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REVIEW ARTICLE

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A systematic review of movement monitoring devices to aid the prediction of pressure ulcers in at-risk adults

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Abstract

The present study sought to explore the impact of movement monitoring devices on risk prediction and prevention of pressure ulcers (PU) among adults. Using systematic review methodology, we included original research studies using a prospective design, written in English, assessing adult patients' movement in bed, using a movement monitoring device. The search was conducted in March 2021, using PubMed, CINAHL, Scopus, Cochrane, and EMBASE databases, and returned 1537 records, of which 25 met the inclusion criteria. Data were extracted using a pre-designed extraction tool and quality appraisal was undertaken using the evidence-based librarianship (EBL). In total, 19 different movement monitoring devices were used in the studies, using a range of physical sensing principles. The studies focused on quantifying the number and types of movements. In four studies the authors compared the monitoring system with PU risk assessment tools, with a variety of high and low correlations observed. Four studies compared the relationship between movement magnitude and frequency and the development of PUs, with variability in results also identified. Two of these studies showed, as expected, that those who made less movements developed more PU; however, the two studies also unexpectedly found that PUs occurred in both low movers and high movers. In the final two studies, the authors focused on the concordance with recommended repositioning based on the results of the monitoring device. Overall, concordance with repositioning increased with the use of a monitoring device. The synthesis of the literature surrounding bed monitoring technologies for PU risk prediction showed that a range of physical sensors can be used to detect the frequency of movement. Clinical studies showed some correlation between parameters of movement and PU risk/incidence, although the heterogeneity of approaches limits generalisable recommendations.

KEYWORDS

mobility, movement, pressure ulcer, prevention, risk assessment

Key Messages

- in the context of pressure ulcers (PUs), mobility may be defined as the physical ability to make postural changes embodying both the concept of frequency and magnitude of the movement or postural adjustments such as moving an arm or leg
- the synthesis of the literature surrounding bed monitoring technologies for PU risk prediction showed that a range of physical sensors can be used to detect the frequency of movement
- research is needed, which clearly explores the relationship between objective assessment of patient movement and PU development, in terms of the frequency, magnitude, and protective nature of the movement

1 | INTRODUCTION

A pressure ulcer (PU) is a localised injury to the skin and/or underlying tissue usually over a bony prominence, as a result of pressure, or pressure in combination with shear.[1] Around the world, PU prevalence in health care settings ranges from 0% to 72.5%, with large variations observed between different countries and clinical settings.[1] Individuals who develop PUs often present with compromised mobility and a reduced tissue tolerance.[2]

In the context of PUs, mobility may be defined as the physical ability to make postural changes embodying both the concept of frequency and magnitude of the movement or postural adjustment such as moving an arm or leg.[3] In terms of mobility, the key thing to remember is that it does not always mean pressure relief. Mobility is commonly assessed using a subjective approach, as identified in the Moore, Cowman[2] RCT, and the Coleman, Gorecki[4] systematic review. However, subjective interpretation may differ between health care workers and is limited in its accuracy.[5] Immobility/impaired mobility is accepted as a primary causal factor. Immobility/impaired mobility might be considered that patients who are unable to independently change position are at increased risk of developing a PU, because of pressure exerted over bony prominences, which results in reduced blood flow to the tissues and subsequent hypoxia.[3,4] Where research has evaluated activity as a risk factor for PU development, mobility is often included as a secondary outcome in epidemiological studies. Furthermore, analysis of mobility status is often undertaken using subscales of structured tools relying on perceived levels of mobility, such as the Braden scale,[6] the Waterlow scale,[7] the Norton scale,[8] and the activity of daily living scale.[9] Nonetheless, from the epidemiological studies, mobility has been found to be independently predictive of PUs development.[4]

In recent decades there has been a growing body of literature that has objectively quantified mobility using a range of devices that estimate either the frequency or the magnitude of movement. Researchers have examined the relationship between movement and PU occurrence, generally during periods of sleep.[10]

Systems to monitor patient mobility can be categorised into three distinct technologies,[11,12]

1. Wearable sensors incorporating accelerometers and gyroscopes—often considered to represent the GOLD standard for mobility monitoring.
2. Load cell systems incorporated into the frame of the bed or chair, to measure perturbations in load while individuals are lying or sitting, respectively.
3. Pressure sensing arrays at the interface between the body and the support surface adapted to monitor over prolonged periods.

Each of these technologies has its advantages and disadvantages. As an example, by connecting a load sensor to a bed, the forces measured at the bed frame are assumed to be indirectly related to the movement of the patient in the bed.[10] However, it is likely that other interactions with the bed, for example, carer or health care worker leaning on the surface could create false positive movement detection. In a review, Schofield, Porter-Armstrong[13] evaluated 27 studies examining the effectiveness of pressure-relieving movements in sitting postures, where sensing arrays were predominately situated at the person-seat interface. These were in the format of mats, cushions, or surfaces with accelerometers, pressure mapping systems, or force platforms to measure sitting movements (frequency and/or magnitude). The authors concluded that none of the studies were able to accurately detect postural adjustments in sitting, adjacent to vulnerable sites such as the ischial tuberosities.

With the expanding sophistication and availability of computing and sensing technologies, new opportunities to assist a person's limited mobility in self-managed care are emerging. In particular, integrating monitoring, support,

and feedback technologies are recommended to promote situational awareness, adherence, and access to professional resources.[14] Indeed, to date, there has been no comprehensive review of the studies evaluating the monitoring technologies for posture and mobility detection in lying postures. There is also an unmet need to understand the role of these devices to support the identification of those individuals at particular risk of PUs and how this information could be used to aid clinical decision-making and inform personalised interventions.

2 | AIM

The aim of this systematic review was to explore whether movement monitoring devices can be used for the prediction of PU risk among adults, and how these technologies could be used to support PU prevention interventions in different healthcare settings.

3 | METHODS

3.1 | Criteria for considering studies for this review

This systematic review included original research studies using a prospective design, and human studies only, written in English, which assessed adult patients' movement in bed using a monitoring device. We excluded studies that focused on the seated population and studies that assessed movement using a traditional PU risk assessment scale. We also excluded retrospective studies, conference papers, opinion papers, and those using qualitative methodology alone. There were no study date or setting restrictions applied.

3.2 | Outcomes

The primary outcome of interest was the ability of the device to predict PU risk through an assessment of the movement status of the individual and the relationship between the movement and PU development. The secondary outcome of interest was patient comfort and health care staff perceptions and preventive interventions based on using monitoring devices results.

3.3 | Electronic searches

The following electronic databases were searched to identify relevant literature:

- Cochrane Central Register of Controlled Trials (CENTRAL) (The Cochrane Library) (latest issue);
- Ovid MEDLINE (1946 to April 2021);
- Ovid MEDLINE (In-Process & Other Non-Indexed Citations) (latest issue);
- Ovid EMBASE (1974 to April 2021);
- EBSCO CINAHL Plus (1937 to search April 2021);
- PubMed;
- Scopus.

To identify further published, unpublished, and ongoing studies, this systematic review:

- scanned reference lists of all identified studies and reviews;
- searched grey literature using OpenGrey (www.opengrey.eu);
- searched conference proceedings, research reports, and dissertations.

The keywords used in the search included:

#1 Pressure Ulcer OR Ulcer, Pressure OR Ulcers, Pressure
#2 Bedsore OR Bedsores OR Bed Sores OR Bed Sore OR Sore, Bed OR Sores, Bed
#3 Pressure Sore OR Pressure Sores
#4 Decubitus Ulcer OR Decubitus Ulcers OR Ulcer, Decubitus OR Ulcers, Decubitus
#5 Pressure Injury OR Pressure Injuries
6: #1 OR #2 OR #3 OR#4 OR #5
#7 Movement OR Mobility OR Sleeping OR Turning
8: #6 AND #7
#9 Assessment OR Evaluation
#10 #8 AND #9

3.4 | Study selection

The article titles were assessed by two authors independently, and their abstracts (when available) were screened for their eligibility, according to the criteria for considering studies for this review. The full-text version of potentially relevant studies was obtained, and two authors independently screened these against the inclusion criteria. Where discrepancies were identified, a consensus between the two authors was reached through discussion.

3.5 | Data extraction

Data from the retrieved articles were extracted and inserted into a data extraction table using the following

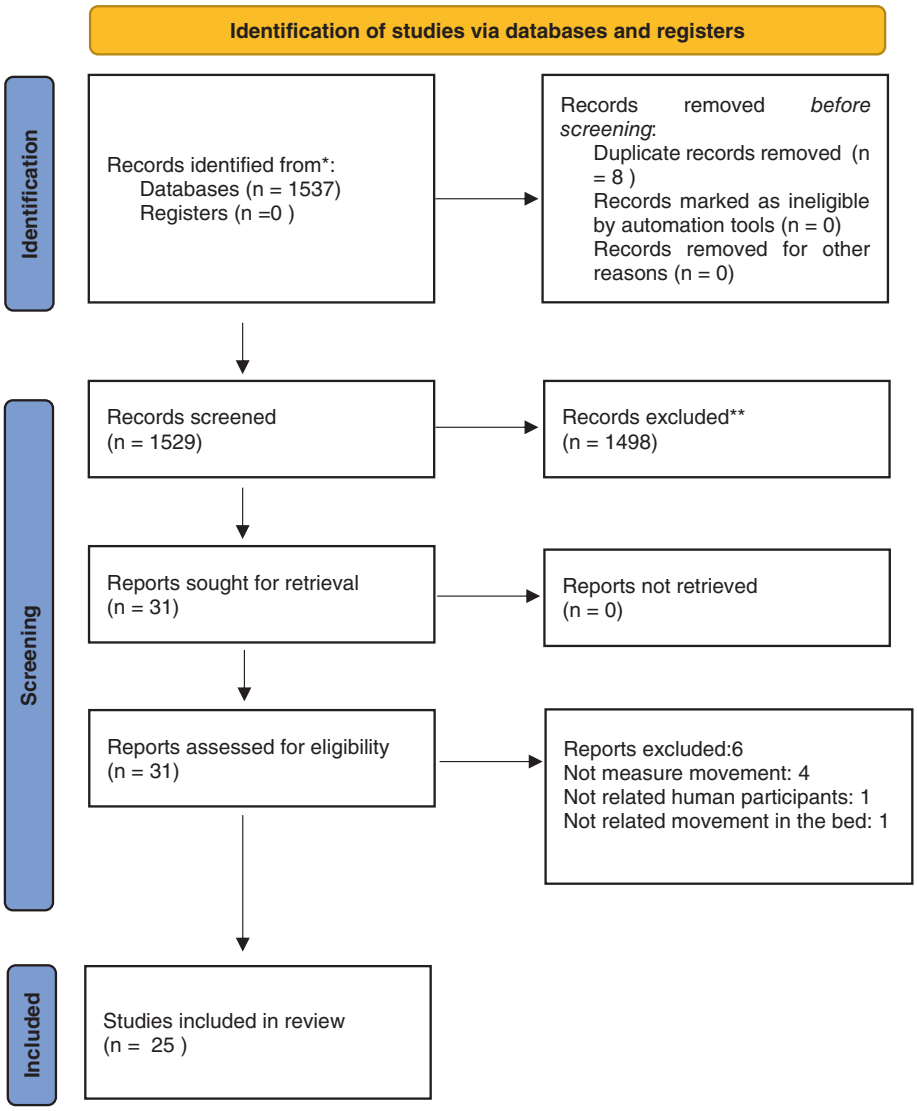

FIGURE 1 PRISMA 2020 flow diagram for study selection[16]. *Consider, if feasible to do so, reporting the number ofrecords identified from each database or register searched (rather than thetotal number across all databases/registers). **If automation tools were used, indicate how many recordswere excluded by a human and how many were excluded by automation tools

headings author, date of the study, setting and sample, monitoring device, and results.

3.6 | Data analysis and quality appraisal

Any meta-analysis was considered inappropriate because of the variation in study design and heterogeneity in the sample populations. Accordingly, the data were narratively summarised, giving an overview of geographical location, study settings, sample sizes, monitoring devices, and results. This was followed by a quality appraisal and a structured narrative synthesis of each of the included studies based on the outcome measures. Each was then quality appraised using the (evidence-based librarianship [EBL]) checklist.[15] This quality appraisal tool assesses the validity, applicability, and appropriateness of each study, based on four main steps of the research process: population; data collection; study design; results. According to this checklist, if the overall validity of the study (Yes/Total) is ≥75% or ([No + Unclear]/Total) is ≤25%, then the study is considered valid.[15]

4 | RESULTS

4.1 | Overview of all included studies

Figure 1 depicts a PRISMA flow diagram of the results following the search and the subsequent removal of studies prior to synthesis. As can be seen, following reviews of a total of 1537 hits, 1507 were excluded. Following the extraction of the full texts, six of the remaining articles were rejected for the following reasons: did not measure movement; not related to movement in bed; and non-eligible participants (animal not human studies; see Table 1).

TABLE 1 Excluded studies

Excluded studies with reasons for exclusion		
Author	**Study**	**Reason for exclusion**
Allen, Becker[17]	Ropinirole decreases periodic leg movements and improves sleep parameters in patients with restless legs syndrome	Relates to EEG measurement
Guillodo, Lemey[18]	Clinical applications of mobile health wearable-based sleep monitoring: Systematic review	Relates to sleep, not movement
Mang, Nicod[19]	Evaluation of a piezoelectric system as an alternative to electroencephalogram/ electromyogram recordings in mouse sleep studies	Relates to an animal study
Meffre, Gehin[20]	New methodology for preventing pressure ulcers using actimetry and autonomous nervous system recording	Relates to seating rather than bed movement
Muzet, Werner[21]	Assessing sleep architecture and continuity measures through the analysis of heart rate and wrist movement recordings in healthy subjects: comparison with results based on polysomnography	Relates to sleep, not movement
Tanaka, Takahashi[22]	The mechanism of persistent undermining of a sacral pressure ulcer: Experimental analyses using a deformable model and examination of skin mobility over different anatomical locations	Explores the undermining of a wound

Abbreviation: EEG, electroencephalography.

Finally, 25 articles were deemed to meet the inclusion criteria.[3,23-45] An overview of these 25 papers derived from the years 1961 to 2021 is provided in Table 2.

4.2 | Characteristics of Studies

4.2.1 | Geographical setting

A substantial proportion of the studies (42%, N = 10) were conducted in the United States,[23,24,30,34,35,37-39,41,44] followed by the United Kingdom (30%, N = 7)[25,26,28,31,36,40,43] and two studies were undertaken in Ireland.[3,45] The remaining studies (N = 6) were conducted in Thailand,[27] Sweden,[33] Israel,[42] Singapore,[32] Taiwan,[29] and India.[46]

4.2.2 | Study settings

The study settings varied and included hospitals,[25-27,29,31-33,35-37,40,42,43,46] nursing homes,[3,23,30,38,39,45] and laboratories.[24,28,34,41,44] It is evident from Table 2 that hospitals represented the most common study setting, and of these (52%, N = 12), 25% (N = 3) were conducted in a geriatric unit.[26,31,36]

4.2.3 | Participants and sample size

Most studies (70%, N = 16) included patients,[23,25-27,29-33,35-40,42,46] while other studies involved healthy participants alone[28,34,41,44] and both patients and healthy participants.[3,43]

The mean sample size was 144 (SD = ±397), ranging from 2[38] to 1812.[47] A mean sample size of 11 (SD = ±5.92) was found in healthy participants' studies, varying between 1[41] and 22.[3] A total of 47% (N = 11) of studies included older adults.[3,23,24,26,30,31,33,36,38-40]

4.2.4 | Study design

The design of the studies varied between observational studies,[3,23,25-27,31,36,45] laboratory studies,[24,28,34,41,44] descriptive studies,[30,43] cross-sectional studies,[29,39] experimental studies,[32,33] prospective clinical studies,[35,46] a randomised controlled trial,[37] a case study,[38] a review,[40] and a non-interventional study[42] (Table 2).

4.2.5 | Monitoring devices used in the included studies

A full description of the monitoring devices is provided in Table 3. In total 19 different monitoring devices were used in the studies. Some (32%, N = 8) of the studies reported the frequency of movements.[3,23,30,31,39,42,43,45] Of

TABLE 2 Characteristics of studies

Author	Country	Setting	Sample size and study group	Study design
Alessi, Schnelle[23]	United States	Nursing home	176 Nursing home residents	Observational
Barbenel, Ferguson-Pell[25]	United Kingdom	Hospital	40 Patients classified as being "at risk" if they had a low Norton score, that is, a score of <13	Observational
Barbenel, Ferguson-Pell[26]	United Kingdom	Elderly hospital	40 Elderly patients	Observational
Bhidayasiri, Sringean[27]	Thailand	One referral hospital	17 Parkinson's disease patients	Observational
Caggiari, Worsley[28]	United Kingdom	X	19 Healthy participants	Descriptive, laboratory
Caggiari, Worsley[43]	United Kingdom	Hospital	2 Spinal cord injured patients + 14 healthy volunteer	Descriptive
Chiang, Lin[29]	Taiwan	Hospital	17 Post stroke patients	Cross-sectional
Cruise, Schnelle[30]	United States	Nursing home	225 Nursing home residents	Prospective descriptive
Duvall, Karg[44]	United States	X	10 Healthy participants	Descriptive, laboratory
Exton-Smith and Sherwin[31]	United Kingdom	Hospital (geriatric unit)	50 Elderly patients	Observational
Jaichandar, Kumar[32]	Singapore	Hospital	15 Hospitalised patients	Experimental
Kallman, Bergstrand[33]	Sweden	Nursing home and hospital	52 Older participants	Cross-sectional design
Kotowski, Davis[34]	United States	X	12 Healthy participants	Laboratory study
Minteer, Simon[35]	United States	Hospital	10 Mobility-restricted patients	Prospective clinical study
Moda Vitoriano Budri, Moore[3]	Ireland	Long-term setting	150 Older adults + 22 healthy volunteer	Observational, quantitative, prospective
Nicholson, Leeman[36]	United Kingdom	Hospital (geriatric unit)	30 Elderly patients	Observational Study
Pickham, Ballew[37]	United States	Hospital (ICU)	1812 Patients admitted to ICUs	Randomised controlled
Renganathan, Nagaiyan[46]	India	Hospital (ICU)	40 ICU patients	Prospective, non-randomised, multiphase, multicentre trial
Sabol, Kennerly[38]	United States	Nursing home	2 Elderly patients	Case study
Schnelle, Ouslander[39]	United States	Nursing home	118 Elderly patients	Cross-sectional survey.
Stinson, Ferguson[40]	United Kingdom	Hospital	21 At-risk cohorts (spinal cord injury; elderly orthopaedic)	A review
Townsend, Goubran[41]	United States	X	1 Healthy participant	Laboratory
Wai, Yuan-Wei[24]	United States	X	X	Experimental, laboratory
Zimlichman, Shinar[42]	Israel	Hospital	116 Hospitalised patients	A non-interventional
Avsar, Budri[45]	Ireland	Long-term setting	53 Older adults	Observational, quantitative

Abbreviation: ICU, intensive care unit.

TABLE 3 Monitoring devices

Author	Monitoring device	Output parameter	Device set-up and principle of operation	Sensitivity, specificity, and predictive value of device	Results
Alessi, Schnelle[23]	Two thin strips of piezoelectric plastic film	Frequency of large movements at shoulder and hip	• Bed mobility (subject movement in bed) at night was measured by device under the bed sheets, one strip at the shoulders and one at the hips. • Only "large" movement was reported, defined as a recorded value corresponding to an observed movement in excess of 45° away from the mattress. • Subject movement on the mattress was converted to an electrical signal; peak activity during each 2-minute period for the shoulders and hips was recorded separately.	Sensitivity: 84% Specificity 93%.	• Mean number of large shoulder movements was **8.1 ± 6.3** per hour for group who did not receive psychotropic medications compared with **5.6 + 5.4** for those who received psychotropic medications.
Barbenel, Ferguson-Pell[25]	Data-logging system	Magnitude of movement	• Loads transmitted by each of the bed legs were measured by supporting it on a specially developed low-profile load cell. • The monitoring programme operated in two modes. During the normal day, the beds were monitored for alterations in baseline weight, usually produced by changes in bedclothes. During the period 23:00-6:00 hours movements were logged. • The mobility of the patients was described by the total number of movements made in the 6 hours recorded period, which altered the position of the centre of gravity by more than 10 ram, twice the noise and footfall threshold.	—	• The relationship between Norton risk assessment score, the incidence of pressure sores and the total number of movements for individual patients was not substantiated by the mobility results. • At-risk patients according to Norton, showed a significant reduction in mobility. • The mean number of moves made on the first night (39.5) was greater than on the second night.[28-6] When the total number of movements made on the first and second night was compared the results showed a highly significant difference ($P < .001$) and the results on the first two nights were analysed separately from the subsequent data.

(Continues)

TABLE 3 (Continued)

Author	Monitoring device	Output parameter	Device set-up and principle of operation	Sensitivity, specificity, and predictive value of device	Results
Barbenel, Ferguson-Pell[26]	The data-logging system	Magnitude of movement	• The weight of a patient in bed was carried by the four bed legs. A movement altered the load transmitted by each leg, and if these forces are measured, the position of the patient's centre of gravity was determined and the magnitude of the movement calculated. To determine the forces, each leg was supported on a specially developed low-profile load cell. • The mobility of 40 patients was obtained for 217 nights. The system was switched on automatically at 10 PM and off at 6 AM using an integral time clock. The magnitude and time of occurrence of every movement in bed made by the patient was recorded. Occasional patterns of rapid, repeated movements lasting up to 1 minute were identified and replaced in the stored data by a representative single movement. • The overnight mobility was characterised by the total number of movements greater than 10 mm, which were made between 11 PM and 5 AM.	The load cells, and the microcomputer-based data-logging and reduction system were robust and reliable.	• Analysis of the number of moves greater than 10 mm made on the first (n1) and second (n2) nights led to the identification of three possible criteria for selecting individual patients at risk: 1. The number of movements made on the first night was 30 or less ($n1 < 30$). 2. The number of movements made on the second night was greater than the number of movements made on the first night ($n1 < n2$). 3. Empirical criterion giving greatest proportion of correctly identified at-risk patients. • Patients with a low Norton score satisfied the criterion that $(n1 - 44)\,2 + (n2 - 22)\,2 > (16.5)\,2$.
Bhidayasiri, Sringean[27]	Wearable sensors (the NIGHT-Recorder)	Magnitude of movement	• The NIGHT-Recorder consists of 16-bit triaxial integrated microelectromechanical system inertial sensors (accelerometers and gyroscopes) that are specifically designed to measure movements (both linear and angular acceleration in three translational planes), register the position of the body with respect to gravity and provide information on rotations on the longitudinal axis while lying in bed.		• The torque of axial rotation, which indicates the ability of PD patients to turn in bed was significantly less than their spouses ($P < .001$). • A significant correlation between a decreased ability to perform axial rotation and the NADCS scores suggests a possible underlying axial akinesia and rigidity among PD patients during their attempt to turn in bed.

TABLE 3 (Continued)

Author	Monitoring device	Output parameter	Device set-up and principle of operation	Sensitivity, specificity, and predictive value of device	Results
			• All subjects wore the NIGHT-Recorder on their sternum, fastened with a Velcro band over their nightclothes. • For this study, the operational definition of turning in bed was a series of rotational movements of the trunk from one static position to another static position that was sustained for at least 5 minutes in a *y*-axis plane.		
Caggiari, Worsley[28]	Pressure monitoring system	Magnitude of movement	• Application of intelligent data processing of biomechanical signals depicting changes in lying posture from angles of body segments (actimetry) and pressures measured at the interface between the body and support surface, ie, contact area of pressures >20 mm Hg. The derivative of signals was assessed to identify changes in posture in both sagittal and lateral planes.	The accuracy in predicting the range of postures from data ranged between 82% and 100%, 70% and 98%, and 69% and 100% for Naïve-Bayes, k-Nearest neighbours and support vector machine classifiers, respectively.	• Identified the occurrence and magnitude of movements based on signal derivative and machine learning algorithms.
Caggiari, Worsley[43]	Pressure monitoring system	Both the frequency and magnitude of large- and small-scale movements	• The set of experimental data used to train the algorithm was derived from a study on able-bodied volunteers (n = 14) performing a series of randomised lying postures. • Each participant was asked to adopt three distinct postures prescribed in a random order on two mattress systems, an air cell mattress functioning in alternating mode, and a castellated foam mattress. Postures involved supine, left lateral lying with the pelvis tilted to 30 and high sitting with the head of bed set at 45°. • Lateral posture was achieved by placing pillows under the back and legs, in a similar manner to that adopted in clinical settings to off-load the sacrum.	The cross-validation demonstrated an average accuracy of 84% (±21%) and 70% (±28%) for lying postures adopted on the foam and air cell mattresses, respectively. The corresponding accuracy of the sitting postures was 84% (±22%) on the foam cushion.	• Examination of the derivative profiles showed some periods of high-frequency postural adjustments and postural movements, identified as clusters of events. • Results in posture and mobility classifications were evaluated in the light of an independent clinical evaluation. Subjective assessment showed a reduced number of postural changes and postural adjustments, when compared with those predicted with the algorithm • There were clear differences in the behaviour of the two SCI patients, which could be attributed to

(Continues)

TABLE 3 (Continued)

Author	Monitoring device	Output parameter	Device set-up and principle of operation	Sensitivity, specificity, and predictive value of device	Results
			• Interface pressures were monitored during each posture and mattress condition, using a high-resolution sensing array, with an acquisition frequency of 1 Hz. • The mat incorporates 5664 pressure measuring sensor cells, with a spatial resolution of 15.9 mm, covering a sensing area of 762 mm × 1880 mm. • Each sensor operates within a range of 5 to 200 mm Hg (0.7-26.6 kPa) and an accuracy of ±2 mm Hg. Static postures were manually labelled, and grey scale images of pressure distributions were exported for each posture and mattress condition. These were then utilised as a training model for prediction of postures using CNN. • To perform image classification, the CNN algorithm uses the intensity of the pixel values corresponding to the pressure distribution, to form features. It consists of multiple feature-detecting layers, where the convolution represents the core of the architect.		intrinsic factors, such as their level of injury and capacity to mobilise.
Chiang, Lin[29]	Mattress Mobility Detection System	Movement time, distance, and peak pressure of counteraction of trunk rolling performance	• Four strain gauges (LFS1CC150 kg, DeltaTransducers Co.) were mounted under the feet of bed and were used to evaluate the centre of mass and centre of pressure during task executing. • All sensors were connected to a laptop computer via a 12-bit analog-to-digital converter to the LabVIEW2010 (National Instruments Corporation, Austin, Texas) data acquisition system. • Data were analysed to identify or distinguish the trunk performances,	—	• A significant longer turning time was observed when turning from the paretic side towards the non-paretic side compared with the other direction, with an estimated mean difference of 0.427 seconds ($P = .005$). • There was a significant difference in the time of rolling back to supine position between two directions.

TABLE 3 (Continued)

Author	Monitoring device	Output parameter	Device set-up and principle of operation	Sensitivity, specificity, and predictive value of device	Results
			such as rolling and sitting up or off the bed.		• The displacement of CoP in rolling back from side lying on the non-paretic side was smaller than that from the paretic side with an estimated mean difference of −0.797 cm ($P = .023$).
Cruise, Schnelle[30]	Kynar brand piezoelectric plastic film strips	Frequency of large movements at shoulder and hip	• A bedside monitor (8″ × 12″ × 2″) was placed on the bedside stand beside each resident's bed and was located near the resident's head; the monitor emitted no noise and recorded information relevant to body movement, noise, and light on six different channels. • Body movement was measured by two Kynar brand piezoelectric plastic film strips placed under the bed sheets across the full width of the bed at the level of the resident's shoulders and hips. • The strips converted resident movement into electrical signals. • The large moves that occurred within the same 2-minute interval at both the resident's shoulder and hip were interpreted as likely turns. • Environmental noise and light changes were measured by the bedside monitor in the same consecutive 2-minute intervals. • A cadmium sulphide photocell monitored the maximum light level in the room near the bedside monitor, while an electric microphone monitored peak sound levels. Peak levels of these environmental factors were encoded simultaneously with each resident's movement data for successive 2-minute intervals throughout the recording period.	—	• Forty-two percent of waking episodes lasting 4 minutes or longer were associated with noise, light, or incontinence care events. • Twenty-two percent of waking episodes of 4 minutes or longer were associated with noise alone, 10% with light or light + noise, and 10% with incontinence care routines. • Seventy-six percent of all incontinence care practices resulted in awakenings. • There was variability between the 10 NHs, with the percentage of waking episodes associated with environmental events (noise, light, or incontinence care events) ranging from 23.6% to 66.0%.

(Continues)

TABLE 3 (Continued)

Author	Monitoring device	Output parameter	Device set-up and principle of operation	Sensitivity, specificity, and predictive value of device	Results
			• Loud noises were defined as those at the level of loud speech or higher (approximately 60 dB or higher). Noise and light changes in combination with large movements at the shoulder and hip (i-e., turns) were interpreted as related to incontinence care by nursing staff. • This association between body movements, noise, light, and incontinence care routines was substantiated by observations of research staff and reported in previous research.		
Duvall, Karg[44]	E-scale	Movement time, distance, and peak pressure of counteraction of trunk rolling performance	• The E-scale is a bed weight monitoring system with load cells placed under the legs of a bed. • This study used a threshold-based detection algorithm and a K-nearest neighbour classification approach.	Greater than 94% accuracy.	• The E-scale could detect and classify four movements (rolls, turns in place, extremity movements, and assisted turns) with greater than 94% accuracy.
Exton-Smith and Sherwin[31]	An inertia switch via a ratchet strip that is attached to the mattress.	Frequency (small or large movements)	The Apparatus • A movement made by the patient operates an inertia switch via a ratchet strip that is attached to the mattress. • A small movement of the trunk operates the switch once or twice, but a larger movement sufficient to cause a complete change of bodily position may operate the switch as many as 12 times. The total motility score is recorded on a counter which is kept in the nurses' station. The Records • Each study extended over 7 hours from 11 PM. to 6 AM. • Records were made on each patient on 3 to 10 consecutive nights, and the	—	• Of the 50 patients, 10 had average nightly scores of less than 20, and in 9 of these pressure sores developed. • Only one other patient had a pressure sore; although her average nightly score was 23, erythema of the pressure areas was noticed after the night when the score fell to 15, and two nights later, when the score was 7, a frank sacral pressure sore had appeared.

TABLE 3 (Continued)

Author	Monitoring device	Output parameter	Device set-up and principle of operation	Sensitivity, specificity, and predictive value of device	Results
			pressure areas were inspected daily for evidence of developing pressure ulcers.		
Jaichandar, Kumar[32]	Intelli-sense bed patient movement sensing	A pressure change in the inflated pressure pads, which are sensed by the pressure sensors	• Air inflated pressure pads were embedded in the mattress at various potential spots. The pressure sensor is a differential pressure sensor that will sense the pressure changes. • The different pressure sensors at various locations produce a constant signal and are connected to the digital I/O channel of the microcontroller unit. • The Microcontroller converted this signal into digital and the processor kept monitoring the signals. • When patient moves there will be pressure change in the inflated pressure pads which are sensed by the pressure sensors and in turn Microcontroller detected a pressure change and it resets the alarm timer. • If the patient has not moved within a pre-set time frame the microcontroller will activate the alarm module.	—	• The system alerts the nurse if the patient has not moved, or the movement is not significant in 2 hours there by replacing the manual two-hour chart.
Kallman, Bergstrand[33]	MovinSense monitoring system	Movements greater than 25° in any direction with a duration of more than 5 seconds, and both spontaneous	• The MovinSense (MiS) care management system (Kinematix, Porto, Portugal) was used to automatically monitor and document the patient's movements. • The system consists of three parts: the MiS software, transmitter, and receiver. • The transmitter is secured onto the patient's upper sternum with adhesive tape. • The transmitter registers when (date and time) and how (angle and position) the patient, either with help from the staff or spontaneously, makes a position change.	A validation test of the congruence between MiS and nursing staff notes was performed based on 26 participants in the study. The congruence of position was 92.3%.	• Patients made median of 16 spontaneous movements during the day and 10 during the night.

(Continues)

TABLE 3 (Continued)

Author	Monitoring device	Output parameter	Device set-up and principle of operation	Sensitivity, specificity, and predictive value of device	Results
			• The data are stored in a log file and downloaded from the transmitter via the receiver to the software after the measurement period is completed. • For this study, the device was configured to register only the movements of more than 25◦ in any direction and with a duration of more than 5 seconds. • The alarm function in the MiS was turned off and the nursing staff had no access to the MiS data.		
Kotowski, Davis[34]	Motion-Capture System	Seven-camera, which is a passive optical motion-capture system that captures three-dimensional positions using markers placed on the subject's body, bed frame, and on the surface of the mattress	• Movements of the shoulder, trochanter, and ankle relative to the bed frame were measured during two different bed articulations. • These movements were used to determine cumulative movement, net displacement, and torso compression during bed articulation. • Given the lack of sensors to adequately measure the shear force between the skin and bed mattress, movement of the body in the bed provides a surrogate measure as a quantification of the summation of sliding movement in the bed (eg, cumulative movement) and net displacement towards the FOB (eg, ending position after the articulation). • The torso compression provided a measure of how much the participant is "scrunched" as a quantification of the distance between the shoulder and trochanter. • The beds were articulated in standard conditions as the "patient" was in a supine position while acting comatose	—	• Bed design and bed movement had a significant effect on most of the dependent variables. • Bed design (eg, type) influenced cumulative movement by up to 115%, net displacement by up to 70%, and torso compression by about 20%. • Bed movement (eg, knee elevation) reduced cumulative migration by up to 35%.

TABLE 3 (Continued)

Author	Monitoring device	Output parameter	Device set-up and principle of operation	Sensitivity, specificity, and predictive value of device	Results
			and not adjusting to the bed until after the articulation was completed. • A seven-camera, passive optical motion-capture system (MotionAnalysis, Santa Rosa, California) quantified the instantaneous 3-dimensional position of seven markers on the body, six markers on the bed frame, and three markers on the surface of the mattress at a sampling rate of 10 Hz. All data were collected, digitised, and analysed with the use of Cortex software.		
Minteer, Simon[35]	PUMP device	Patient repositioning activity.	• Two different sensor devices: PUMP1 and PUMP2. • PUMP1, is a wearable sensor that conveniently fits on a patient gown or clothing near the chest, directly monitors patient rotation. • PUMP1 contains a microprocessor, a rechargeable lithium-ion battery, a microSD card for storing the measured data, and several sensors. The sensors include an accelerometer (3D acceleration measurement), gyroscope (3D angular velocity), magnetometer (direction), light sensor (lamination measurement), and a thermometer (ambient temperature).	85% reliability in detecting patient repositioning.	• An average of 6.5 to 1.9 movements per subject were detected by PUMP1 (gown sensor) and an average 7.2 to 1.9 movements per subject were detected by PUMP2 (under-bed sensors). • Eleven movements were missed by PUMP1 (wearable gown sensor) and seven movements were missed by PUMP2 (bed sensor). • Two false positives were detected by PUMP1 and one by PUMP2, which was the same event. • PUMP1 detected a total of eight more movements than PUMP2.
Moda Vitoriano Budri, Moore[3]	EarlySense	Frequency of large and small movements	• Movement assessment was performed using data from the EarlySense system. These data were collected when the participant was in the bed from 8 PM to 8 AM (referred as night-time) • The motion sensor measured the participant's movement every 2 seconds and stored data in a Comma Separated Values (.csv) format file together with	—	• The movement was assessed using the motion sensor and results showed that Among 150 older participants, the mean movement score was 121.1 mov/h (min: 1.11 mov/h; max: 641.3 mov/h; SD: 143.5 mov/h) • Among the 22 healthy adult participants, the mean movement

(Continues)

TABLE 3 (Continued)

Author	Monitoring device	Output parameter	Device set-up and principle of operation	Sensitivity, specificity, and predictive value of device	Results
			the participant's identification, date, hour, heart rate and respiration rate. • To make sense of the measures exported in clinical practice, a tool to make all needed calculations from the raw data was developed by the researcher and further checked and improved with the advice of an IT expert. • Data were extracted from the bedside unit every 6 days, until the 20 days follow-up was completed.		score was 111.9 mov/h (min: 41.2 mov/h; max: 251.0 mov/h).
Nicholson, Leeman[36]	A system with a load-transducer	Magnitude of the movement	• A system with a load-transducer under each bed leg was used to obtain a continuous plot of the lateral position of the patient's centre of gravity. • Each transducer consisted of a cantilever, whose deflection was sensed by a resistive strain gauge. • The four strain-gauge resistor elements were connected in a bridge configuration so that the out-of-balance signal was related linearly to the position of the patient's centre of gravity across the bed. • The records for the hour after retiring to bed and the hour before arising in the morning were eliminated from the analysis. • A section of trace of the same length was discarded around the times when the subject received attention during the night. • The absolute displacement of the patient's centre of gravity was calculated from body weight and a calibration by known weight. • A displacement as small as 4 mm could reliably be detected. Only displacements	—	• The number of movements correlated inversely with the cognitive function score: the 12 patients with a score of 3 or less made nearly twice as many moves per hour [mean 9 (6)] as those with a higher score [5 (3)]. • The number of moves made by patients with Parkinson's disease was not significantly different from that made by the other patients. • In the patients with pressure sores, pain had been controlled by non-narcotic analgesics. These patients had a significantly smaller mean move size [11 (2) mm] than the rest of the group [19 (16) mm]. • In patients who were suffering pain, the mean size of move was significantly greater [21 (18) mm] than in those who were pain free [12 (4) mm].

TABLE 3 (Continued)

Author	Monitoring device	Output parameter	Device set-up and principle of operation	Sensitivity, specificity, and predictive value of device	Results
			greater than this, and sustained for 1 minute or longer, were used in the analysis. • For each night studied the number of moves by the patient greater than 4, 10, and 20 mm were counted, and all distances of more than 4 mm were summed. • These values were adjusted proportionately according to the length of record analysed. The mean size of the movements was calculated.		
Pickham, Ballew[37]	A wearable patient sensor (Leaf Healthcare, Inc., Pleasanton, California)	Movement data on turn frequency, turn angle, and position frequency and duration into an integrated position index	• This study investigates the effect of optimal turning, defined as patient turning every 2 hours with at least 15 minutes of tissue decompression, on reducing HAPUs. • It compares outcomes in the treatment group with a control group. The treatment group consists of patients receiving clinical care that is optimised by the Leaf Patient Monitoring System (Leaf Health Care).	—	
Renganathan, Nagaiyan[46]	A wearable sensor (PRESENSE)	Movement data on turn frequency, turn angle, and position frequency and duration into an integrated position index	• In Phase I (control group), the function of the device was not showed to nurses to observe their baseline adherence to turn protocol, while Phase II (intervention group) used a continuous patient position monitoring system to generate alerts, when non-compliant with the turn protocols. • In both phases, nurses recorded the position and the orientation of the device during the nursing handover.	—	• Turn protocol compliance was significantly higher in Phase II (80.15_8.97%) compared to Phase I (24.36_12.67%); $P < .001$.

(Continues)

TABLE 3 (Continued)

Author	Monitoring device	Output parameter	Device set-up and principle of operation	Sensitivity, specificity, and predictive value of device	Results
Sabol, Kennerly[38]	The Leaf Patient Monitoring System (Leaf Healthcare)	Movement data on turn frequency, turn angle, and position frequency and duration into an integrated position index	• Movement and position were assessed using the Leaf Patient Monitoring System (Leaf Healthcare) • Based on a pre-set threshold, changes in position were recorded in real time. When residents were recumbent, the lateral roll angle threshold was set at ±20° to detect either a left or right position change. • For seated positions, the tilt angle threshold was set at ±10° to detect leaning to the left or right, and a head elevation ±30° was set for an upright position in bed or chair.		• Both residents (BMI 39 kg/m^2 and 50 kg/m^2) had limitations in movement with prolonged periods spent in a single body position. • Each resident addressed movement challenges unique to their desire to remain mobile and level of dependency on nursing staff.
Schnelle, Ouslander[39]	A bedside monitor	Frequency of large movement (45° turn) at the shoulder and hip	• A bedside monitor (8″ × 12″ × 2″) was placed on a table at the front of each resident's bed. This monitor recorded information relevant to sleep, body movement, noise, and light on six different channels. • Their signals were transmitted to the bedside monitor via miniature 5 conductor ultraflexible 30-G stranded wire cable (Brim #1210/5) that was attached to the subject's bed clothes. • Two additional channels of the bedside recording instrument monitored gross body motion as detected by strips of "Kynar" brand piezoelectric plastic film under the bed sheeting. Placed across the full width of the bed at the level of the resident's shoulders and hips. • The strips converted resident motion against the mattress into electrical signals and were sensitive enough to record movement from respiration and from the subject's extremities. Software was developed that interpreted and	—	• There is an average of 6.1 and 7.0 large moves at the shoulder and hip per hour, respectively. • There was a significant correlation between large moves at the shoulder and hip within the same night: Night 1, $r = 0.51$; Night 2, $r = 0.59$; $P < .05$. • There were also significant correlations between night 1 and night 2 on all three bed mobility measures ($r = 0.35$, shoulder; $r = 0.28$, hip; $r = 0.38$, resident-initiated hip + shoulder, $P < .05$ in all cases). • A substantial number of residents demonstrated fewer than one large move per hour at either the shoulder or hip area. • A total of 37 (or 33%) of the residents did not show at least one such resident-initiated move or turn per hour in the absence of a nurse entry.

TABLE 3 (Continued)

Author	Monitoring device	Output parameter	Device set-up and principle of operation	Sensitivity, specificity, and predictive value of device	Results
			provided a printout of all information from each channel concerning wrist activity, body movement, noise, and light within 2-minute intervals. The first two channels recorded movement of the subject's dominant wrist from a matched pair of wrists worn accelerometers. These sub miniature solid-state accelerometers (ICSenors #303 1-005) were mounted orthogonally in a wristwatch case together with low voltage instrumentation amplifiers. • For each channel, the monitor subtracted the lowest reading from the highest reading during each 2-minute period to measure and record the peak activity during that epoch. • Peak levels of environmental factors were encoded with the subject's movement data for successive 2-minute epochs throughout the study period.		• There was a significant difference in average Norton scores between this low movement group and the high movement group, with the lower movement group assessed at higher risk (average score 10.8 and 12.5, respectively, $P < .01$).
Stinson, Ferguson[40]	Accelerometery and seated interface pressures	Magnitude of movement	Two technology systems were used in these studies to explore repositioning. • The XSensor X3 interface pressure mapping system comprises a thin, flexible pressure sensing mat and a hand held computer that graphically displays the distribution of interface pressure. • In use, the sensing mat is placed on the seating surface between the service user and the seating surface and provides a continuous measurement of interface pressures at the seating interface in visual, graphical and numerical outputs yielded in mm Hg. • The Activpal3 is a triaxial activity monitor that uses piezoelectric	—	• Both studies illustrated that most individuals did not adhere to the frequency or magnitude of movements currently recommended to redistribute seating interface pressures. • When repositioning was performed it was ineffective in reducing seated pressures.

(Continues)

TABLE 3 (Continued)

Author	Monitoring device	Output parameter	Device set-up and principle of operation	Sensitivity, specificity, and predictive value of device	Results
			accelerometers to measure movement in three perpendicular axes • In the current application, however, a novel algorithm was developed to enable the accelerometer to be fixed to the sternum and record angle of trunk tilt during static and dynamic periods of upper body movement. The technology is fixed to the body plane using hydrogel PalStickies.		
Townsend, Goubran[41]	The pressure sensor array as an instrument for rollover detection	Rollover of the patient	• The sensor output is used to calculate a centre of gravity signal, from which five features are extracted. • These features are used in a decision tree to classify detected movements in two categories; rollovers and other movements.	Sensitivity and specificity of 82% and 100%, respectively.	• Correctly classified 81.67% of rollovers (49 out of 60) and 100% of movements (117 out of 117). • The proportion of movements in the correct class was 93.79%, which compares with other measures reported in the literature and its MCC is 0.86.
Wai, Yuan-Wei[24]	Customised hardware and developed software system	Body position	• The movements detection may be classified into fine-grained, articular movements and coarse-grained, body movements.	—	• Sleeping posture classification and fusion approach is applied to evaluate posture classification accuracies according to different posture types: 95.3% Body Shapes; 73.9% Posture; 74.5% Directional Posture
Zimlichman, Shinar[42]	Piezoelectric sensor connected to the EverOn control unit.	Frequency of large and small movements	• EverOn motion: The piezoelectric sensor was placed under the mattress and connected to the EverOn control unit. • After activation of the unit, the EverOn system automatically started measuring respiratory rate, heart rate. • For developing a motion level score, or EML, it identified posture changes and bed exits. Then it devised a motion level score, based on a formula that was later validated against the Norton scale to achieve the highest correlation, based on	Sensitivity, Specificity, PPV, and NPV of the Motion Level Score Compared With the Norton Scale • High Risk according to Norton Score: Sensitivity (0.85); Specificity (0.93); PPV (0.71); NPV (0.97) • Intermediate Risk according to Norton	

TABLE 3 (Continued)

Author	Monitoring device	Output parameter	Device set-up and principle of operation	Sensitivity, specificity, and predictive value of device	Results
			the number of posture changes and bed exits during the night. The EML was calculated for each patient for the first night of hospitalisation only and later compared with the Norton scale calculated for each patient at admission. • To measure only spontaneous movements, it subtracted from the total motion score 2 posture changes per night for patients with a Norton score of 12 to 14, and 3 posture changes per night for a patient with a Norton score.	Score: Sensitivity (0.63); Specificity (0.98); PPV (0.92); NPV (0.86) • Low Risk according to Norton Score: Sensitivity (0.85); Specificity (0.98); PPV (0.89); NPV (0.96)	
Avsar, Budri[45]	EarlySense	Frequency of large and small movements	• Movement assessment was performed using data from the EarlySense system. These data were collected when the participant was in the bed from 8 PM to 8 AM (referred as night-time) • The motion sensor measured the participant's movement every 2 seconds and stored data in a Comma Separated Values (.csv) format file together with the participant's identification, date, hour, heart rate and respiration rate. • To make sense of the measures exported in clinical practice, a tool to make all needed calculations from the raw data was developed by the researcher and further checked and improved with the advice of an IT expert. • Data were extracted from the bedside unit every 6 days, until the 20 days follow-up was completed.	—	• The mean movement (mov) score was 102.8 mov/h (min = 1 mov/h; max = 365 mov/h; SD = ±102.8 mov/h)

Abbreviations: BMI, body mass index; CNN, convolutional neural network; EML, EverOn motion level score; FOB, foot of the bed; HAPU, hospital acquired pressure ulcer; IT, information technology; NH, nursing homes; NPV, negative predictive value; PD, Parkinson disease; PPV, positive predictive value; PUMP, pressure ulcer monitoring platform; SCI, spinal cord injury.

TABLE 4 Properties of monitoring devices in terms of classification of movement classification and pressure ulcer

Monitoring system	Classification of movement	Relationship between movement and PU
1. Two thin strips of piezoelectric plastic film[23,30]	Not reported	Not reported
2. The data-logging system[25,26]	High risk/low risk: Analysis of the number of moves greater than 10 mm made on the first (n1) and second (n2) yielded three possible criteria for selecting individual patients at risk: 1. The number of movements made on the first night was 30 or less (n1 < 30) 2. The number of movements made on the second night was greater than the number of movements made on the first night (n1 < n2). 3. Empirical criterion giving greatest proportion of correctly identified at-risk patients.	Correctly identified 9 of the 10 high-risk patients in the study, but incorrectly identified two of the 11 low-risk patients classified according to Norton Scale.
3. Wearable sensors (the NIGHT-Recorder)[27]	Not reported	Not reported
4. Machine learning approaches, The combination of biomechanical parameters acquired using pressure monitoring and actimetry technologies[28]	Not reported	Not reported
5. An intelligent deep learning algorithm, namely convolutional neural network[43]	Not reported	Not reported
6. Mattress Mobility Detection System[29]	Not reported	Not reported
7. E-scale[44]	• Rolling (rolling from back to side) = 16 movements with 10 seconds between turn in place (rotate) (rotate from back to side while staying at the same location on the bed) = 16 movements with 10 seconds between extremity movements while supine • Movement of a single extremity (leg or arm) without changing position on bed or hip contact location = 15 movements with 10 seconds between random generated movements (Random set of rolling, turn in place, and extremity movements) = Up to 15 movements with 10 seconds between • Assisted turn from back to side lying with positioning wedge (Clinician rolled person from back to side lying using a 30° positioning wedge behind torso and pillow between legs) = 16 movements with 10 seconds between	Not reported
8. inertia switch via a ratchet strip attached to mattress[31]	Moved less than 20 times per night moved more than 20 times per night	Patients moving <20 times very likely to develop a PU unless preventive measures adopted

TABLE 4 (Continued)

Monitoring system	Classification of movement	Relationship between movement and PU
9. Intelli-Sense Bed Patient Movement Sensing[32]	Not reported	Not reported
10. The MovinSense monitoring system[48]	Not reported	Not reported
11. Motion-Capture System[34]	Not reported	Not reported
12. PUMP devices: PUMP1 and PUMP2[35]	Not reported	Not reported
13. Piezoelectric movement sensor[3,42,45]	Moda Vitoriano Budri et al and Avsar, Budri[45]: • Low movers • High movers Movement of older participants was categorised into two groups "low movers" or a "high movers" using the healthy participants mean number of movements (108.2 movements per hour) as the cut-off point. Zimlichman et al Not reported	Moda Vitoriano Budri et al Pressure ulcer incidence using visual skin assessment was 12.7% (low movers = 6.7; high movers = 6%) and 78.7% using sub-epidermal moisture assessment (low movers = 40.0%; high movers = 38.7). Zimlichman et al The authors compared their mobility score measured using the sensor to the Norton score of the participants hospitalised in an acute department, and found a high correlation between their mobility score and the Norton score.
14. A system with a load-transducer[36]	Not reported	In the patients with PUs, pain had been controlled by non-narcotic analgesics. These patients had a significantly smaller mean move size [11 (2) mm] than the rest of the group [19 (16) mm].
15. A wearable patient sensor (Leaf),[37,38] PRESENSE[46]	Not reported	Optimal pressure ulcer prevention defined as regular turning every 2 hours with at least 15 minutes of tissue decompression.
16. A bedside monitor[39]	Not reported	Not reported
17. Accelerometry and seated interface pressures[40]	Not reported	Not reported
18. The pressure sensor array as an instrument for rollover detection[41]	Two classification rollovers and bed entry and exit, arm, leg, and other movements	Not reported
19.Customised hardware and developed software system[24]	(a) Subject lying in left (b) Subject lying in centre (c) Subject lying in right	Not reported

Abbreviation: PU, pressure ulcers; PUMP, pressure ulcer monitoring platform.

these, three reported the frequency of large movements[23,30,39] and five studies reported both large and small movements.[3,31,42,43,45] A further five studies estimated the magnitude of movements.[25,26,28,36,40] As an example, Moda Vitoriano Budri, Moore[3] and Avsar, Budri[45] used 108.2 movements per hour as a mean cut-off value point to classify whether the participants demonstrated a low frequency of movements ("low mover") or a high frequency of movements ("high mover"). By contrast, Exton-Smith and Sherwin (1961) used 20 - movements per hour during the night as a threshold value. Duvall, Karg,[44] Townsend, Goubran,[41] and Wai, Yuan-Wei[24] classified the type of movement according to whether the patient rolled, moved an arm or leg, or was repositioned by attendant health care staff. In addition, large-scale movements were defined as postural changes, and small-scale movements were defined as within-posture adjustments by Caggiari, Worsley.[43]

Movement frequency was assessed in eight studies (32%),[3,24-26,31,41,44,45] five of which differentiated between high and low movement frequency.

In three studies, the authors compared the movement system with the Norton scale PU risk assessment tool. The studies of Barbanel and colleagues (1985; 1986) reported that the monitoring device correctly identified 9 of the 10 high-risk patients, but 2 of the 11 low-risk

TABLE 5 Analysis of evidence-based librarianship appraisal checklist domains

Studies	Validity (%) not reported/unclear issues identified in each domain				Overall validity (%) of study
	Population domain	Data collection domain	Study design domain	Results domain	
Alessi, Schnelle[23]	100%	85% **Comment**: The statistics are not free from subjectivity	80% **Comment**: No ethics approval	100%	92%
Barbenel, Ferguson-Pell[25]	60% **Comment**: Informed consent not obtained, inclusion and exclusion criteria not clearly outlined	83% **Comment**: The statistics free are not from subjectivity	80% **Comment**: No ethics approval	50% **Comment**: Confounding variables were not accounted for. Suggestions not provided for further areas of research. There is no external validity.	68%
Barbenel, Ferguson-Pell[26]	60% **Comment**: Informed consent not obtained, inclusion and exclusion criteria not clearly outlined	83% **Comment**: Outcome measure time not clearly stated, the statistics free not from subjectivity	80% **Comment**: No ethics approval	67% **Comment**: Suggestions not provided for further areas of research. There is no external validity.	74%
Bhidayasiri, Sringean[27]	100%	85% **Comment**: The statistics are not free from subjectivity	100%	83% **Comment**: Suggestions not provided for further areas of research.	92%
Caggiari, Worsley[28]	83% **Comment**: Informed consent not obtained	86% **Comment**: The statistics are not free from subjectivity	100%	100%	92%
Caggiari, Worsley[43]	100%	86% **Comment**: The statistics are not free from subjectivity	100%	100%	95%
Chiang, Lin[29]	100%	88% **Comment**: The statistics are not free from subjectivity	80% **Comment**: No ethics approval	100%	92%
Cruise, Schnelle[30]	80% **Comment**: Inclusion and exclusion criteria not clearly outlined	88% **Comment**: The statistics are not free from subjectivity	80% **Comment**: No ethics approval	67% **Comment**: Suggestions not provided for further areas of research confounding variables were not accounted for	80%
Duvall, Karg[44]	80% **Comment**: Inclusion and exclusion criteria not clearly outlined	88% **Comment**: The statistics are not free from subjectivity	100%	100%	92%
Exton-Smith and Sherwin[31]	67% **Comment** inclusion and exclusion criteria not clearly outlined, informed consent not obtained	88% **Comment**: The statistics are not free from subjectivity	80% **Comment**: No ethics approval	83% **Comment**: Suggestions not provided for further areas of research.	80%

TABLE 5 (Continued)

Studies	Validity (%) not reported/unclear issues identified in each domain				Overall validity (%) of study
	Population domain	Data collection domain	Study design domain	Results domain	
Jaichandar, Kumar[32]	67% inclusion and exclusion criteria not clearly outlined, informed consent not obtained	88% **Comment**: The statistics are not free from subjectivity	80% No ethics approval	67% **Comment**: Confounding variables were not accounted for. Suggestions not provided for further areas of research.	76%
Kallman, Bergstrand[33]	83% **Comment**: Inclusion and exclusion criteria not clearly outlined	88% **Comment**: The statistics are not free from subjectivity	100% **Comment**: No ethics approval	83% **Comment**: Suggestions not provided for further areas	88%
Kotowski, Davis[34]	83% **Comment**: Inclusion and exclusion criteria not clearly outlined	86% **Comment**: The statistics are not free from subjectivity	80% **Comment**: No ethics approval	83% **Comment**: Suggestions not provided for further areas of research.	88%
Minteer, Simon[35]	80% **Comment**: Informed consent not obtained	86% **Comment**: The statistics free not from subjectivity not allow its replication	100%	100%	91%
Moda Vitoriano Budri, Moore[3]	100%	88% **Comment**: The statistics are not free from subjectivity	100%	100%	96%
Nicholson, Leeman[36]	66% **Comment**: Inclusion and exclusion criteria not clearly outlined, informed consent not obtained	88% **Comment**: The statistics are not free from subjectivity	80% **Comment**: No ethics approval	66% **Comment**: Suggestions not provided for further areas of research. Confounding variables were not accounted for	76%
Pickham, Ballew[37]	100%	88% **Comment**: The statistics are not free from subjectivity	100%	83% **Comment**: Suggestions not provided for further areas of research.	92%
Renganathan, Nagaiyan[46]	100%	88% **Comment**: The statistics are not free from subjectivity	100%	83% **Comment**: There is no external validity.	92%
Sabol, Kennerly[38]	100%	86% **Comment**: The statistics are not free from subjectivity	100%	83% **Comment**: Suggestions not provided for further areas of research.	92%
Schnelle, Ouslander[39]	66% **Comment**: Inclusion and exclusion criteria not clearly outlined, informed consent not obtained	88% **Comment**: The statistics are not free from subjectivity	80% **Comment**: No ethics approval	83% **Comment**: Suggestions not provided for further areas of research.	80%

(Continues)

TABLE 5 (Continued)

Studies	Validity (%) not reported/unclear issues identified in each domain				Overall validity (%) of study
	Population domain	Data collection domain	Study design domain	Results domain	
Stinson, Ferguson[40]	100%	83% **Comment**: The statistics are not free from subjectivity	100%	100% **Comment**: Suggestions not provided for further areas of research.	91%
Townsend, Goubran[41]	100%	83% **Comment**: The statistics are not free from subjectivity	80% **Comment**: No ethics approval	100%	88%
Wai, Yuan-Wei[24]	66% **Comment**: Informed consent not obtained	83% **Comment**: The statistics are not free from subjectivity	80% **Comment**: No ethics approval	100%	86%
Zimlichman, Shinar[42]	80% **Comment**: Informed consent not obtained	83% **Comment**: The statistics are not free from subjectivity	80% **Comment**: No ethics approval	100%	88%
Avsar, Budri[45]	100%	88% **Comment**: The statistics are not free from subjectivity	100%	100%	96%

patients were incorrectly classified according to Norton scale. In the study by Zimlichman, Shinar,[42] the authors reported a high correlation between their mobility score estimated from their sensor and the Norton score (Spearman correlation coefficients = 0.59; $P < .0001$).

In four studies, the assessment of movement was examined in the light of the development of PUs. As an example, Exton-Smith and Sherwin[31] reported that 10 of the 50 patients presented with a mean nightly movement score of less than 20, and, of these, 9 developed a PU. In Nicholson, Leeman[36] patients with PU demonstrated significantly smaller movements, that is, 11 ± 2 mm compared with a value of 19 ± 16 mm mean move size [11 (2) mm] for the other group. However, the precise number of patients with PUs was not provided. Moda Vitoriano Budri, Moore[3] reported that PU incidence using visual skin assessment (VSA) was 12.7% (low movers: 6.7%; high movers: 6%). Avsar, Budri[45] showed that of the eight PUs observed using VSA, 62.5% (n = 5) occurred among the low movers, and 37.5% (n = 3) occurred among the high movers.

4.2.6 | Preventive interventions based on using monitoring devices results

Three studies focused on the concordance with recommended repositioning based on the results of the monitoring device. In the study by Pikham et al, the total turning compliance was significantly different in the movement monitoring group vs control group (67% vs 54%; difference 0.11, 95% confidence interval, CI [0.08, 0.13], $P < .001$). In this study, there were less PUs in the group monitored using the monitoring device vs usual care (5 patients [0.7%] vs 15 patients [2.3%]) (odds ratio = 0.33, 95% CI [0.12, 0.90], $P = .031$). However, this was related to the monitoring device acting as a reminder of the need for repositioning, rather than actually focusing on movement frequency and its relationship with PU development. Sabol et al described two case studies of residents with obesity and examined concordance with recommended 2 hourly repositionings, using their monitoring device. Results showed great variability in movement, and less than optimal repositioning throughout the day and night, which would most probably have been overlooked in the absence of the monitoring system.

Theoretical cohort-based recommendations for PU prevention were proposed by Moda Vitoriano Budri, Moore.[3] The authors indicated that for low movers, it is recommended that pressure redistribution surfaces and repositioning should be used as a preventive measure based on the fact that these individuals spend a long time in bed and have impaired movement levels. For individuals who are bedfast/chairfast but are also high (abnormal) movers/agitated, it is recommended pressure

redistribution surfaces, microclimate control, and protective dressing. Finally, the authors proposed that for individuals with higher levels of activity, such as those who walk occasionally/frequently, and are also identified as high movers in bed, it is recommended the aforementioned microclimate control strategies and dressings to protect the bony prominences against shear forces (Table 4).

4.3 | Quality appraisal of studies

The EBL Appraisal checklist was used to assess the methodological quality of the studies, by focusing on the four main domains, namely, population, data collection, study designs, and results. The assessment of these domains is summarised in Table 5, where, if available, validity values are reported in addition to unclear issues identified in each domain.[15] The mean validity score for all studies was 87 ± 0.07%, ranging from 68%[25] to 96%.[3,45]

All studies presented methodological issues in terms of The EBL Appraisal checklist. In the population domain, the main criticisms in all studies could be levelled at the lack of clarity associated with the inclusion and exclusion criteria and the lack of informed consent. In the data collection domain, there was a failure to use regularly collected statistics. In the study design domain, there was also a lack of clarity associated with the ethics approval. Finally, in the results domain, the main areas of concern were associated with external validity, and suggestions were provided for further areas of study.

5 | DISCUSSION

The primary objective of this systematic review was to determine the impact of monitoring devices to assess movement on the prediction of PU risk in adults, and to determine their relative effectiveness. This review has synthesised the findings of 25 studies. There was clear heterogeneity between the studies showing differences in study design, evaluation perspective, and type of monitoring device, which precludes comparison and makes interpretation of the results difficult. Accordingly, the results are reported in narrative terms.

It is worthy to note that Bader and Worsley argue that although mobility and activity are considered as one of the primary causal factors for PU development, there remain technological challenges in defining these parameters. This is because historically the assessment has been based on subjective clinical judgement, meaning that although the mobility status is noted, the method of assessment is unreliable.[4] Therefore, there is a clear clinical need for an objective monitoring device to assess movement. However, the results of this review indicate that there are a plethora of devices used in research and practice to assess the patients' mobility, with no one device standing out as being more superior or clinically useful from the others.

Among the studies, the identification and classification criteria for movement differ substantively. Another important finding was that although some of the studies counted large movements, some of them also included small movements, which could be interpreted as postural adjustments. It is not known what the relative benefits are between large postural changes and smaller perturbations of movement are, although it is likely that both are needed to maintain local tissue perfusion in lying positions.[3,28] Indeed, if only large movements are considered, one of the issues that emerge is that the effects of small movements are missing. Although some of the studies did not record all small movements, they did describe a large variation among the patient's spontaneous repositioning frequencies during both day and night. Caggiari, Worsley[43] reported patient-specific thresholding of large- and small-scale movements, which are needed to improve the accuracy of detection. Furthermore, Moda Vitoriano Budri, Moore[3] showed that PUs occurred both in low and high movers, which was unexpected as a similar finding has not been previously reported in the literature. The sensor used by Moda Vitoriano Budri, Moore[3] was able to capture from very small movements to big postural changes and all the variability in between. Thus, the authors' most striking finding was that both categories of participants (high and low movers) presented with signs of tissue deterioration. Therefore in general, it seems that it is important to consider small movements for the identification of high movers who also have the risk of development of PUs (primarily arising because of the adverse effects of friction and shear). Using traditional methods for the assessment of movement does not provide insight into the protective nature of the movement. Given that both low- and high-moving patients can develop tissue damage, it is important to focus on the assessment of movement using more objective measures and algorithms, which enable real-time assessment of the protective nature of the movement. This would enable to development of person-centred PU prevention strategies to reduce the burden of this significant health care problem. Another finding was that the classification of high and low mover was made based on the frequency of movement; in general, distinguishing normal from abnormal movement is still a challenge in practice because current devices do not adequately focus on the protective nature of the movement, rather focus only on the frequency of the movement. However, Caggiari, Worsley[43] also used convolutional neural network classifiers of pressure signatures to define spatial changes in

pressure, which were indicative of off-loading, which was cross-validated by clinical observations.

The EBL Appraisal checklist was used to evaluate the methodological quality of the included studies, and two studies were considered invalid.[25,26] Among the remaining studies, in the population domain, the main areas of concern that arose were a lack of clarity around the inclusion and exclusion criteria and lack of informed consent. In the data collection domain, the main aspects of concern were outcome measure time, the statistics free from subjectivity, and lack of clarity on the data collection method. In the study design domain, the main issue was unclear if ethical approval was obtained. In the results domain, the key findings were failure to account for confounding variables and recommendations for future research as well as unclear subset analysis. Despite these limitations, 91% of the studies were valid in terms of overall validity score.

5.1 | Limitations

The main limitation of the review involves the broad methodological heterogeneity of the studies, which precluded both their direct comparison and the use of a meta-analysis. It is also accepted that the systematic review was limited to English language studies only.

6 | CONCLUSION

This systematic review assessed the impact of monitoring devices on the prediction of PU risk among at-risk adults and aimed to determine what the most appropriate device to use is. The synthesis of the literature surrounding bed monitoring technologies for PU risk prediction showed that a range of physical sensors can be used to detect the frequency of movement. Clinical studies showed some correlation between parameters of movement and PU risk/incidence, although the heterogeneity of approaches limits generalisable recommendations. Future research is needed, which clearly explores the relationship between objective assessment of patient movement and PU development, in terms of the frequency, magnitude, and protective nature of the movement.

CONFLICT OF INTEREST

There is no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as it is a systematic review.

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