

Review

A Review of Intelligent Sensor-Based Systems for Pressure Ulcer Prevention

Arlindo Silva * , José Metrôlho , Fernando Ribeiro , Filipe Fidalgo, Osvaldo Santos and Rogério Dionísio 

R&D Unit in Digital Services, Applications and Content, Polytechnic Institute of Castelo Branco, 6000-767 Castelo Branco, Portugal; metrolho@ipcb.pt (J.M.); fribeiro@ipcb.pt (F.R.); ffdalgo@ipcb.pt (F.F.); oas@ipcb.pt (O.S.); rdionisio@ipcb.pt (R.D.)

* Correspondence: arlindo@ipcb.pt; Tel.: +351-272-339-300

Abstract: Pressure ulcers are a critical issue not only for patients, decreasing their quality of life, but also for healthcare professionals, contributing to burnout from continuous monitoring, with a consequent increase in healthcare costs. Due to the relevance of this problem, many hardware and software approaches have been proposed to ameliorate some aspects of pressure ulcer prevention and monitoring. In this article, we focus on reviewing solutions that use sensor-based data, possibly in combination with other intrinsic or extrinsic information, processed by some form of intelligent algorithm, to provide healthcare professionals with knowledge that improves the decision-making process when dealing with a patient at risk of developing pressure ulcers. We used a systematic approach to select 21 studies that were thoroughly reviewed and summarized, considering which sensors and algorithms were used, the most relevant data features, the recommendations provided, and the results obtained after deployment. This review allowed us not only to describe the state of the art regarding the previous items, but also to identify the three main stages where intelligent algorithms can bring meaningful improvement to pressure ulcer prevention and mitigation. Finally, as a result of this review and following discussion, we drew guidelines for a general architecture of an intelligent pressure ulcer prevention system.

Keywords: artificial intelligence; sensor-based systems; literature review; machine learning; pressure injury prevention; pressure ulcers prevention



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1. Introduction

A pressure ulcer (PU) is a localized injury to the skin or underlying tissue, usually over a bony prominence, as a result of unrelieved pressure [1]. Healthcare professionals are required to closely monitor people who are at risk of developing pressure ulcers, since timely and accurate prediction of pressure injury risk can significantly facilitate early prevention and treatment and avoid adverse outcomes [2]. If pressure ulcers develop, close monitoring is still essential to ensure that the condition does not become more severe. Risk assessment and monitoring allows healthcare professionals to implement specific prevention measures, such as following a patient repositioning schedule, minimizing possible consequences, and helping to reduce the risk of developing or worsening a pressure ulcer. This is a health care intensive task and many technological approaches have been proposed to help both to improve the outcome of patients with PU (or in risk of developing it) and to alleviate the burnout risk of healthcare professionals who must monitor many patients throughout the day. These solutions typically rely on intrinsic data about the patient (e.g., limited mobility, poor nutrition, comorbidities, aging skin) [1–4] and/or extrinsic data (e.g., pressure from hard surfaces, shearing from involuntary muscle movements, excessive moisture) to provide the healthcare provider with additional information that can facilitate the definition of appropriate monitoring schedule and treatment.

In our current research project, denominated SensoMatt, we aim to develop a system for pressure ulcer prevention centered around pressure data acquired from a matt placed

under the patient. One of the tasks in this project was to perform a systematic review of existing solutions that use sensors to help to prevent the occurrence of pressure ulcers. We focused on intelligent solutions, i.e., solutions that incorporate complex algorithms at some stage of the process, such as machine learning (ML) or other artificial intelligence-based algorithms, since we believe that these approaches are the most promising to produce predictive results from intrinsic and extrinsic data that are useful for healthcare professionals.

With this review, we intended to answer research questions such as: (1) which sensors are commonly used in PU prevention systems; (2) which features are acquired from the processing of raw data provided by the sensors; (3) which algorithms are used for ulcer prevention and at which stage of the process are they applied (e.g., to process data, to provide useful information for healthcare professionals, to predict the outcome of patient at risk, etc.); (4) what type of recommendations these systems are capable of providing and (5) what were the practical results of their deployment.

The review was organized according to an eight-step guide to conduct a systematic literature review of information systems research [5]. This process includes identifying the purpose and intended goals of the review, searching for the literature, formulating inclusion and exclusion criteria, data extraction and analysis, and writing the review. After presenting the review, we proceed to broadly describe the three decision-making components that should be incorporated in a system built to assist the healthcare professional at different stages of the decision-making process for pressure ulcer prevention. The remainder of this article is organized as follows. In Section 2, we present the differences between our study and similar reviews. In Section 3, we describe and apply the methodology chosen to perform this review. In Section 4, we discuss the results obtained and, in Section 5, we describe the major components, which, based on the previous review and discussion, we believe to be essential in an intelligent pressure ulcer prevention system. Finally, in Section 6, we draw some conclusions and discuss future work on the SensoMatt project.

2. The Scope of This Review vs. Previous Reviews

Before starting the review process that led to this article, we searched and analyzed related reviews published in recent years. We found that several articles reviewed works related to the use of technology for pressure ulcer prevention. Tables 1 and 2 summarize some of their goals and findings.

Table 1. Studies reviewing solutions for PU prevention: year, focus and timespan.

Review	Year	Focus	Studies	Timespan
[6]	2015	To identify the state-of-the-art approaches that use software to assist health professionals in PU prevention support.	36	1989–2014
[7]	2021	To analyze the use of ML technologies in PU management, identifying their strengths and weaknesses.	32	2007–2020
[8]	2020	To identify the outcomes from nurses when using support systems on clinical decision making for PU management.	16	1995–2017
[9]	2020	To describe imaging techniques used for the analysis and monitoring of pressure injuries, as an aid to their diagnosis, and proof of the efficiency of Deep Learning.	82	1998–2018

Table 2. Studies reviewing the use of Intelligent Sensor-Based Systems for PU prevention.

Review	Analysis/Results	Identified Opportunities and Future Research
[6]	<p>Most of the approaches use sensors to monitor the patient's exposure to pressure, temperature and humidity to generate reports regarding the intensity of each one of these risk factors, as well as the patient's position in bed. Some approaches perform automated management of the risk factors using ventilation tubes and mattresses with porous cells to decrease the body's temperature and movable cells to automatically redistribute the pressure over the body.</p>	<p>Perform Randomized Control Trials to verify which approaches are effective to reduce PU incidence and to verify which information provided by each of the approach is relevant to health professionals to support them in PU prevention.</p>
[7]	<p>Studies were classified and organized into three groups: 12 (38%) reported using ML technologies to develop predictive models to identify risk factors, 11 (34%) reported using them in posture detection and recognition, and 9 (28%) reported using them in image analysis for tissue classification and measurement of PU wound.</p>	<p>Apply these technologies on a large scale with clinical data to further verify and improve their effectiveness, as well as to improve methodological quality. The prevention of PU was studied under different approaches; however, they are related and should be studied together. For example: ML technologies on predictive model and posture recognition need feedback from PU wound image analysis to improve their performance.</p>
[8]	<p>All the analyzed studies describe knowledge-based systems that assessed the effects on clinical decision making, clinical effects secondary to clinical decision support system use, or factors that influenced the use, or intention to use, clinical decision support systems by health professionals and the success of their implementation in nursing practice.</p>	<p>Carry out studies that prioritize better adoption and interaction of nurses with clinical decision support systems, as well as studies with a representative sample of health care professionals.</p>
[9]	<p>This study focuses on previous contributions to wound image analysis, as well as an introduction to the usage of Deep Learning techniques as a more accurate approach for pressure injuries and chronic wound assessment. One of the findings is that one of the most limiting factors in the future evolution of pressure injury analysis via image processing is the scarcity of publicly available pressure injury image databases that allow a fair comparison between techniques</p>	<p>Concludes that 3D imaging techniques have proven successful for the retrieval of wound metrics that are essential for the efficient treatment of these wounds, and that the combination of these methods with Deep Learning techniques in a single system will eventually create a new optimal tool for accurate wound assessment and prognosis through imaging techniques.</p>

From the analysis of these reviews, and to the best of our knowledge, there is no previous systematic literature review of this area that addresses the full path of technologically assisted PU prevention, from the sensing methods to the support mechanisms for healthcare professionals' decision-making. Previously published reviews are usually focused on the analysis of some components of that path. The most similar review to the work presented in this article, which also tried to cover aspects related to the acquisition of signals from bedridden patients for supporting the prevention of pressure ulcer harmful effects, is published in [6]. However, this article was published in 2015 and this area has since undergone several relevant advances, resulting from contributions of new research published in more recent years. In this review, we are also more focused on approaches based on intelligent algorithms and not in all software supported methods.

The study presented in [7] is focused on ML applications for PU prevention. In this study, the authors analyze works that use ML technologies to lessen the burden of medical staff by improving the prognosis and diagnostic accuracy of PU. In [9], the focus is also on using ML for image analysis. There are also other reviews that are out of the scope of our work, such as [10], which is specifically focused on mobile applications used for the identification of PU.

In short, when compared to previous reviews of this field, this work has three main distinct features which we believe are important for its relevance and topicality. It is focused on intelligent approaches, which we believe are the most promising for this problem. It analyzes works that have proven their practical applicability by describing methodologies

that range from collecting data from real sensors to providing some form of decision-making information for healthcare providers. Finally, it includes new advances that were not included in the most similar review, which dates from 2015.

3. Methodology and Review

This section presents the systematic review of studies that addressed the use of intelligent sensor-based systems for pressure ulcer prevention. The review was performed following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [5]. It includes the following steps, which correspond to the section or subsection of this article listed after each step:

- Identifying the purpose and intended goals of the review (Section 3.1);
- Search strategy (Section 3.2);
- Screening for inclusion (Section 3.3);
- Screening for exclusion (Section 3.4);
- Data extraction (Section 3.5);
- Analysis and Discussion (Sections 4 and 5);
- Writing the review.

3.1. Purpose of the Review

The purpose of this review was to identify the inputs and outputs considered in the selected studies, the algorithms used, the strengths and weaknesses of each approach and the results achieved. These data were then used to answer a predefined set of research questions: (1) which sensors are commonly used in PU prevention systems; (2) what features are acquired from the processing of raw data provided by the sensors; (3) which algorithms are used for ulcer prevention and at which stage of the process are they applied (e.g., to process data, to provide useful information for healthcare professionals, to predict the outcome of patient at risk, etc.); (4) what type of recommendations these systems are capable to provide and (5) what were the practical results of their deployment. The answers to these questions allowed us to identify and describe the major components we believe are essential in an intelligent pressure ulcer prevention system.

3.2. Searching the Literature

The search for literature was performed using Scopus and b-on.pt, a Portuguese online library to which academic institutions can subscribe to search and access most of the relevant scientific databases in the field, including IEEE, ACM, ScienceDirect, Springer, Web of Science and several other smaller databases. We found that the results from a unified search over these databases were similar to the ones returned by Scopus, which can be used by international researchers to replicate the search (while b-on is a national paid service). To perform the search, a set of search terms related to pressure ulcer prevention was chosen. After some initial experiments, and considering the initial analysis of previous literature reviews, the final complete string for the search was defined as follows and performed over titles, abstracts and keywords:

(((pressure AND ulcer) OR (pressure AND injur*) OR (pressure AND sore*) OR bedsore* OR (bed AND sore*)) AND bed AND sensor)*

The search was performed on 5 May 2021. No time range was defined. The search produced 154 relevant results. After removing duplicated results, this step resulted in the selection of 151 studies.

3.3. Screening for Inclusion

Two reviewers examined the obtained set of studies by title and, when necessary, reading the abstract, to decide whether, for the purposes of the review, they were worth reading further or if they should be excluded. In this screening, the reviewers considered that studies should only be included in the review if they met the following criteria: (1) studies that presented a solution for pressure ulcer prevention; (2) studies where the

proposed approach was based on bed instrumentation; (3) studies that were published in a scientific peer-reviewed publication; (4) studies that were written in English; and (5) studies with full text available. Studies that did not meet all these criteria were excluded.

At this stage, the reviewers did not judge the quality or evaluate the information found in each study. Criteria (1) and (2) were determined merely by reviewing the title and, when necessary, the abstract. After applying criteria 1 to 5, 102 studies were excluded resulting in a selection of 49 studies.

3.4. Screening for Exclusion

The final list of studies was assessed by two reviewers to determine whether they should be included in the detailed analysis. At this stage, each reviewer went over the full text of each study to assess its purpose, strategy and outcomes. Only studies focusing on pressure ulcer prevention, describing their design methodology and experimental results, and including some form of intelligent algorithm in their approach were considered. Studies that did not satisfy these conditions were excluded. At this stage, after analyzing the full text of the 49 previously selected studies, 28 were excluded and only 21 remained for detailed analysis.

3.5. Data Extraction and Article Synthesis

Each study was then reviewed and analyzed based on the 5 items described in Table 3. These items were selected for their relevance in providing information to answer the research questions identified in Section 3.1.

Table 3. Type of data to be extracted and its description.

Item	Description
sensors	Type of sensors (pressure, temperature, moisture, etc.)
features	Pre-processed features obtained from raw sensory data
algorithm	Algorithms used to process the data
alert	If and how the systems alert the caregivers
results	Main results achieved with the proposed approach

Following the methodology described in the previous sections, and presented in Figure 1, the review identified 154 studies that included 3 duplicates, which were removed. The remaining 151 studies were evaluated in terms of title and abstract, resulting in the exclusion of 102 studies, which were excluded because they lack the use of a sensory bed. The full-text evaluation of the remaining 49 studies was then performed, excluding 26 studies that did not match the defined inclusion criteria. The remaining 21 studies were used for data extraction (Table 4), synthesis and detailed analysis, which are presented in the rest of this section.

From the 21 articles selected for synthesis and analysis, 17 included some type of pressure sensors as an essential source of information for the system being implemented. Pressure sensors are very flexible and can provide pressure maps that are obviously very useful to tackle a problem where continuous pressure on a body part is an essential factor. This type of sensor has other interesting properties, discussed in more detail in the following Section, which promote their use in different approaches to pressure ulcer prevention. Most of those approaches use posture information changing over time to detect the posture, or lying position, of the patient. Of the 17 studies that use pressure sensors, 7 have as the only output the classification of the patient's posture, while the remaining 11 use that information to provide additional outputs to the caregiver or healthcare provider, such as monitoring and notifications. In the following paragraphs, we provide a brief synthesis of the works that use pressure information only for posture classification.

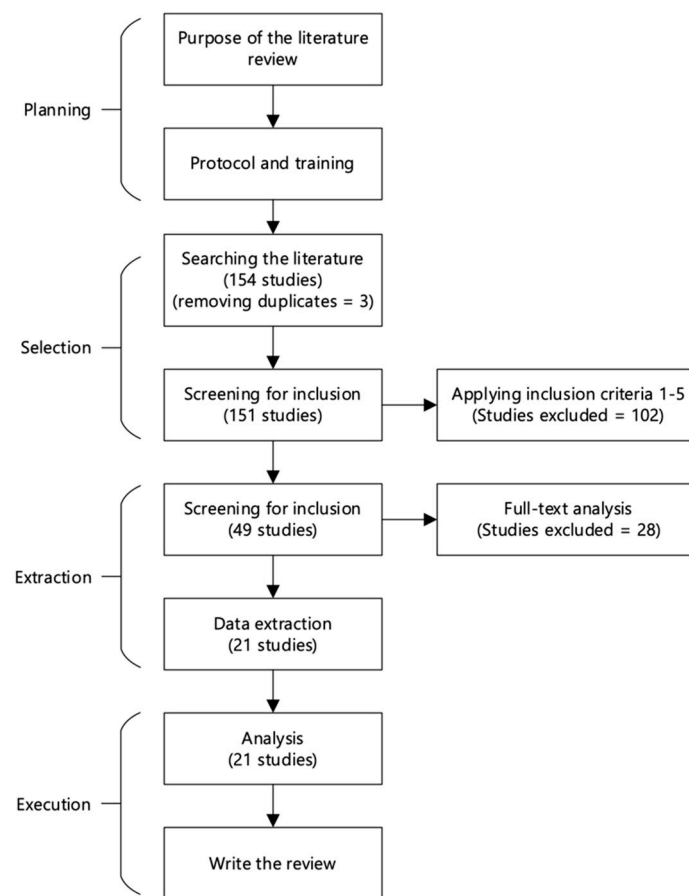


Figure 1. Flowchart of the systematic review process, including planning, selection, extraction and execution stages.

Table 4. Summary of the articles selected for analysis and synthesis, including used sensors, features extracted, algorithms applied, type of recommendation and final results.

	Sensors	Features	Algorithm	Recommendation	Results
[11]	Single accelerometer	Amplitude, mean, minimum, and maximum values of the lateral and vertical axes	Ensemble trees, AdaLSTM to detect lying postures	NA	NA
[12]	Pressure and vibrational signals	Signal waves	Neural Network (NN) and Bayesian network for posture classification	Message notifications for going out of bed, period in same position and too frequent movement	Test household deployment with some problems
[13]	Three inertial sensors	Values for x, y, z data streams	SVM for posture classification, fuzzy knowledge-based system for protocol implementation	Priority of postural change for body zones	Preliminary tests with 7 users in controlled environment

Table 4. Cont.

	Sensors	Features	Algorithm	Recommendation	Results
[14]	Humidity, temperature sensors and force sensors	Sensor values, processing not described	A simple rule set to send notifications	Humidity and temperature values sent to a mobile application, so the caregiver can remotely adjust its levels. Notification of prolonged immobility.	Test performed with a mannequin, but results are not discussed
[15]	Pressure sensors	Gray image	A fuzzy approach to pre-process the signal, convolution NN for classification	NA	Good posture classification, but not tested with patient data
[16]	Pressure sensors	Histograms of oriented gradients and local binary patterns are computed from the original pressure image	Feed forward NN	NA	Competitive four posture classification when compared with state-of-the-art approaches
[17]	Humidity and temperature RFID sensors	Sensor values	Not described	Position change notifications	Tested in two homes with four patients, but with no significant results from the sensors
[18]	Accelerometer, gyroscope, magnetometer, light sensor and a thermometer for prototype 1, four pressure sensors for prototype 2	Nine output channels for prototype 1, for pressure measures for prototype 2	Not described	NA	Clinical trial with 10 patients, relatively high success in detecting repositioning
[19]	Pressure from Force Sensitive Application (FSA) pressure mapping mattresses.	Sensor values regarding both the average body size by age and the frequent location of bedsores	A sensing algorithm for fall risk assessment and pressure ulcer occurrence warning	Alerts using Google Firebase Cloud Messaging	Works well for several human models of various heights and weights
[20]	Pressure, using a commercial pressure mat	The input is a frame of the body pressure map. The pressure mat has 2048 sensor points.	Deep learning for subject identification in three common sleeping postures using statistical features extracted from the pressure distribution. Use of Restricted Boltzmann Machines to pretrain the model and find proper initial weights for training deep belief networks.	NA	Experiments showed promising results in subject identification and further validated the personal sleeping style of each participant
[21]	Force-sensitive sensor-strips placed under the patient on the bed on specific pressure zones, and a smart camera with embedded image processing	Values of the pressure sensors	Image processing algorithm developed to enhance the accuracy of determining whether the patient was moved	Displays/alerts for the medical staff	Initial results are very encouraging

Table 4. Cont.

	Sensors	Features	Algorithm	Recommendation	Results
[22]	Pressure sensors and patient's body weight	Pressure sensing pad, containing force sensing resistor sensors, is used to detect patient's body posture	Recognition algorithm based on fuzzy theory	The system notifies caregivers to change the patient's body posture	The average posture recognition accuracy of this proposed module is 92%
[23]	Pressure sensor pad with 18 × 12 array of force sensing resistors	Pressure maps	Fuzzy c-means (FCM) algorithm used to transform the pressure contours and identify regions of interest (ROI) with high pressure for pressure ulcer prevention. An artificial neural network (ANN) model was applied for posture classification using the reduced feature vector.	NA	Posture classification
[24]	Temperature and pressure values from an array of sensors to prevent pressure ulcers (64 pressure and 64 temperature sensors)	Temperature map and pressure vs. time map	A MATLAB software developed to report real-time pressure and temperature maps, retrieve previous maps and risks, and generate alarms	Alarm is generated by the software if the pressure intensity of one sensor exceeded the adjusted threshold, and the pressure duration was longer than the time threshold	The proposed method for detecting posture was verified using a statistical analysis
[25]	Low-resolution pressure sensor array	Pressure maps from values acquired using a pressure sensor array	HOG and SIFT descriptors extracted from the pressure maps, that are considered as gray scale images	NA	The classification of posture pressure maps can be classified with a performance of 99.7%
[26]	Unconstrained ECG data measured from 12 CC electrodes on a bed were used for classification of four basic lying postures.	Average of ECG signals from contacted electrodes	Body posture estimation algorithm based on the QRS (Q wave, R wave, and S wave of ECG) complex of ECG measured capacitively from 12 channels on a bed. The features are extracted based on the morphology of the QRS complex and used in linear discriminant analysis, support vector machines with linear and radial basis function (RBF) kernels, and artificial neural networks (one and two layers).	NA	Body postures
[27]	Pressure sensitive mats. A 3 by 8 fiber optic pressure sensor array, embedded in polymer foam.	Mat software on a laptop receives data via Bluetooth and collects it in a file. A video is also recorded with patient movements.	Subject dependent algorithm that was able to detect when and where pressure points were relieved from underneath a supine subject, without any user inputs or assumptions	NA	The algorithm is able to detect when and where a pressure point was relieved

Table 4. Cont.

Sensors	Features	Algorithm	Recommendation	Results
[28] Used two types of sensor data: (1) posture-independent (e.g., physiological) data, such as blood pressure, and (2) posture-dependent values, such as pressure, temperature, or moisture on each point of body in contact with bed	Pressure images based on values acquired using pressure sensors	Support vector machines (SVM) are used to train a model for assessing a patient's risk of developing pressure ulcers, by combining the features extracted in the modeling and profiling	The bed has a surface that creates a movable surface that can manipulate a patient without grasping her/him. Machine intelligence is used to analyze data, assess the risk and alert caregivers to intervene at an early stage to prevent pressure ulcers.	NA
[29] Pressure sensors matrix	Values from pressure sensors	Algorithm to determine sleeping postures using Kurtosis and Skewness Estimation Approach, principal component analysis and support vector machines (SVM) for classification	NA	Results show that a 16-sensor configuration can detect the 3 sleeping postures with high accuracy for patients with low mobility. Its accuracy starts to drop when patients move and sleep on different angles.
[30] Piezoresistive pressure sensors	Values of pressure sensors from a mattress of 10 sensors laid in bed to explore 8 states.	Alarm on/off based on pressure variation measured over time	Time-based alarm sent by a message to computer or mobile phone	No results are presented
[31] Passive RFID tags. A 30 × 18 tag matrix on a thin plastic film.	Snapshot (a gray-scale image that consists of 30 × 18 pixels) of sleeping postures.	Sleep postures are identified in TagSheet by pre-processing each snapshot using Gaussian blur, Ostu-based binary conversion of the gray-level image and removal of scattered pixels.	NA	According to authors, experimental results show that TagSheet has a great performance

Article [15] describes a methodology to classify in-bed human posture for the prevention of pressure ulcers using pressure mat sensors. Fuzzy processing is applied to the raw values provided by the sensors to produce a gray-scale image representing the patient's posture. A dataset produced by data augmentation was used to compare two convolutional neural network models. The approach produced good classification results, but it was trained with data from simulated patients, so it is still at an early stage of development.

In article [16], a novel approach to feature extraction from data acquired from a pressure mattress is presented. Discriminative features, such as histograms of oriented gradients and local binary patterns, are computed from the original pressure image and used to train a simple feedforward neural network to recognize four body lying postures, discriminating between supine and prone with a classification accuracy superior to several other state-of-the-art approaches. The system was still only tested with data from healthy subjects and was still not used in a practical context.

Article [20] reports the results of a data collection study using two commercial pressure mats. Authors have employed an algorithm based on DL for subject identification in the three common sleeping postures using statistical features extracted from the pressure distribution. This approach incorporated Restricted Boltzmann Machines to pretrain the

model and find proper initial weights for training the deep belief networks. Experiments showed promising results in subject identification and further validated the personal sleeping style of each participant.

In article [23], an approach is presented in which, from pressure images gathered from a developed sensor pad system, an activity scoring mechanism was applied for differentiating rest and movement periods. The fuzzy c-means (FCM) algorithm was used to transform the pressure contours and identify regions of interest with high pressure for pressure ulcer prevention. An artificial NN model was applied for posture classification using the reduced feature vector. The output is the posture classification.

Article [25] presents a system for posture recognition of lying-down human bodies using a low-resolution pressure sensor array. Four basic positions were considered in the study. The pressure maps are obtained from an array of pressure units. In one of the system's modules, image descriptors are computed. An image descriptor is a vector that represents the most relevant features in an image. HOG and SIFT descriptors were extracted from the pressure maps, that are represented by gray scale images. The classification is performed using classification models and a majority voting scheme to output a prediction, according to the classification results, for each classification model. The experiments show that the classification of posture pressure maps can be classified with a performance of 99.7% using a support vector machine with a linear kernel.

Article [27] explores an algorithmic approach for pressure ulcer prevention that does not require any user inputs, makes no assumptions about the human body and could eventually be incorporated into an improved pressure ulcer prevention device. Pressure sensitive mats, associated software, a laptop, and a video camera were used to measure and collect pressure signals generated by a supine subject performing 3 movements. Pressure and video (for confirmation purposes) data corresponding to each movement were collected and stored on a laptop. Data for each movement were collected in separate csv files. Every csv file contained a data value for each sensor gathered every 0.1 s. An algorithm was developed to detect which of six pressure points (underneath each shoulder blade, each hip and each foot) had been lifted off the bed and when this occurred. The study demonstrates the potential of the algorithm to detect when and where a pressure point was relieved.

Article [31] presents a sleep monitoring system, called TagSheet, based on passive RFID tags, which provides a convenient, non-intrusive and comfortable way of monitoring 6 sleeping postures. The authors deployed a 30×18 tag matrix on a thin plastic film, which is placed under a mattress. Sleep postures are identified in TagSheet by pre-processing each snapshot (a gray-scale image that consists of 30×18 pixels) using Gaussian blur, Otsu-based binary conversion of the gray-level image and removal of scattered pixels. The system also estimates the respiration rate.

The articles described in the previous paragraphs generally produce very good results in posture classification, and this contribution is important, since detecting changes in the patient's posture is an essential step in most of the reviewed approaches to PU prevention. Nevertheless, on its own, posture detection is not enough to fight PU, and additional outputs must be provided, so that this kind of system can be useful to healthcare providers. From the 17 approaches that use pressure sensors, 6 provide information with more direct usefulness for caregivers, including notifications of changes in the patient's position, monitoring of this or other factors, or both. This group of works, described in the following paragraphs, take posture classification a step forward by making it a useful component of larger systems.

In article [12], an Elder Care System is proposed for monitoring elderly patients on a bed equipped with their system. This includes a notification system, an in-bed position prediction system and a real-time monitoring system. In-bed posture detection is made using vibrational signals obtained via piezoelectric sensors, and pressure signals obtained from weight sensors. The wave signs from the sensors are used to classify the users' position using a neural network and a Bayesian network. A web app is available to the system admin to monitor signals and adjust parameters. The system notifies caregivers using a

popular mobile messenger application. Notifications include getting out of bed (using the sequence lying, sitting, and off-bed positions), period in the same position and too frequent movement. Parameters for these notifications can be adjusted. The authors reported some problems with the system when deployed in households, with its performance being affected by several factors, such as harmonic frequency of electrical devices, type of bed and different activities at each household.

Article [21] presents a hybrid solution using force-sensitive sensor-strips placed under the patient on the bed on specific pressure zones, and a smart camera with embedded image processing. Using both image processing and force sensors, an accurate account of the patient's position can be kept continuously, and the duration of inactivity can be determined. An innovative image processing algorithm was developed to enhance the accuracy of determining whether the patient was moved or not. The goal is to activate an alarm if the patient does not have the required spontaneous or nurse-assisted change of posture at predetermined time intervals. This timeout value depends upon the individual patient and can be determined by the doctors at the time of admittance. The activation of alarms when movement is not detected will allow for frequent nursing intervention and thus avoidance of pressure bedsores. The camera captures images to determine whether the patient moved or not.

Article [22] presents a system that continuously detects the patient's body posture and records the length of time for each body posture. The input consists of pressure sensor data and the patient's body weight data, and the output is the patient's bed posture. If the patient remains in the same body posture long enough to develop pressure ulcers, the system notifies caregivers to change the patient's body posture. A pressure sensing pad, containing force-sensing resistor sensors, is used to detect the patient's body posture. A bed posture recognition algorithm based on fuzzy theory is used. The algorithm can detect the patient's bed posture whether it is right lateral decubitus, left lateral decubitus or supine. The detected information of the patient's body posture can be then transmitted to the server of the healthcare center by the communication module to perform the functions of recording and notification. Experimental results showed that the average posture recognition accuracy of the proposed method is 92%.

Article [24] presents an approach that consists of sampling temperature and pressure values from an array of sensors to prevent pressure ulcers. Using MATLAB, a software was developed to report real-time pressure and temperature maps, retrieve previous maps and risks, and generate alarms. The alarm is generated by the software if the pressure intensity of one sensor exceeds the adjusted threshold, and the pressure duration is longer than the time threshold. Moreover, the temperature map corresponding to the same risk condition was checked to find whether there was any significant temperature change in areas experiencing excessive pressure. The temperature changes could be used for identifying pressure ulcer development. Authors conclude that identifying the different sitting postures of a patient and including this information in an alarm setting of the system may be helpful.

Article [29] describes the use of Kurtosis and skewness estimation, principal component analysis and support vector machines for sleeping posture classification using a cost-effective pressure sensitive mattress. Different sensor configurations of pressure sensing beds with the same type of pressure sensor are presented. The system has four tiers, including one composed of an intelligence unit and application container to perform various levels of sensor processing and management in distributed ways. There is also a client tier that provides live pressure readings, subject states, and clinical operations through visualization and user interfaces. The results presented show the detection of three sleeping postures with high accuracy for patients with low mobility. However, accuracy starts to drop when patients move and sleep in different angles. The proposed two-level data fusion architecture of a pressure sensitive bed system was also evaluated using pressure sensor layouts and posture classification algorithms.

Article [30] presents an alarm system solution based on pressure readings. An array of piezoresistive pressure sensors placed in a bed mattress are used. If the weight distribution remains constant for some time (e.g., 100 min), the system determines that the patient has not moved and notifies the nursing staff, sending messages to the computer or mobile phone of the caregiver. The study categorized the major patient positions into 8 states. Each state is associated with different pressure levels as sensed by 10 sensors in the mattress. This system senses and determines bed exit and prolonged bed rest.

The most complete systems for pressure ulcer prevention try to provide some form of prediction of future occurrence of this type of injury. These are the most useful to health care providers, since they can further help to prevent the initial occurrence of the lesion, by taking additional measures to mitigate the factors that may cause it. From the 17 articles analyzed that use pressure information, only two, described in the next paragraph, have predictive abilities.

Article [19] presents a real-time pressure-sensing algorithm that can decide on the possibilities of bedsores and falling accidents by considering both the intensity and the duration of pressure of specific body parts. A design and implementation of a smart bed is presented. In the bed, several pressure sensors are deployed underneath the mattress cover to consider both people's standard physical characteristics and the specific body parts where bedsores commonly occur. The body area is divided into three vertical areas and three horizontal areas. Each microcontroller unit manages pressure-sensing information in one of the body regions divided horizontally. Experimental results demonstrate that a prototype works well for several human models of various heights and weights. In the case of a high possibility of a bedsore or a falling accident from a bed, an alarm message is sent to the caregiver's smart device immediately via the Google FCM (Firebase Cloud Messaging) server. A sensing algorithm is presented for fall risk assessment and pressure ulcer occurrence warning. If the ulcer position is depressed for more than 30 min, a warning message is generated every five minutes. To prevent ulcer occurrence, the algorithm performs tests to determine the patient's posture (supine, repose, left position, right position, half position, etc.) according to the pressure pattern applied to the bed.

Article [28] presents the implementation of a proof-of-concept platform for pressure ulcer monitoring and prevention. The platform has combined four key aspects of a support system, i.e., data collection, modelling, ML, and acting. It uses two types of sensor data: (1) posture-independent (e.g., physiological) data, such as blood pressure, and (2) posture-dependent values, such as pressure, temperature, or moisture on each point of body in contact with bed. ML techniques are applied to train a model for assessing a patient's risk of developing pressure ulcer, by combining the features extracted in the modelling and profiling unit. Moreover, the bed has a surface that creates a movable surface that can manipulate a patient without grasping her/him.

The remaining 2 articles, from the 17 that use pressure information, do not directly use that information to classify the patient's posture. Instead, in those articles, that information is used in combination with information from other sensors to detect if the patient has moved and to act accordingly, e.g., by sending notifications to the healthcare provider. These approaches, described in the next paragraphs, do not make full use of pressure information, and cannot provide the healthcare professional with as much useful information as the ones that can identify the patient's lying position and consequently discriminate between the different postures it can assume.

In article [14], an IoT-based approach is proposed to prevent pressure ulcers. The system includes humidity and temperature sensors, as well as force sensors to measure the pressure on the patient's skin. This system also has actuators, namely two cooling and heating ventilation kits that release cold or hot air as needed by the patient's situation. The caregiver receives a mobile notification about the lack of mobility of the patient if the monitorization of the pressure sensors detects that the patient has not moved in a given period of time. Information about the humidity and temperature sensors' readings is also sent to the mobile application and then the caregiver can choose to activate a new

cooling or heating level for the patient through the available actuators. The system can also be configured so that this decision is taken automatically. Tests were performed using a mannequin, but specific results are not discussed.

Article [17] describes a Geriatric Home Care System that includes passive RFID sensors that are installed in the patient's bed. The sensors can detect the presence of the patient and monitor humidity and temperature values. These values can influence the development of pressure ulcers. The authors also intend to develop a mattress that will not only maintain the alternation of position, but that can also detect if any bone prominence is above the pressure limits even when the standard time between change of position is not exceeded. Information gathered from the sensors and notifications for position change is sent to the caregiver through a proprietary gateway. The article does not describe the used algorithms.

Finally, from the 21 articles selected for analysis, 4 do not rely on pressure information for pressure ulcer prevention. Instead, changes in position are detected using different types of sensors, such as accelerometers and gyroscopes. These approaches can be less expensive than the ones based on pressure information, which frequently require complex sensor mats. Their primary disadvantage, similar to the previous group, is that posture classification and pressure maps are not available to provide caregivers with richer information. These approaches are described in the next paragraphs.

Article [11] presents the use of a single tri-axial accelerometer sensor to detect lying postures. The work identifies the amplitude, mean, minimum and maximum values of the lateral and vertical axes as the optimal set of time-domain features to use with a traditional ML scheme, ensemble trees, in this task. Thighs and chest were determined to be the optimal placement site for a single accelerometer. The results were marginally improved when using a deep recurrent neural network, AdaLSTM. The work was not used in a practical context.

In article [13], the authors describe a fuzzy monitoring system for postural changes to avoid pressure ulcers. In-bed postures are recognized by means of inertial sensors attached to the patients' socks and T-shirt. The sensor information produces a tri-axial inertial representation (x, y, z) , resulting in three data streams that are used for in-bed posture classification. A support vector machine was trained to recognize six different postures with a precision higher than 99%. The authors also developed a knowledge-based fuzzy method that calculates the priority of postural changes from an expert-defined protocol, which is defined by a set of postures L that are changed every time interval T . The system was used to model three heterogeneous in-bed postural protocols and can alert caregivers for position change according to those protocols. This approach was tested on 7 users in controlled environments at the University of Jaen with some success, but it has not yet been tested in a real environment.

Article [18] compares two different prototype pressure ulcer monitoring platform devices to promote the optimal bed repositioning of hospitalized patients to prevent pressure ulcers. One prototype fits on a patient gown or clothing near the chest and has several sensors: accelerometer, gyroscope, magnetometer, light sensor, and a thermometer. The second prototype uses four sensor pads placed under the four wheels of the bed to measure changes in body weight distribution. The algorithms used to detect movement are not described. The prototypes were tested in a clinical trial over a 5-month period with 10 human subjects and achieved 85% success in detection of repositioning events. The authors propose to extend the system to send notifications to the caregivers.

Article [26] presents a novel body posture detection algorithm based on ECG. It proposes a body posture estimation algorithm based on the QRS complex of ECG measured capacitively from 12 channels on a bed. The main advantages of this contribution are: (1) the system can be applied for multiple subjects without individual calibration; (2) users do not need to care about the battery because the system uses a power adaptor; (3) users do not need to wear any devices on their body; and (4) the system is built up on modality and fewer sensors. The authors argue that, unlike other sensors, the developed system

and algorithm have the potential for daily ECG monitoring and sleep monitoring in an unobtrusive way, as well as for body posture detection.

For a different—and easier to analyze visually—way of presenting the relations between the outputs of each of the selected work with the sensors and algorithms being used, Figures 2 and 3 present bubble diagrams where the bubble size for each data pair is proportional to the number of works that match that respective pair. These charts complement the previous more descriptive analysis and facilitate the discussion in Section 4.

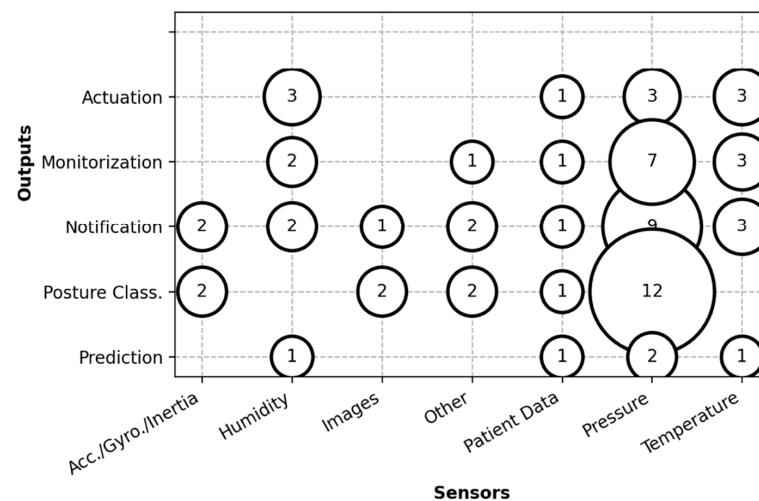


Figure 2. Bubble diagram representing the relation between the outputs of each study and the used sensors. Bubble size is proportional to the number of studies.

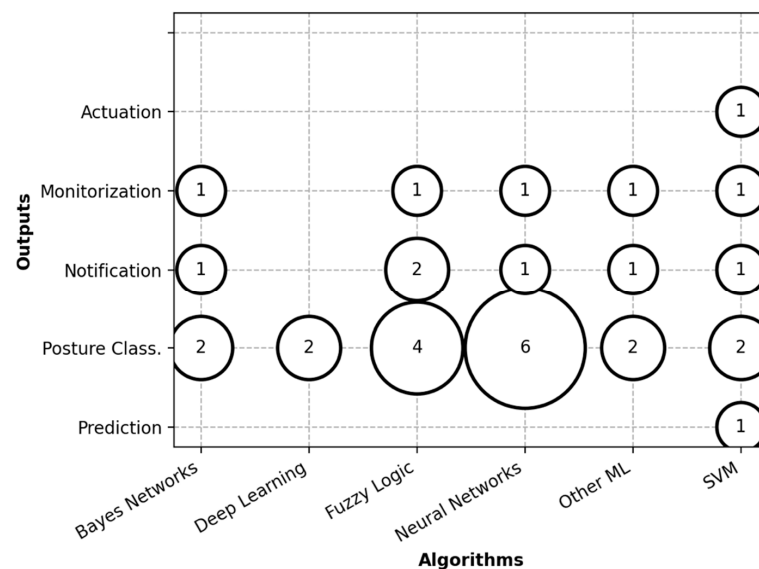


Figure 3. Bubble diagram representing the relation between the outputs of each study and the used algorithms. Bubble size is proportional to the number of studies.

4. Discussion and Findings

The analyzed articles provided a vast panoramic of the technical approaches used to gather sensorial information deemed useful for pressure ulcer prevention. The minimum goal for the generality of the reviewed works was to acquire the information needed to classify the lying position of the patient. The most common approach, as expected, included some sort of pressure sensors usually placed below the patient's sheets. This does not mean that this approach is the only one successful, as several other methods with satisfactory results are described in the analyzed articles [11,13,18,26]. These include

approaches based or complemented by several types of inertial sensors [11,13,18], video images [21,27] and others [26]. The fact that pressure sensors do not need to be attached to the patient, are relatively flexible in the information they provide, are easily installed, and can be used successfully with different algorithms for lying position classification seems to have resulted in an increase, over the years, of the number of approaches based on this type of sensor. Several approaches use additional sensory information that can be relevant to predict pressure ulcer development. The most common are temperature and humidity sensors [14,17,18,24,28]; however, from the reviewed papers, it seems their information is mostly used to control some form of bed installed actuators (e.g., fans).

The information acquired from the sensors was processed in varying ways in accordance with the sensor type. Mostly, it included simple processing steps of the numerical raw data obtained from the sensors, but, mainly in the case of the pressure sensors, some effort was made by various authors to obtain higher level features from the original data matrix (e.g., [15,16]). There were different techniques applied, but the most common seems to be some the fuzzy logic-based technique to transform the raw data into more informative features [15,22,23]. From an overall analysis of the results provided by the articles for lying position classification, it does not appear to exist a meaningful difference in results that is correlated with the level of preprocessing. In fact, the algorithms that used reasonably unprocessed pressure data were able to achieve classification results, similar to those obtained by algorithms applied to more complex features.

From our review, we could identify three stages where complex algorithms can be used in pressure ulcer prevention approaches. The first stage is in the preprocessing of data to produce higher level features. As stated in the previous paragraph, in this stage the processing was usually relatively simple, and only in a few cases more sophisticated algorithms (e.g., based in fuzzy logic) were used (e.g., [15,22,23]). The second stage, which was the one where the most significant effort was clearly placed in the analyzed articles, was the lying position classification stage. Lying position (and its change) is clearly the most important factor for pressure ulcer prevention, and from the analyzed articles we can conclude it can successfully be identified using many combinations of different sensors and algorithms. We already concluded that some form of pressure sensor matrix is possibly the most common sensor used. Regarding the classification algorithms, we found successful approaches based on neural networks (including deep networks) (e.g., [11,12,15,16]), support vector machines [13,26,28,29], Bayesian networks [12], principal component analysis [26,29] and tree- or rule-based systems [11,14]. Overall, in the set of analyzed articles, neural network-based approaches are the most popular, followed by support vector machines. This result was expected since we are discussing a classification problem and both deep learning techniques and support vector machines have clearly been established as state-of-the-art approaches for these problems over the last decade.

The third stage for possible complex algorithm utilization, and the most related with this work, is the stage at which the decision towards ulcer avoidance or prevention is made, considering information about the lying position and other relevant information obtained from other sensors or other sources (patient history, etc.). Unfortunately, most of reviewed articles stop at lying position classification. The ones that move forward tend to contribute to pressure ulcer prevention in the following ways:

- Monitoring [12,14,17,22,24,29]—Information gathered from the sensors is stored in a server and can be accessed remotely by caregivers. This can include pressure maps for the platform or other relevant values (e.g., time since last change in position, physiological data, etc.). There are also some approaches where historical data regarding some of those values can be displayed, usually in graphical form. Mobile applications are often used by caregivers to access this information.
- Notifications [12–14,17,18,21,22,24,30,31]—The most common approach to ulcer prevention based on sensor information tends to be the raising of alarms in the caregivers' mobile devices running a dedicated app. The most important alarm is raised when the patient is resting in the same position for longer than a specified amount of time. This

reduces the risk of the patient resting for extended periods in the same position (the most common cause of pressure ulcers) and can save the caregiver's time if the patient changes position spontaneously. Other alarms can be raised if the patient moves too much—when restlessness is a risk—or gets up from bed (maybe falling). Generally, the algorithms used for these alarms are very simple, relying in a few predefined rules to make the decision to raise an alarm or not.

- Personalization, e.g., [13,22,28]—Closely related with the previous points, several applications allow for the personalization of some items, both regarding visualization and alarms, dependent on the specific patient being monitored. Data to be visualized can be selected if it is relevant for that particular patient. Information regarding the patient's medical history can be inputted into the application, to be displayed or used in some decision-making process. A specific example of this can be observed when patient dependent time limits are used for each lying position, e.g., to ensure less time is passed in a position that already has an ulcer.
- Actuation [14,17,28]—Some approaches use beds with actuators. These are not common and tend to be very expensive. As an example, temperature and humidity sensors can be used in conjunction with fans to control humidity and temperature. A few beds have pressure actuators that can control pressure in specific areas. Some of these actuators can be controlled remotely by the caregivers.
- Prediction [19,28]—The approaches we were most interested in were the ones that offered some kind of prediction of pressure ulcer occurrence based on diverse sources of information, both sensor-based and obtained in other ways, such as patient history or physiological data. Only two of the analyzed articles tackled this issue and, of these, only [28] provided a complete developed prediction approach, where instances constructed from both posture and non-posture data (only blood pressure is specifically mentioned) are labeled by health professionals and used to build a prediction model using a support vector machine algorithm. While the results of this approach are only validated in a simulated environment, and are not very conclusive, it still remains the only approach we have identified at this stage that tries to predict a probability of pressure ulcer occurrence based on multiple data streams and a complex ML algorithm.

After reviewing the selected articles, we can state that very good results can be achieved in lying position detection using a variety of techniques. Unfortunately, these results are rarely tested in real conditions and are obtained in some form of simulated environment. In the approaches that were effectively deployed or tested with real patients, it is frequent to find observations regarding the effects of those environments on the sensors and, consequently, on the classification accuracy [12,18,29]. For example, some studies mention that the use of cushions by caregivers to relieve pressure can interfere in the pressure sensors accuracy. Nevertheless, as can be seen in Table 3, several approaches were deployed and successfully used to raise alarms that were helpful to the caregivers and health professionals, namely as a warning system for the position changing cycle and as an alarm for dangerous situations, such as restlessness or getting up of bed (or falling). Unfortunately, if this review identified successful approaches to the lying position detection problem with clear practical implications, it was less successful in finding approaches able to use this information in conjunction with other data sources to effectively predict pressure ulcer development risk.

5. A General Architecture for an Intelligent PU Prevention System

The final goal of any pressure ulcer prevention system should be to assist the healthcare professional in making the correct decisions that lead to a favorable outcome, i.e., the avoidance or delay of pressure ulcer occurrence, when they are not present. If pressure ulcers are already present, the system goal should be to avoid the worsening of the existing lesions and the occurrence of new ones.

The analysis performed in this review leads us to conclude that sensor-based systems used for pressure ulcer prevention very rarely achieve an effective connection between the

sensor information gathering stage, with possible detection of the lying position and its duration, and the decision-making process performed by the healthcare professional. Even so, it is possible to identify three decision-making components that such a system should incorporate to assist the healthcare professional at distinct stages of the decision-making process. The first component is visualization. Information regarding the status of the patient, as well as historical data, stored in the information system, should be accessible by the healthcare professional using some form of mobile application. This information can then be used to make more informed decisions. The second component includes alarms generated by the system. Here, the health-care provider assumes a more passive stance, as these alarms should be actively pushed by the system into the mobile applications. The healthcare provider can then decide to act based on the warning/alarm received. The final component is a predictive component that should be able to use ML techniques on the collected data to provide some prognosis on how the ulceration process will evolve for a given patient for whom intrinsic and extrinsic factors are collected. The healthcare professional can then use this information to choose a protocol that may lead to a better outcome. In the next paragraphs, each one of these components is described in more detail.

Visualization component—A major component of the information to be displayed in the visualization component is the pressure map returned by the sensor system (e.g., [20,22,23]). The lying position and possible alarms raised by the sensor system should also be visualized. In addition to this extrinsic information, intrinsic data related to pressure ulcer risk should also be accessible. The healthcare professional should also have access to historical data regarding previous alarms, warnings, and occurrences regarding each patient. Ideally all intrinsic and extrinsic data that is relevant for pressure ulcers occurrence and development should be easily accessible to the healthcare professional through mobile applications. This will allow the professional to define and follow the execution of a repositioning protocol or any other proceeding that is adequate for a specific patient.

Alarm component—The most common decision-making assistance mechanism found in the literature analysis is the repositioning alarm (e.g., [12–14]), since immobilization in the same position for extended periods of time is still the most important risk factor for pressure ulcer occurrence. Most of the approaches discussed in the previous sections perform some form of lying position identification (e.g., [12,14–16]), so that a caregiver can be sent an alarm if a predefined time period in the same position is surpassed. Ideally, the caregiver should be able to set personalized time limits for each patient and position, since a unique interval may not be appropriate for a patient with different ulcers with variable degree of gravity. The system should be able to assess if the patient changed position on its own and alert the caregiver or health professional if a threshold for a given position is reached. From the literature analysis, it is clear that pressure data can also be used to raise alerts in other possibly dangerous situations [12,19,30]. These include detection of the patient leaving the bed (or falling) when no pressure is felt for a given period of time and restlessness (when the patient changes positions more than some limit number of times in a pre-defined period). These alarms should again be customizable (including disabling) by the health professional. Assuming the sensor system can detect positional change, these alarms will be easily implemented using a simple set of rules.

Predictive component—The development of predictive models for pressure ulcer occurrence and/or progression has been notoriously difficult, as can be attested by the almost absence of fully documented instances of this type of work in the bibliography analyzed in the previous sections, where only [19,28] tackled this component. Ideally, we would like to build a model based on the data of previous patients, which, given the information of a new patient, could make useful predictions in terms of ulcer occurrence and/or progression after a predefined period of time. The data used to build the model should include both intrinsic data, recorded by the healthcare professional, and extrinsic information, available through the sensor system. A consequence of the rarity of previously developed models is the lack of freely available datasets that are essential for predictive data analysis algorithms, e.g., ML algorithms. This makes the development of predictive

systems hard, since there is no initial data to feed the ML algorithms to produce a model, as well as to validate it. This data, especially for a new system with extrinsic specificities, e.g., a new sensor system, can only be acquired from patients in a real-world environment. The system must focus on recording the intrinsic and extrinsic information of each patient, at predefined intervals, to build a data set that can posteriorly be fed to a ML algorithm. After enough data is collected, models can be built and improved periodically and used to give the healthcare professional predictive information that can help to define the protocol for a given patient. From the analysis of previous work, neural networks (e.g., [11,12,15,16]) and support vector machines [13,26,28,29] appear to be suitable candidate algorithms to be used for the ML task. While being state-of-the-art algorithms in this field, they are both what can be called black box algorithms, in the sense that the prediction is very hard to explain based on the model. Other algorithms, e.g., tree- and rule-based algorithms, produce models that are easy to read, and it must be discussed with the healthcare professionals if this is a relevant factor in the choice of the final algorithm. The chosen algorithms can be implemented in the system and proof-of-concept tested with synthetic data.

In Figure 4, we present an architectural diagram that depicts the integration of the decision-making components described in this Section (visualization, alarm, and predictive components) into a general pressure ulcer prevention system, such as SensoMatt. When compared to general architectures that support intelligent decision making in the healthcare context, such as the one presented in [32], the main characteristics that differentiate the proposed architecture are the clear separation between the Data Acquisition, Data Processing and Data Visualization modules as well as the explicit inclusion and delineation of the specific components proposed in this section, including the Visualization, Alarms, and Predictive components. The same characteristics also differentiate our proposal from more specific architectures found in the reviewed literature (e.g., [28]).

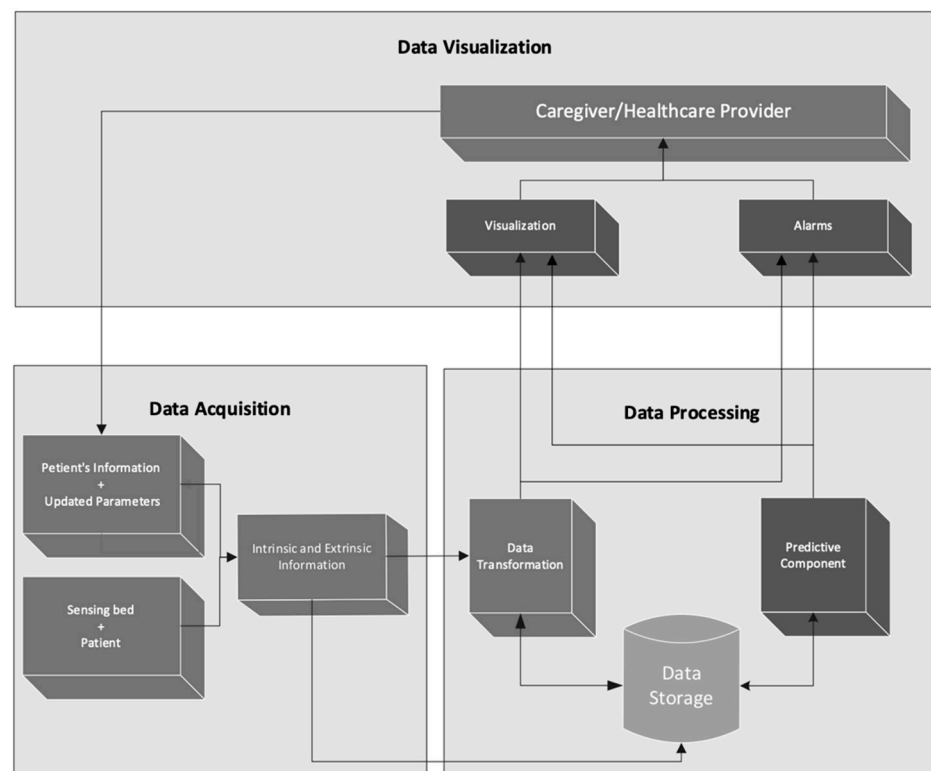


Figure 4. Architectural diagram representing the integration of the visualization, alarm and predictive components in a pressure ulcer prevention system, such as SensoMatt.

The implementation stage of the SensoMatt project, which will instantiate the proposed architecture, is at an early stage. We propose to implement the system using webservice

to share functionalities and data between modules. Implementation will also follow a multi-platform path, to implement client applications in the Data Visualization module for the major mobile application platforms.

6. Conclusions and Future Work

In this article, we performed a systematic review of the literature related to sensor-based pressure ulcer prevention using intelligent algorithms. After selecting and reviewing the relevant articles, we identified three stages where intelligent algorithms are being used to help in pressure ulcer prevention and management. These include preprocessing of data to produce higher level features, lying position classification and decision-making aids for health professionals. We concluded that most sensor-based approaches to PU prevention are mainly concerned with lying position classification using simulated environments and only a few were deployed with real patients and/or raised alarms that facilitated the work of caregivers and health professionals with these patients. We also found that very few approaches described in the literature effectively integrate sensor-collected data, lying position and other intrinsic and extrinsic information in an effective decision-making aiding system for pressure ulcer prevention and mitigation. Based on these findings and the most interesting contributions of the reviewed works, we laid out guidelines for the general architecture of an intelligent PU prevention system, as we hope to see implemented in the SensoMatt project. This architecture is organized around three intelligent modules: a visualization component, an alarm component, and a predictive component.

As the SensoMatt project moves forward, work is being carried out in several fronts. A robust process for pressure data collection and lying position determination is being developed. An information system to support the proposed architecture, including back-office storage of relevant information and mobile applications for healthcare professionals is being designed and implemented, with specific care being taken to ensure that privacy, security, and other specific regulations in the healthcare field are fully met. Work is also being conducted with our healthcare professional partners to instantiate different aspects of the proposed system, including the requirements for the apps being developed, the definition of the intrinsic and extrinsic information that is both useful and practical to store in the information system and the several aspects of the visualization, alarm and predictive components that these professionals consider more helpful to manage patients at risk of developing—or that already have developed—pressure ulcers.

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References

1. Bluestein, D.; Javaheri, A. Pressure ulcers: Prevention, evaluation, and management. *Am. Fam. Physicians* **2008**, *78*, 1186–1194.
2. Garcia, A.D.; Thomas, D.R. Assessment and management of chronic pressure ulcers in the elderly. *Med. Clin. N. Am.* **2006**, *90*, 925–944. [[CrossRef](#)]
3. Haesler, E. (Ed.) National Pressure Ulcer Advisory Panel, European Pressure Ulcer Advisory Panel and Pan Pacific Pressure Injury Alliance. In *Prevention and Treatment of Pressure Ulcers: Quick Reference Guide*; Cambridge Media: Osborne Park, Australia, 2014.
4. National Institute for Health and Care Excellence: Pressure Ulcers. Quality Standard [QS89]. 2015. Available online: <https://www.nice.org.uk/guidance/qs89> (accessed on 6 October 2021).

5. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [[CrossRef](#)] [[PubMed](#)]
6. Marchione, F.G.; Araújo, L.M.Q.; Araújo, L. V. Approaches that use software to support the prevention of pressure ulcer: A systematic review. *Int. J. Med. Inform.* **2015**, *84*, 725–736. [[CrossRef](#)] [[PubMed](#)]
7. Jiang, M.; Ma, Y.; Guo, S.; Jin, L.; Lv, L.; Han, L.; An, N. Using Machine Learning Technologies in Pressure Injury Management: Systematic Review. *JMIR Med. Inf.* **2021**, *9*, e25704. [[CrossRef](#)] [[PubMed](#)]
8. Araujo, S.M.; Sousa, P.; Dutra, I. Clinical Decision Support Systems for Pressure Ulcer Management: Systematic Review. *JMIR Med. Inf.* **2020**, *8*, e21621. [[CrossRef](#)] [[PubMed](#)]
9. Zahia, S.; Garcia Zapirain, M.B.; Sevillano, X.; González, A.; Kim, P.J.; Elmaghraby, A. Pressure injury image analysis with machine learning techniques: A systematic review on previous and possible future methods. *Artif. Intell. Med.* **2020**, *102*, 101742. [[CrossRef](#)] [[PubMed](#)]
10. Koeppe, J.; Baron, M.V.; Hernandez Martins, P.R.; Brandenburg, C.; Kira, A.T.F.; Trindade, V.D.; Ley Dominguez, L.M.; Carneiro, M.; Frozay, R.; Possuelo, L.G.; et al. The Quality of Mobile Apps Used for the Identification of Pressure Ulcers in Adults: Systematic Survey and Review of Apps in App Stores. *JMIR mHealth uHealth* **2020**, *8*, e14266. [[CrossRef](#)] [[PubMed](#)]
11. Alinia, P.; Samadani, A.; Milosevic, M.; Ghasemzadeh, H.; Parvaneh, S. Pervasive Lying Posture Tracking. *Sensors* **2020**, *20*, 5953. [[CrossRef](#)] [[PubMed](#)]
12. Pongthanisorn, G.; Viriyavit, W.; Prakayapan, T.; Deepaisam, S.; Somlertlamvanich, V. ECS: Elderly Care System for Fall and Bedsore Prevention using Non-Constraint Sensor. In Proceedings of the 2020 International Electronics Symposium (IES), Surabaya, Indonesia, 29–30 September 2020; pp. 340–344. [[CrossRef](#)]
13. Bernal Monroy, E.; Polo Rodríguez, A.; Estevez, M.; Medina, J. Fuzzy Monitoring of In-bed Postural Changes for the Prevention of Pressure Ulcers using Inertial Sensors Attached to Clothing. *J. Biomed. Inform.* **2020**, *107*, 103476. [[CrossRef](#)] [[PubMed](#)]
14. Abdelmoghith, A.; Shaaban, R.; Alsheghri, Z.; Ismail, L. IoT-Based Healthcare Monitoring System: Bedsores Prevention. In Proceedings of the 2020 Fourth World Conference on Smart Trends in Systems, Security and Sustainability (WorldS4), London, UK, 27–28 July 2020; pp. 64–69. [[CrossRef](#)]
15. Polo Rodríguez, A.; Gil, D.; Nugent, C.; Medina, J. In-Bed Posture Classification from Pressure Mat Sensors for the Prevention of Pressure Ulcers Using Convolutional Neural Networks. In *Bioinformatics and Biomedical Engineering*; Springer: Cham, Switzerland, 2020. [[CrossRef](#)]
16. Matar, G.; Lina, J.-M.; Kaddoum, G. Artificial Neural Network for in-Bed Posture Classification Using Bed-Sheet Pressure Sensors. *IEEE J. Biomed. Health Inform.* **2020**, *24*, 101–110. [[CrossRef](#)] [[PubMed](#)]
17. Barroso, I.; Soares, S.; Rodrigues, V.; Silva, S.; Monteiro, M.; Rainho, C.; Duarte, D.; Valente, A. Assisted Care. In *HCI International 2020—Late Breaking Papers: Universal Access and Inclusive Design*; Springer: Cham, Switzerland, 2020. [[CrossRef](#)]
18. Minter, D.; Simon, P.; Taylor, D.; Jia, W.; Li, Y.; Sun, M.; Rubin, J. Pressure Ulcer Monitoring Platform—A Prospective, Human Subject Clinical Study to Validate Patient Repositioning Monitoring Device to Prevent Pressure Ulcers. *Adv. Wound Care* **2019**, *9*, 28–33. [[CrossRef](#)] [[PubMed](#)]
19. Hong, Y.-S. Smart Care Beds for Elderly Patients with Impaired Mobility. *Wirel. Commun. Mob. Comput.* **2018**, *2018*, 1780904. [[CrossRef](#)]
20. Pouyan, M.B.; Birjandtalab, J.; Heydarzadeh, M.; Nourani, M.; Ostadabbas, S. A pressure map dataset for posture and subject analytics. In Proceedings of the 2017 IEEE EMBS International Conference on Biomedical & Health Informatics (BHI), Orlando, FL, USA, 16–19 February 2017; pp. 65–68. [[CrossRef](#)]
21. Qidwai, U.; Al-Sulaiti, S.; Ahmed, G.; Hegazy, A.; Ilyas, S.K. Intelligent integrated instrumentation platform for monitoring long-term bedridden patients. In Proceedings of the 2016 IEEE EMBS Conference on Biomedical Engineering and Sciences (IECBES), Kuala Lumpur, Malaysia, 4–8 December 2016; pp. 561–564. [[CrossRef](#)]
22. Hsiao, R.-S.; Mi, Z.; Yang, B.-R.; Kau, L.-J.; Bitew, M.A.; Li, T.-Y. Body posture recognition and turning recording system for the care of bed bound patients. *Technol. Health Care* **2016**, *24*, S307–S312. [[CrossRef](#)] [[PubMed](#)]
23. Hung, Y.-W.; Chiu, Y.; Jou, Y.-C.; Chen, W.-H.; Cheng, K.-S. Bed posture classification based on artificial neural network using fuzzy c-means and latent semantic analysis. *J. Chin. Inst. Eng.* **2015**, *38*, 415–425. [[CrossRef](#)]
24. Daneshvarfard, F.; Moghimi, S.; Lotfi, R. Design and Evaluation of a Pressure and Temperature Monitoring System for Pressure Ulcer Prevention. *Iran. J. Med. Phys.* **2014**, *11*, 242–252. [[CrossRef](#)]
25. Cruz-Santos, W.; Beltrán-Herrera, A.; Vázquez-Santacruz, E.; Gamboa-Zúñiga, M. Posture classification of lying down human bodies based on pressure sensors array. In Proceedings of the 2014 International Joint Conference on Neural Networks (IJCNN), Beijing, China, 6–11 July 2014; pp. 533–537. [[CrossRef](#)]
26. Lee, H.J.; Hwang, S.H.; Lee, S.M.; Lim, Y.G.; Park, K.S. Estimation of Body Postures on Bed Using Unconstrained ECG Measurements. *IEEE J. Biomed. Health Inform.* **2013**, *17*, 985–993. [[CrossRef](#)] [[PubMed](#)]
27. Bennett, S.L.; Goubran, R.; Rockwood, K.; Knoefel, F. Monitoring the relief of pressure points for pressure ulcer prevention: A subject dependent approach. In Proceedings of the 2013 IEEE International Symposium on Medical Measurements and Applications (MeMeA), Gatineau, QC, Canada, 4–5 May 2013; pp. 135–138. [[CrossRef](#)]

28. Yousefi, R.; Ostadabbas, S.; Faezipour, M.; Nourani, M.; Ng, V.; Tamil, L.; Bowling, A.; Behan, D.; Pompeo, M. A smart bed platform for monitoring & Ulcer prevention. In Proceedings of the 2011 4th International Conference on Biomedical Engineering and Informatics (BMEI), Shanghai, China, 15–17 October 2011; pp. 1362–1366. [[CrossRef](#)]
29. Hsia, C.C.; Liou, K.J.; Aung, A.P.W.; Foo, V.; Huang, W.; Biswas, J. Analysis and comparison of sleeping posture classification methods using pressure sensitive bed system. In Proceedings of the 2009 Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Minneapolis, MN, USA, 3–6 September 2009; pp. 6131–6134. [[CrossRef](#)]
30. Lee, C.-N.; Yang, S.-C.; Li, C.-K.; Liu, M.-Z.; Kuo, P.-C. Alarm System For Bed Exit And Prolonged Bed Rest. In Proceedings of the 2018 International Conference on Machine Learning and Cybernetics (ICMLC), Chengdu, China, 15–18 July 2018; pp. 439–443. [[CrossRef](#)]
31. Liu, J.; Chen, X.; Chen, S.; Liu, X.; Wang, Y.; Chen, L. TagSheet: Sleeping Posture Recognition with an Unobtrusive Passive Tag Matrix. In Proceedings of the IEEE INFOCOM 2019—IEEE Conference on Computer Communications, Paris, France, 29 April–2 May 2019; pp. 874–882. [[CrossRef](#)]
32. Azeez, N.A.; Oyeniran, S.O.; der Vyver, C.; Misra, S.; Ahuja, R.; Damasevicius, R.; Maskeliunas, R. Diagnosing Oral Ulcers with Bayes Model. In *Innovations in Bio-Inspired Computing and Applications*; Abraham, A., Gandhi, N., Pant, M., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 485–494. [[CrossRef](#)]