

We understand that where you have been is sensitive information. All information will be made anonymous; no one will be able to identify you from the information. All information will be securely stored and only made available to the research team. Your specific location information, such as your address, will not be used. However, along with other participants your data may be categorised more generally such as home, work or supermarket. We will also not use your specific route information. However, we may categorise your route more generally such as the distance of the route, the types of road on which your route takes you and how long the route takes.

Proximity system

What is a proximity device?

The proximity device uses low energy Bluetooth to determine when you are near to the device.

How do I use the proximity device?

The proximity device uses the two activity monitors that you are already wearing on your wrist and waist. The 3 remaining monitors are placed around your environment; 1 in your car, 1 in your office and 1 in your home. We ask that you place the 3 monitors as follows:

Car- stuck to the centre your dashboard i.e. near to the radio

Home- Stuck to the wall behind your sofa, ideally halfway up the way and half length of the sofa

Office- stuck to the top of your computer screen

The 2 activity monitors you are wearing will then automatically record when you are near to your car, sofa and office.

What will happen to my information?

We understand that where you have been is sensitive information. All information will be made anonymous; no one will be able to identify you from the information. All information will be securely stored and only made available to the research team. Your specific location information, such as your address, will not be used. However, along with other participants your data may be categorised more generally such as how much time you are near the sofa, car and desk.

Wearable Camera information

How do I wear Autographer?

You can wear Autographer by using the clip on the back of the device to clip it to a shirt pocket or on to your top. You will also be provided with a lanyard and shown how to wrap the lanyard around the device. You are free to choose which of these two ways you would like to wear the device.

How do I switch Autographer on?

Open the lens cover by rotating clockwise and then press the ‘Action’ button for 6 seconds.

Autographer will say ‘Hello’ and start capturing images immediately.

How do I start capturing images?

Autographer automatically captures images when it’s switched on and the lens cover is open. Image capture is paused when Bluetooth is enabled and whenever the menu is being used.

How do I know Autographer is capturing images?

By default Autographer is set to display a ‘blink’ on screen (a flashing blue circle) when it starts capturing an image.

How many images can Autographer store and how long does the battery last?

Autographer holds more than 27,000 images and shoots for 10 hours at a time. We therefore ask that you charge the device every night during the study. You will be sent a text message each night to prompt you to charge the device.

How do I switch Autographer off?

You can switch off the device by holding the ‘Action’ button for 6 seconds. Autographer will say ‘Goodbye’ and power off. Remember to close the lens cover to protect the lens. You can also pause image capture for up to 5 minutes by closing the lens cover. You may wish to use this option when you go to the bathroom or for any other activity that you do not want the research team to see. Please remember to open the lens cover when you are finished and check that the blue light is flashing again.

Autography Etiquette

Autography and friends

- Autographer is at its best when it’s naturally capturing your life; documenting those personal moments that are unique to you.
- Where these moments involve your friend and family networks, it’s polite to check they’re happy for you to take images of them and the event (as you would with a normal camera).

Autography in public

- Different environments have a different set of unwritten rules and in some cases laws that govern them. Always check before Autographing a new country, museum or exhibition space and – as with any camera or smartphone – ensure you only use Autographer where it’s acceptable to do so.
- Pause your image capture if you are in close proximity to people you don’t know for a long period of time – for example, if you are seated opposite someone at an event or on a packed commuter train.
- If anyone expresses concern, we recommend showing them that you have closed the camera shutter, and that the yellow lens cover means the device is no longer capturing images.

Respecting privacy

- If you capture an image of someone and they take offence, you should connect to Autographer with your smartphone and delete the image/s as soon as possible. You may want to show the person that you have done this for their peace of mind.
- If it’s not practical or possible to do this straightaway, you should ensure that you delete the images when you import them to your desktop

What will happen to my images?

Following your completion of the study, the research team will collect the device and download the stored images. You will be given the opportunity to go through the images and delete any which you do not want the research team to analyse. The images may then be used to determine a wide range of information such as whether you are alone or with someone, whether you are eating or drinking and what type of television show you are watching.

Power monitoring equipment

What is a Plogg?

A Plogg is a small device into which an appliance is plugged. The Plogg then plugs into a power socket and measures how much power the appliance is using.

How do I use the Plogg?

We ask that you place 1 Plogg on your work computer and 1 Plogg on your living room television set. When you use an appliance that is fitted with a Plogg, you do not need to do anything different. Simply turn on the socket as normal and the Plogg will measure how much power the appliance is using. You do not need to do anything to the Plogg. Using a Plogg will not affect your electricity.

What will happen to the data?

We understand that your power usage may contain sensitive information. All information will be made anonymous; no one will be able to identify you from the information. All information will be securely stored and only made available to the research team. Your specific power usage will not be used by the research team. However, along with other participants your data may be categorised more generally such as for how long the television is turned on or how much time you use a computer for.

Lumoback

How to wear the LUMOback

The LUMOback will be attached using adjustable plastic straps. The LUMOback should we worn on base of the back with the logo outward facing, and in a readable orientation.

Removal of the LumoBack.

Night Removal

When removing the LumoBack at night please take it off immediately before you go to sleep and place it on charge using the charging plug and cord provided in your pack. It is best to place this on your bed side table so as a reminder to put it on the when you wake up in the morning

It is important that you place the device on charge every night so that we can have a data stream to note removal time.

Removal for water-based activities

Please remove the device immediately before and immediately after the water based activities – making sure to place the device horizontal on a flat surface with Lumo sign facing upwards.

LumoBack FAQ's

Wearing the sensor

1. Place the LUMO on your lower back, either directly on your skin or over a thin layer of clothing. The LUMO logo and circular Touch button should be facing out.

2. Wrap the belt around your waist directly above your hip bones, and secure the Velcro near your belly button.
3. If your belt doesn't fit snuggly around your waist, take it off and adjust the Velcro straps inside the belt.

Checking the LumoBack charge.

Tap the Touch Button to view charge level:

Green - The sensor has more than one day of charge remaining.

Orange - The sensor has one day or less of charge remaining. Recharge soon

Alternatively – touch the three horizontal bars on the top left corner of the app which will display the side menu will display the battery charge next to the Lumo tab.

Charging the LumoBack

1. Plug the sensor into a USB power source using the included cable.
2. It takes about 2 hours to charge the sensor completely.
3. A complete charge will last for about 5 days of continuous use
4.

When to calibrate your sensor.

The LumoBack sensor works for everybody, but only if it is calibrated correctly. This process stores your good posture position on the sensor and determines when the sensor will vibrate, indicating bad posture.

When should you calibrate?

1. When you first setup your sensor.
2. Everytime you put the sensor back on after any period of removal.

How do I clean my Lumo? Is it water resistant?

You can simply take a damp cloth or a wipe and wipe the sensor down. Also, if needed you can remove the Velcro straps from the actual sensor moulding and you can hand wash the belt straps and line dry.

Lumo Back is not completely water resistant. While it is ok to have moisture and sweat from normal use and activities, you can NOT submerge the Lumo Back sensor in water or shower with it, etc. It has a Lithium battery and other hardware components that can be damaged if it gets wet.

Connectivity issues. What do I do?

Please try the following:

1. Turn the Bluetooth on your iOS device off and then on again through the iOS Settings icon. Go to Settings>Bluetooth>On/Off in your iOS device.

2. Kill the app: first double-click on the home screen of your iOS device, then hold down the Lumo Back icon in the tray for 3 seconds, then press the red delete button.
3. Restart the LUMOback app.
4. If this doesn't work, try turning off your iOS device completely, and then turn it back on.
5. Alternatively – try turning the LumoBack on and off again – this can be achieve by touching the button on the device for a period of 5 seconds until the red light flashes. Perform the same action again to turn it back on. A green light should flash to let you know it is turned on again.

Please make sure your battery is charged as the app works best when it is charged.

The LUMOback will still be collecting data during this time even if it isn’t connected to the app.

10 Appendix C – Consent form used in Study Three

Loughborough University

Contextual sedentary behaviour sensing

INFORMED CONSENT FORM

The purpose and details of this study have been explained to me. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethics Approvals (Human Participants) Sub-Committee.	Yes ☐	No ☐
I have read and understood the information sheet and this consent form.	Yes ☐	No ☐
I have had an opportunity to ask questions about my participation.	Yes ☐	No ☐
I understand that I am under no obligation to take part in the study.	Yes ☐	No ☐
I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.	Yes ☐	No ☐
I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.	Yes ☐	No ☐
I agree to participate in this study.	Yes ☐	No ☐

Your name ________________________________

Your signature ________________________________

Signature of investigator ________________________________

Date ________________________________

11 Appendix D – Participant information sheet used in Study Four

Sedentary behaviour in older adults: investigating a new therapeutic paradigm

Dr Paul Sanderson, P.W.Sanderson@lboro.ac.uk, School of Sport, Exercise and Health Sciences, National centre for Sport and Exercise Medicine, NIHR Leicester-Loughborough Diet, Lifestyle and Physical Activity Biomedical Research Unit

Adam Loveday, A.Loveday@lboro.ac.uk , School of Sport, Exercise and Health Sciences, National centre for Sport and Exercise Medicine, NIHR Leicester-Loughborough Diet, Lifestyle and Physical Activity Biomedical Research Unit

Dr Dale Esliger, D.Esliger@lboro.ac.uk , School of Sport, Exercise and Health Sciences, National centre for Sport and Exercise Medicine, NIHR Leicester-Loughborough Diet, Lifestyle and Physical Activity Biomedical Research Unit

What is the purpose of the study?

This study is seeking to measure how much time you spend sitting and the locations where you sit. This research will help us to better understand your indoor environment and how this can encourage more activity.

Who is doing this research and why?

This research is being conducted by Paul Sanderson, Adam Loveday and Dale Esliger. All three are researchers at Loughborough University.

What will I be asked to do?

The researchers will visit you and take a couple of measurements such as height and weight. You will then be issued with the two devices (shown below) and advised on where to wear them. You will also be given an opportunity to ask any questions you may have about the devices.
You will be asked to wear the devices for one week whilst you go about your normal life.

A monitor for when you are sitting

A monitor for how active
you are and where you are

Once I take part, can I change my mind?

Yes! After you have read this information and asked any questions you may have we will ask you to complete an Informed Consent Form, however if at any time, before, during or after the sessions you wish to withdraw from the
study please just contact the main investigator. You can withdraw at any time, for any reason and you will not be asked to explain your reasons for withdrawing. After the completion of the study, the data will be anonymised. After the data is anonymised, it may not be possible to withdraw your data as it will not be possible to determine what is your data. Your anonymised data will also be included in publications by the researchers, after this has been published it will not be possible to withdraw your data from the publication.

How long will it take?

You will then be asked to wear the devices for 1 week.

What personal information will be required from me?

We will take some basic measurements, such as height and weight and you will also be asked to provide basic demographic information such as gender and age via a questionnaire. We appreciate that your location and activity data is also personal. This data will be anonymised; you will not be identifiable from your data.

Are there any risks in participating?

We don't anticipate any risks to your participation in this study. We would like you to maintain your normal routine. The only downside to you will be 30-45 minutes of time for the initial visit.

Will my taking part in this study be kept confidential?

All of your data will be anonymised; you will not be identifiable from your data. You will be given a participant number which will be associated with all data collected. This number will be confidential to the research team. Your data will only be accessible to the research team.

I have some more questions; who should I contact?

Please contact Paul Sanderson or Adam Loveday. Paul can be reached at P.W.Sanderson@lboro.ac.uk. Adam can be reached at A.Loveday@lboro.ac.uk or 01509226452.

What will happen to the results of the study?

The results of this study are intended for use in conference presentations and submission to an academic journal. The results of this study may form part of Adams PhD Thesis. The data from the study will be destroyed six years after completion of the study.

What do I get for participating?

After completing the study you will be provided with detailed feedback on your activity levels. By participating in this
study you will also be contributing to research and knowledge.

What if I am not happy with how the research was conducted?

If you are not happy with how the research was conducted, please contact Ms Jackie Green, the Secretary for the University's Ethics Approvals (Human Participants) Sub-Committee:

Ms J Green, Research Office, Hazlerigg Building, Loughborough University, Epinal Way, Loughborough, LE11 3TU. Tel: 01509 222423. Email: J.A.Green@lboro.ac.uk

The University also has a policy relating to Research Misconduct and Whistle Blowing which is available online at http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm

12 Appendix E- consent form used in Study Four

Sedentary behaviour in older adults: investigating a new therapeutic paradigm

INFORMED CONSENT FORM

The purpose and details of this study have been explained to me. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethics Approvals (Human Participants) Sub-Committee.	Yes ☐	No ☐
I have read and understood the information sheet and this consent form.	Yes ☐	No ☐
I have had an opportunity to ask questions about my participation.	Yes ☐	No ☐
I understand that I am under no obligation to take part in the study.	Yes ☐	No ☐
I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.	Yes ☐	No ☐
I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the	Yes	No

researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.	☐	☐
I agree to participate in this study.	Yes ☐	No ☐

Your name ____________________________

Your signature ____________________________

Signature of investigator ____________________________

Date ____________________________

13 Appendix F – Participant diary used in Study Three

1. How to fill in the daily log

- The log is divided into 7 days. Please complete each day's questions as accurately as possible – record the exact times or to the nearest 5 minutes.

1. Indicate the date.
2. Record the time that you **woke up** and when you put the waist device on.
3. Indicate if you have worn the waist device or not on that night by ticking the correspondent box.
4. State if it a **work or non-work day**.
5. If it was a work day, please record the time you **started and finish working** and if you had **breaks**.
6. Record any times you **removed** any of both devices for more than 15 minutes during the day.
7. Finally, if you take off the waist monitor to sleep, please **record the time that you removed** it and tick the corresponding box the following morning.

NOTES:

- Midnight = 12am; midday = 12pm
- **Sleep and awaking times are very important**

Date: ___/___/___ Waking up time?	What time did you put the waist device on?	Is today a work or non-work day?	What time did you start working?	Did you have a lunch break?	What time did you finish working?	Did you go to sleep with the waist device on?	At what time did you go to bed?	Did you remove the thigh device?	Did you remove the waist device?
01/04/14 7:30 am/pm	7:35 am/pm	Work Non-work	8:30 am/pm	12:30am/pm 1:30 am/pm	5:00 am/pm	Yes / no	23:30 am / pm	____ am/pm ____ am/pm	20:20am/pm 20:50am/pm
Day 1 ___/___/___ ____ am/pm	____ am/pm	Work Non-work	____ am/pm	____ am/pm ____ am/pm	____ am/pm	Yes / no	____ am/pm	____ am/pm ____ am/pm	____ am/pm ____ am/pm
Day 2 ___/___/___ ____ am/pm	____ am/pm	Work Non-work	____ am/pm	____ am/pm ____ am/pm	____ am/pm	Yes / no	____ am/pm	____ am/pm ____ am/pm	____ am/pm ____ am/pm
Day 3 ___/___/___ ____ am/pm	____ am/pm	Work Non-work	____ am/pm	____ am/pm ____ am/pm	____ am/pm	Yes / no	____ am/pm	____ am/pm ____ am/pm	____ am/pm ____ am/pm