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Low cost and batteryless sensor-enabled radio frequency identification tag based approaches to identify patient bed entry and exit posture transitions

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ABSTRACT

Introduction: Falls in hospitals and residential care facilities commonly occur near the bed. The aim of this study was to investigate the accuracy of a continuously wearable, batteryless, low power and low cost monitoring device (Wearable Wireless Identification and Sensing Platform) with a single kinematic sensor capable of real-time monitoring to automatically detect bed entry and exit events.

Materials and methods: Three dimensional acceleration readings and the strength of the transmitted signal from the WISP was interpreted to identify bed exit events and sensitivity, specificity and Receiving Operator Curves (ROC) were determined.

Results: The sensor located over sternum method performed best with sensitivity and specificity values of 92.8% and 97.5% respectively for detecting bed entry and values of 90.4% and 93.80% respectively for bed exit. On the other hand, the sensor-on-mattress algorithm achieved sensitivity and specificity values of 84.2% and 97.4% respectively for bed entry and 79% and 97.4% for bed exit detection.

Conclusion: The WISP located over the sternum method is the preferred method to detect bed entry and exit. However, further work in frail older people is required to confirm the performance of this method.

1. Introduction

Falls occur commonly in residential care and hospital settings where older people are major consumers of care. In both hospitals and residential care facilities, falls commonly occur around the bed [1,2]. In one acute care study, 65.9% of falls occurred in the bedroom with 80.1% of these falls occurring around the bed [2]. We undertook an audit of falls in our hospital (unpublished data) and found that in almost 50% of cases, falls occurred in patients with documented confusion. Falls commonly occurred between 5 pm and 7 am, in the room, and when staffing levels are lower with 13% of falls related to getting in and out of bed. Bed exiting detection systems are one approach being employed clinically, and trialled in research to provide staff with warning that patients with increased risk of falls (often older patients with cognitive impairment and multiple comorbidities) are about to get up from the bed or chair without the required supervision or assistance [5–7]. An older underpowered study ($n = 70$) in a geriatric hospital ward found no reduction in falls or falls related injury with pressure sensor bed exist alarms [3]. Similarly, a more recent, larger cluster randomized control trial did not find a reduction in falls rate even though there was increased use of pressure sensor alarms [4]. A variety of sensing systems attached to the body, bed and floor exist in the market despite the lack of evidence [3,5–8] and a recent evaluation of 16 devices reported that only three pressure sensor alarm systems were acceptable for use [8]. The presence of multiple bed exit alarm devices in the market is evidence that clinicians are searching for methods to alert them to patients or residents trying to get out of bed so that they might be able to intervene with the hope of possibly preventing a fall.

Wireless Identification and Sensing Platform (WISP) devices are batteryless, low power and low cost, capable of continuous wear, contain a kinematic sensor and are suitable for real-time monitoring of static postures and posture transitions. In this paper, our aim was to investigate the accuracy of two new technological approaches using WISP devices to automatically identify posture transitions associated with bed exiting with the

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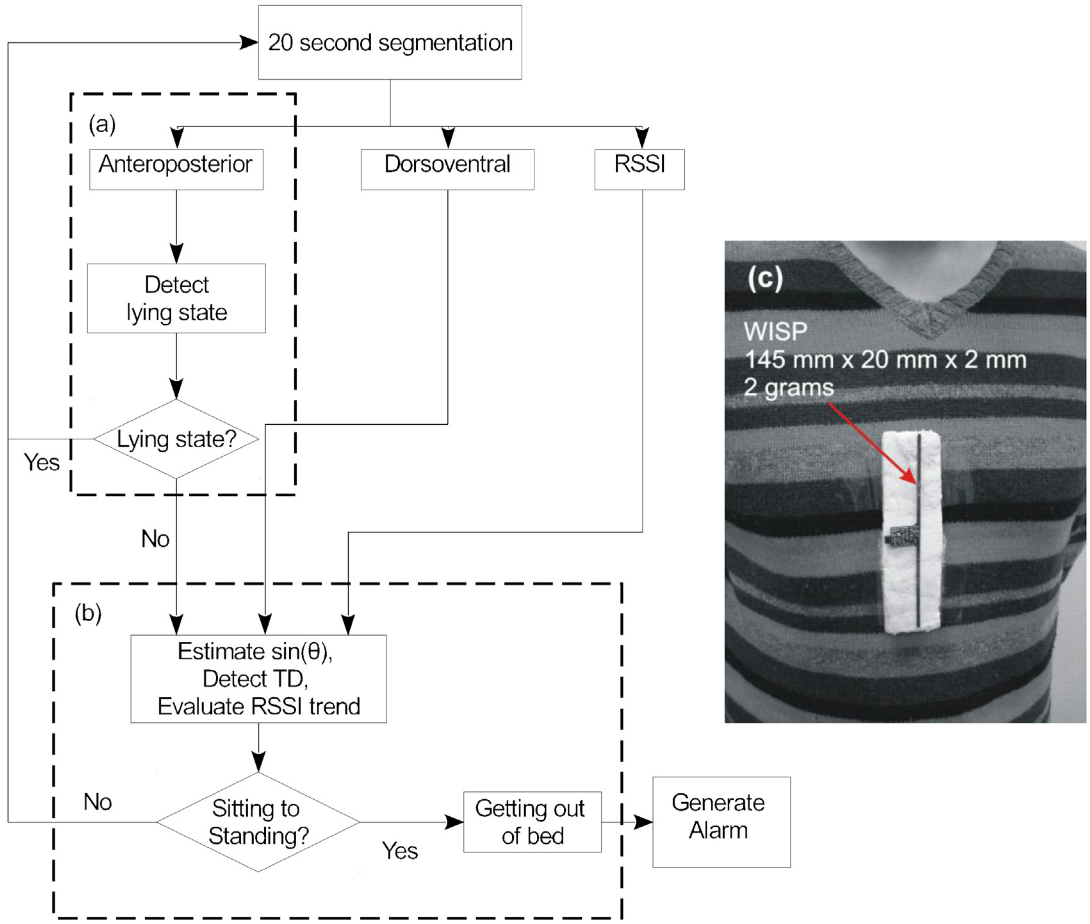

Fig. 1. Algorithm for bed exiting detection, (a) transition to a lying state: standing to lying was detected using the anteroposterior axis data. (b) Bed exit event detection: PTs of standing-to-sitting and sitting-to-standing were classified in the absence of lying and using sin(θ), RSSI and the duration of the posture transition where a bed exit event activates an alarm. (c) WISP attached over a garment on top of the sternum.

hope that this would provide caregivers with the opportunity to intervene earlier [9]. The two different technological methods evaluated are: (i) WISP located over sternum; and (ii) WISP attached to mattress on the lateral side away from the entry or exit side.

2. Materials and methods

2.1. The technology

The technological backbone of this study is the application of an acceleration sensor enabled passive (batteryless) radio-frequency identification (RFID) device, a wireless technology capable of precise and automatic identification of objects or people without requiring sight of the device [10–12]. The proposed system consists of: (i) a WISP for activity monitoring and identification [13]; (ii) RFID readers and antennas infrastructure for reading WISPs; and (iii) Patient Monitoring Software. The details of the system are available elsewhere [9,14]. Given that the WISP was positioned in different orientations for each method, the acceleration sensor axes are referred to as follows in this study: (i) *y-axis*: the mediolateral axis; (ii) *x-axis*: anteroposterior axis; and (iii) *z-axis*: dorsoventral axis. Generally, each sensor required calibration since raw values for 0 ms^{-2} and 9.8 ms^{-2} varied among accelerometers, while linearity and sensitivity was as described by the manufacturer [19].

2.2. WISP attached over sternum method

A WISP tag was located over the sternum of subjects (Fig. 1) on top of their attire employing double sided adhesive tape [14]. The acceleration data used in this approach was transformed to a gravitational scale, expressed in terms of g (1 g = 9.8 ms^{-2}) and the data was considered in 20 s (more than twice the average time for a posture transition) segments. The algorithm, shown in Fig. 1, uses acceleration readings from the three axes, denoted by x_g, y_g and z_g, which vary with the alignment of the WISP sensor with respect to gravity during postural transitions. The algorithm considers the strength of the wireless signal sent from the WISP tag and received at an RFID reader antenna referred to as the RSSI (Received Signal Strength Indicator) [16,17] to estimate the location of the subject with respect to the reader's antennas (such as near the bed or chair).

A bed exit event is defined as a sequence of two actions; a posture transition (PT) of *lying to sitting* (Fig. 1 part (a)) followed by a PT of *sitting to standing* (Fig. 1 part (b)). The reverse sequence of PTs indicates bed entry. Each of these PTs were differentiated to determine a bed exit or entry event.

2.2.1. Lying to sitting and sitting to lying

A static lying state can be discriminated from a sitting and standing state by analysing acceleration readings from the anteroposterior axis (x_g). Readings from the anteroposterior axis will be approximately 0g when lying and around 1g when standing. However to identify possible onset of a bed exit event, lying-to-sitting and sitting-to-lying PTs as described in part (a) of the algorithm presented in Fig. 1 must be identified.

PTs of lying-to-sitting and sitting-to-lying were detected based on a threshold based method first established by Najafi [15]. The lying-to-sitting and sitting-to-lying PTs can be detected using the

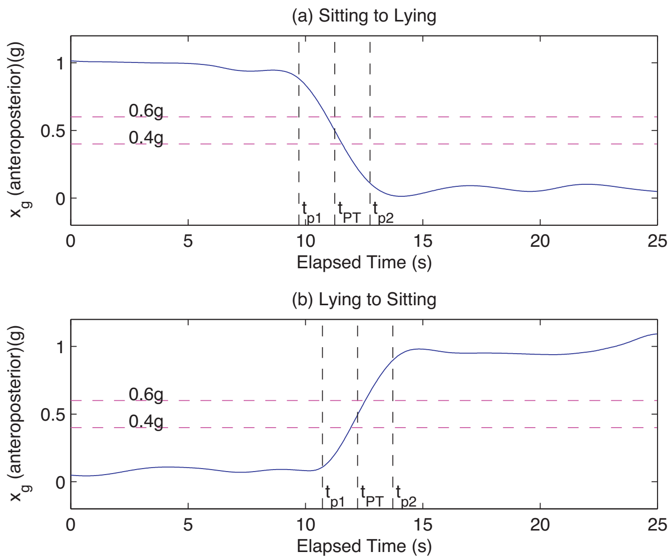

Fig. 2. (a) Detection of sitting to lying start (t_{p_1}) and ending (t_{p_2}) points from the anteroposterior axis information and (b) detection of lying to sitting process.

filtered (to remove noise) vertical acceleration (x_g) as shown in Fig. 2. The time of occurrence of a PT (t_{PT}) is the estimated time at which a posture transition occurs. PT of sitting-to-lying was confirmed if the mean of x_g between $t_{p1} = t_{PT} - 1.5$ s and t_{PT} (before) and between $t_{p2} = t_{PT} - 1.5$ s and t_{PT} (after) was higher than 0.6g and lower than 0.4g respectively. PT of lying-to-sitting transition was classified if the mean of x_g before and after t_{PT} was below 0.4 g and above 0.6 g respectively as illustrated in Fig. 2(b).

2.2.2. Sitting-to-standing and standing-to-sitting

To classify standing-to-sitting or sitting-to-standing PTs, a threshold based approach using the information from a subject's trunk displacement angle, time duration (TD) of the posture transitions and the RSSI pattern was used.

Both standing-to-sitting and sitting-to-standing transitions have two phases: an initial leaning forwards followed by a leaning backwards. The displacement of θ (angle between trunk and vertical axis) in the mid-sagittal plane for both transitions generates a maximum and then recovers. In contrast to the more accurate but more power consuming gyroscope based method in Najafi [15] we have estimated θ using (1) based only on accelerometer information because the contribution of acceleration components from the posture transition that can be assumed to be negligible compared to that of gravity [14].

$$\theta \simeq \tan^{-1}\left(\frac{z_g}{x_g}\right) \quad (1)$$

We use the pattern of $\sin(\theta)$ as a classifier [15]. The $\sin(\theta)$ values were filtered using a forward–backward third order Butterworth band pass filter (BPF) with cut-off frequencies at 0.04 Hz and 0.7 Hz to isolate the information signal associated with sitting-to-standing and standing-to-sitting transitions. From the filtered signal $\sin_F(\theta)$, t_{PT} was considered as the time corresponding to the maximum of $\sin_F(\theta)$. The $\sin_F(\theta)$ at their t_{PT} exceeding a threshold value of 0.16 were observed for sitting-to-standing and standing-to-sitting PTs. TD is measured as the time interval from the beginning, t_{p_1}, to the end, t_{p_2}, of a PT. For sitting to standing and standing to sitting transitions, TD is measured from the beginning of the leaning forwards phase at t_{p_1} to the end of the leaning backwards phase at t_{p_2}; t_{p_1} and t_{p_2} correspond to the minimum of $\sin_F(\theta)$ before and after t_{PT}. PTs of sitting to standing and standing to sitting TDs exceeded a threshold value of 1.725 s (this result confirms that reported by Najafi [15] using a gyroscope to estimate $\sin(\theta)$).

RSSI, which describes the strength of the WISP signal detected at an RFID reader antenna, was used as a method of estimating the distance of the person to the antenna and hence whether the person was standing or sitting at the end of the PT. RSSI is inversely proportional to the quadruple power of distance [16,17]; this indicates that the distance variation from the antenna due to the displacement of the body will cause an increase or decrease in RSSI depending on the location of the receiving antenna. In the test environment, antennas were located higher than 1.6 m above floor level; as a result, when standing the distance from the WISP to the antenna is shorter than that when the person is sitting. This caused an RSSI negative gradient when standing-to-sitting and a positive gradient when sitting to standing. RSSI was reported by the RFID reader for each received signal from a WISP. A sensor at any given time would have different RSSI readings on different RFID reader antennas making each antenna a reference point for location and displacement purposes.

2.3. Mattress attached WISP method

The researchers used only one WISP attached to the side of the bed opposite the side frequently used for getting in or out of bed to avoid damages to the device or occlusion from the subject's body. The signal of interest corresponds to the acceleration readings of the z-axis (z_p), perpendicular to both gravity and the side of the mattress, in percentage values (where 50% is equivalent to 0g) and its derivative z'_p. If a subject lies or sits on the mattress, the change of the alignment of the sensor as a result of the deformation of the mattress during the activity causes a change in z_p.

It is known that if a subject keeps a static posture in bed or if the mattress is empty, the derivative of z_p (z'_p) remains in a defined value range [18]. For this research, it was observed that the value range for z'_p for static posture was [−20,20]. A static state was defined as: (i) sitting on bed; (ii) lying on bed; or (iii) an empty bed. Readings from z_p obtained when the mattress was empty were observed to be 49.94% ± SD 0.11%. The mean value of z_p for empty, sitting and lying conditions were below 50%, between 50% and 50.5% and above 50.5% respectively.

A novel algorithm (Fig. 3) was developed considering the changes in z'_p and z_p to identify a significant movement in bed as a PT out of a static state or significant movement made by the subject while remaining in a static state. Detection of getting into and getting out of the bed was realized by monitoring two successive static states. A possible static state is triggered by: (i) the occurrence of an *out-of-range event* (z'_p exiting the static state value range [−20,20]); and (ii) if there was no other out-of-range event in the following 5 s. However, if the next out-of-range event duration was shorter than 5 s the first out-of-range event was discarded and the system waited for the next event. The first event was discarded because the activity was considered a significant movement made by the subject while remaining in a static state and too rapid to qualify as a posture transition. The mean value of z_p during the 5 s period was subsequently used to determine the current static state. A transition was classified as getting into bed if the next state of the patient belonged to either sitting or lying and was preceded by an empty state. Similarly, a posture transition was classified as getting out of bed if the next static state was empty and was preceded by a sitting or lying static state. In addition, the next static state was updated with the current static state for the next classification iteration. When a new static state did not match any classification, the current static state was left unaltered.

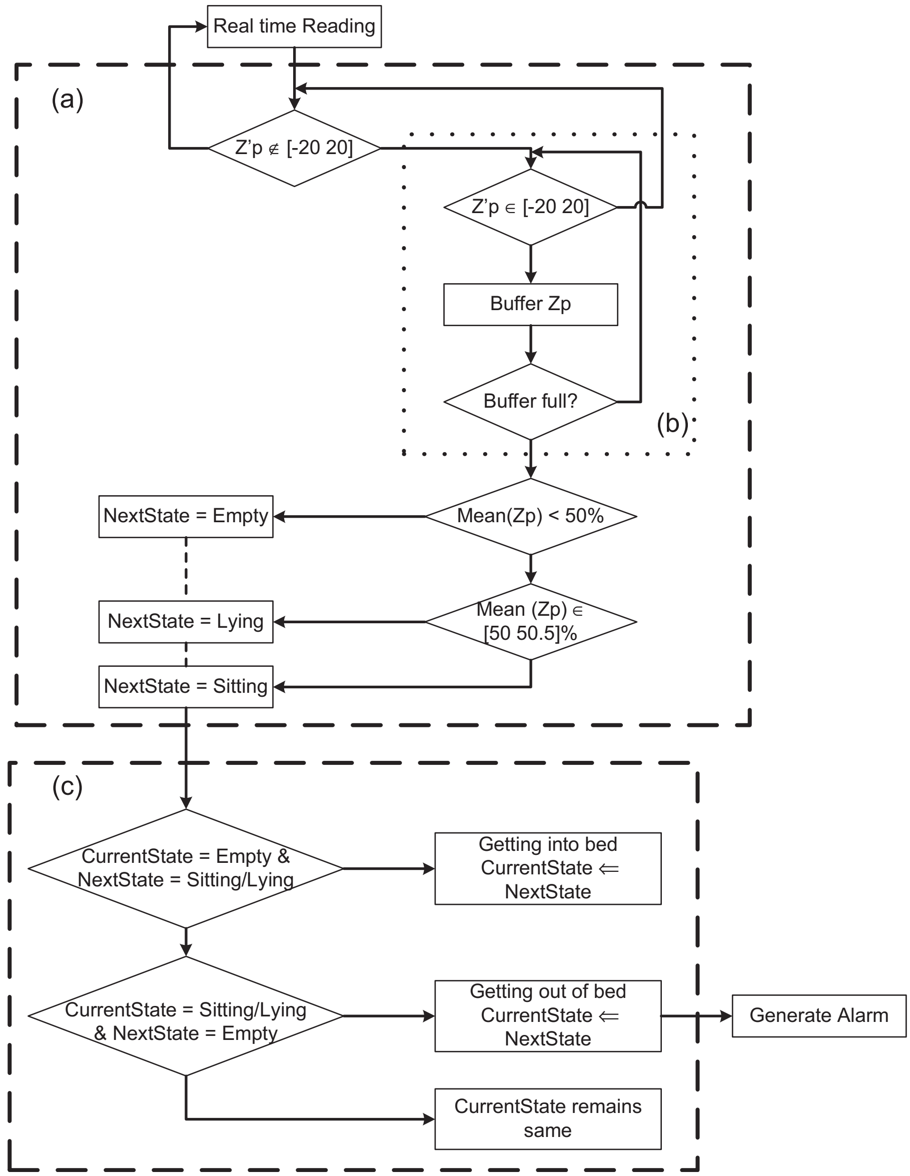

Fig. 3. Algorithm based on the mattress attached WISP tag: (a) detection of static state given the mean value of buffered acceleration data, resulting states can be empty, lying or sitting. (b) Buffer memory collecting data for 5 s, if another out-of range event occurs within the 5 s, the buffering is restarted from the new event. (c) Activity classification based on comparison of static states and update of current static state.

2.4. Sample and setting

Ten healthy adult volunteers aged between 23 and 30 (mean 26.4 [SD 2.12]) years participated in this study. The study occurred within a clinic trial room in the Basil Hetzel Institute, Woodville, South Australia.

2.5. Data collection

Each subject was given scripted routines of postural transitions that included: (i) getting into bed, lying and getting out of bed; (ii) walking (for example walking from the bed to the chair and vice versa); and (iii) sitting down on or getting up from a chair. Each subject was given three separate scripts with random orderings of these postural transitions. The algorithms were not customized to each subject. The transitions were recorded by the patient monitoring software and annotated simultaneously in the software system by a researcher during the data collection process [9]. This allowed for subsequent evaluation of the results.

2.6. Statistical analysis

True positives were the correctly identified bed exit events (in the case of WISP on sternum algorithm, both lying to sitting followed by sitting to standing was detected correctly). True negatives were events of no-interest that were correctly identified as not bed exits events (for example, getting into bed). False negatives were known bed exit events that were not identified (i.e. misses). False positives are other movements that were identified as a bed exit event. Sensitivity, given by (2), and specificity, given by (3), of identifying bed entry and exit was then estimated to compare the performance of the two methods. Receiver operating characteristic (ROC) curves were also evaluated.

$$\text{Sensitivity} = \frac{\text{true positives}}{\text{true positives} + \text{false negatives}} \times 100 \quad (2)$$

$$\text{Specificity} = \frac{\text{true negatives}}{\text{true negatives} + \text{false positives}} \times 100 \quad (3)$$

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Table 1
The performance of two technological methods in accurate classification of posture transitions (WISP located over sternum vs. WISP attached to mattress) and comparison with existing approaches.

Algorithm	Postural transition	True positives	True negatives	False positives	False negatives	Sensitivity	Specificity
WISP located over sternum	Getting into bed (stand-sit-lying)	39	40	1	3	92.8%	97.5%
	Getting out of bed (lying-sit-stand)	38	45	3	4	90.4%	93.8%
WISP attached to mattress	Getting into bed (empty-lying/sitting)	32	37	1	6	84.2%	97.4%
	Getting out of bed (lying/sitting-empty)	30	37	1	8	79%	97.4%

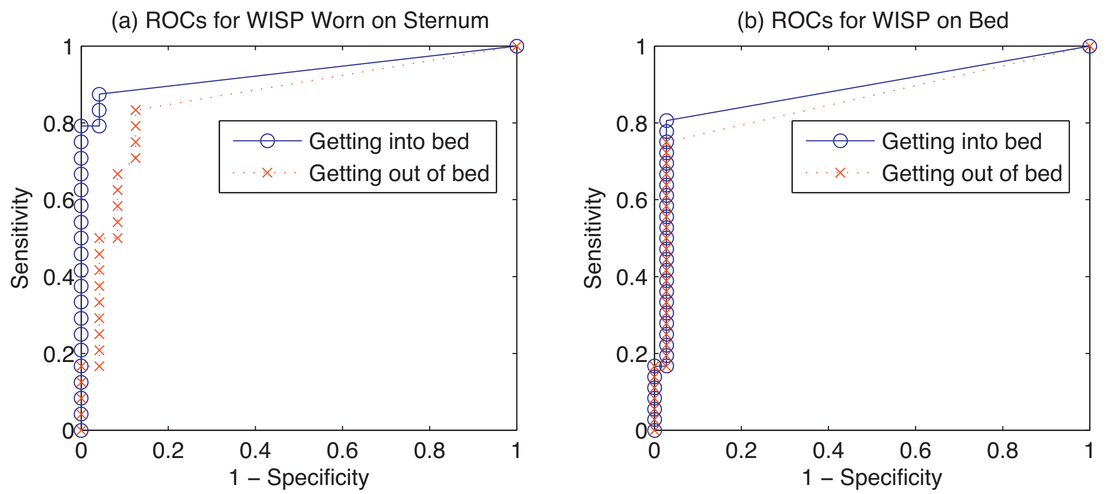

Fig. 4. ROC curves corresponding to position transitions: (a) ROC curve for the sensor located over sternum method, (b) ROC curve for the case of the sensor attached to mattress method.

3. Results

Subjects performed over 180 PTs including standing-to-sitting, sitting-to-lying, lying-to-sitting and sitting-to-standing for the WISP attached a body trunk algorithm and 100 PTs for the algorithm based on the WISP sensor attached to mattress including, sitting, standing (implying bed empty) and lying. The results (Table 1) suggest that the WISP over the sternum method demonstrated higher sensitivity in detecting entry into and exit out of bed when compared to the WISP on mattress method. Whilst both methods recorded similar specificity in terms of detecting entry into bed, the WISP on mattress method had marginally better (97.4% vs. 93.8%) specificity in terms of identification of bed exit events.

Both methods have most of their data scattered close to the left side of their graphs indicating low False Positives (i.e. false alarms) (Fig. 4). We calculated the areas under the ROC curves (AUC) by trapezoidal integration of the data. The body worn WISP AUCs were 0.931 and 0.859 for getting in and out of bed respectively and the sensor on bed algorithm had AUCs of 0.882 and 0.855 respectively. The WISP over sternum method demonstrated a better response as its curves depicted closer alignment to optimal performance (top left corner) and larger AUC for both getting in and out of bed compared to the WISP on mattress method.

4. Discussion

The main finding of this study was that a single WISP placed over the sternum accurately identified movement into and out of bed. The small, battery free and low cost nature of WISPs are an advantage, especially in settings where there is significant risk of infection such as hospitals where the device offers both disposability and user-friendliness. The WISP located over the sternum method performed better with few false negatives and positives with bed exits. These low error rates are likely to be associated with higher levels of nurse acceptance of the system.

Recently, several bed-exit alarm systems to prevent falls have been developed [6,7]. Hilbe et al. achieved high sensitivity and specificity values of approximately 95% but the system was dependent on the amount of force applied by subjects on a pressure sensor located on a bed rail. The system was wired, integrated onto beds, and required maintenance such as checking for correct functionality, cleaning and disinfection. Furthermore, bed rails are not recommended as it can result in falls from a higher height [3,21]. Bruyneel et al. used multiple sensors [6] (presence in bed, movements in bed, temperature) to reduce false alarms associated with pressure mat based systems [7] and achieved sensitivity and specificity of 91% and 100% respectively [6]. Albeit the reduction in false alarms, there was increased cost from the use of multiple sensors, exposure to fluids from incontinent patients, demands on servicing and cleaning, correct placement and delayed signal of absence (over 2 min in contrast to a maximum of 20 s for the WISP over sternum method).

WISPs themselves do not radiate but reflects energy received back to the reader. The radiated power from RFID reader antennas is reported to be well below the level for human safety published by the International Commission on Non-Iodizing Radiation Protection (ICNIRP) guidelines [20].

However, WISPs have limitations. Wireless transmissions can be blocked in certain positions. For example, readings are absent when subjects lie prone on their stomach with the WISP over sternum method. It will need to be determined if this is clinically important and should be overcome. Because the WISP harvests its own power from radiofrequency signals, it can only work within a range of 3–4 m of an antenna without intervening RF-opaque materials and therefore, multiple antennas and readers are likely to be required to provide adequate coverage within a clinical or care area.

Loosely fitted hospital garments may not allow the sensor to closely follow body movements affecting the effectiveness of body worn WISP algorithms to detect bed exit posture transitions. However, since the algorithms are based on thresholds and patients are automatically and uniquely identified by their electronic ID within a WISP it will be possible for staff to adjust the threshold levels for each patient. Nevertheless the tolerance of the algorithm to inadvertent sensor repositioning and loosely fitted clothing still needs to be investigated. Finally, evaluation was undertaken in healthy adult subjects but frail older patients may not get out of or into bed as quickly or in the same way as younger people. Other types of bed exits (such as shuffling down to the foot of the bed to exit, or exiting over bedrails), and those involving use of support (e.g. walking aids or holding on to a chair or table) also warrant investigation to ensure the system identifies less conventional bed exit methods.

To summarize, the researchers have progressed two technological methods involving WISPs to accurately detect entry and exit out of bed, a postural transition often associated with falls in hospitals and aged care settings. It was demonstrated that the WISP over sternum method was superior and further investigations in frail people are required.

Acknowledgements

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Conflict of interest

There are no conflicts of interest to declare.

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