CNN Based Smart Sleep Posture Recognition System

**ABSTRACT:** Sleep pattern and posture recognition has become of great interest for a variety of clinical applications. Autonomous and continuous monitoring of sleep postures provides useful information for lowering health risk. Existing systems are designed based on electrocardiogram, cameras and pressure sensors, which are expensive to deploy, intrusive to privacy, or uncomfortable to use. We propose an unobtrusive and affordable Consmart system based on electronic mat called Sleep Mat-e for monitoring the sleep activity and sleep posture of individuals living in residential care facilities. The system uses a pressure sensing mat constructed using piezo-resistive material to be placed on a mattress. The sensors detect the distribution of the body pressure on the mat during sleep and we use Convolution Neural Network (CNN) to analyze collected data and recognize different sleeping postures. The system is capable of recognising the four major postures Faceup, Facedown, Right Lateral, and Left Lateral. A real-time feedback mechanism is also provided through an accompanying smartphone application alerting the users to correct the posture if person is sleeping too close to the edge of the bed and may fall from the bed. It also generates summaries of postures and the activities over a specified period of time. Finally, we conducted experiments to evaluate the acuuracy of the prototype and proposed system achieved a classification accuracy of around 90%.

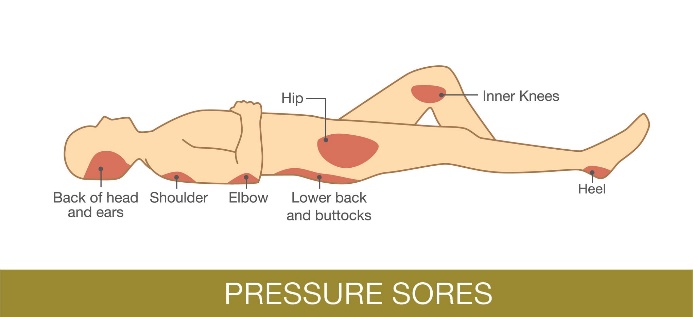
**Keyword:** *Force-sensing resistor, Sleep posture recognition; Sleep activity; Internet of Things; Machine Learning; Healthcare.*

# Introduction

The population of elderly people is on the rise in the world and the number of elderly people in New Zealand, is expected to reach 20% of the total population by 2032 [1]. The elderly tend to suffer from poor sleep quality and this has effects on their physical health, cognitive function, and overall quality of life [2, 3, 4]. Adequate, restful sleep is as important as it allows the body and brain undergo necessary restorative activities. Inadequate sleep leads to reduced alertness and drowsiness [2]. Health issues stemming from poor sleep quality include weakened immune system and cardiovascular disease[5].

Another issue that is prevalent in the elderly population is pressure injuries (PI), that arise due to prolonged sleep in a single posture without moving, as shown in Figure 1. The PI can cause constant pain, loss of mobility, depression, and even death. Studies have found that sleep issues were more prevalent within the residential care population [6]. A report into pressure injuries commissioned by the New Zealand Ministry of Health revealed that the prevalence of PI could be reduced if caregivers could monitor and take proactive action [7].

Furthermore, certain sleep positions and postures are considered to be major cause of sleep apnea [8]. Research has shown that people sleeping in the decubitus position have higher risk of developing subacromial impingement syndrome compared with those who sleep in the supine position [9]. People sleeping in supine position are more likely to develop the symptoms of sleep paralysis [10]. Similarly, sleeping on the right side poses a higher risk of development of transient lower esophageal sphincter relaxation, which is a main factor in nocturnal gastroesophageal reflux [11]. Falling out of bed during sleep is another major risk to the elderly, resulting in injuries and even death in extreme cases.



**Fig. 1** Pressure Sore Face Up [12]

The aforementioned risks can be mitigated if staff actively and regularly monitors the patient at the elderly care facilities. Clinical evidences suggest that body posture during sleep serves as a diagnostic indicator for a variety of chronic diseases and as an aid in medical therapies. Detecting and monitoring these symptoms can be challenging and may also require the use of extra staff resources. This will lead to increased healthcare costs and can be a significant source of stress for the patients, as well as their families. Funding for District Health Boards (DHBs) in 2018 was almost a billion dollars ($983 million) [13, 14] and this is expected to rise, as an increase in the elderly population will require more caregivers at care homes [15]. In 2018 alone, accidental claims amounted to $200 million for fall-related injuries for the age group of 65 and above [16].

The challenges, rising costs of care and effects of sleep related issues on the elderly, motivates the need for a system that can assist medical practitioners and caregivers in residential-care in monitoring patients more efficiently. We propose an autonomous system that is capable of monitoring sleep pattern, sleep posture, actitvities, and alerting about potential fall during the sleep. This will also help people learn about their sleep habits and find ways to improve sleep health by obtainin feedback on their sleep postures and activities. This will not only reduce the cost and burden on the health system but also provides caregivers and healthcare professionals with sleep related data, so that they could implement preventative measures to reduce and manage the risks of poor sleep as necessary. The healthcare community has also emphasized the need and importance of a long-term sleep tracking system to identify trends and help people create personalized sleep goals. The system may be used to assess the sleep efficiency (the ratio of total sleep time to time spent in bed), sleep latency (the duration from bedtime to the onset of sleep). These measures can help physicians detect and diagnose sleep-related disorders such as insomania and sleep apnea [18].

This paper is organized as follows. The following Section II provides the research carried out in the related areas and Section III gives a detailed description of the overall system architecture. System design and implementation are discussed in Sections IV. Experimental results are presented in Section V followed by conclusion at the end.

# Related Work

Sleep is a major part of health and well-being. Researchers have explored diverse techniques on capturing and providing feedback on aspects related to sleep health. In many early studies on sleep postures, an empirical approach was favored and data was collected by interviewing subjects. In recent years, advancements in Internet of Things (IoT) and sensing modalities have enabled researchers to more accurately determine the posture and patterns during sleep.

There are numerous solutions available that in one way or another try to quantify the quality of sleep. These solutions use different techniques to acquire data for an individual’s sleep. In a clinical sleep assessment setting, the current ‘gold standard’ for diagnosing sleep disorders and issues is the use of polysomnography (PSG) [18]. This method involves the measurement of multiple physiological parameters, such as brain activity, blood oxygen level, heart rate, breathing, and leg and eye movements. It also requires a number of sensors and equipment to be physically attached to the patient’s body. Although this method provides accurate results and insight into one’s sleep, it is obtrusive, disruptive, expensive, and requires monitoring in a highly controlled and unnatural setting. Therefore, it is only suitable for medical-supervised evaluations and not feasible for daily use. A similar device called *WatchPAT* [19] is worn on wrist by the subject and comes with a finger clip. It monitors the sleep of the patients within the comfort of their own home and usual sleeping environment. This method is much more informal, however, it is still intrusive in nature as it requires the device to be worn on wrist tightly. This may cause discomfort in subjects, especially, elderly persons.

There are a plethora of readily available smartphone applications that can monitor sleep patterns using built-in sensors [20-24]. *Toss 'N' Turn sense* is an Android app that models the sleep and sleep quality without requiring significant changes in people’s behavior [20]. It collects data from seven sensors found in smartphones and predicts the aspects of sleep quality with an accuracy of 81-83% [20]. *My Sleep APP* [21] monitors the sleep and sends alerts to the caregivers if an anomaly is detected. The nature of the anomaly has not been specified in the research. Similarly, ‘*Sleep as Android*’ [22] and ‘*Runtastic Sleep Better’* [23], *iSleep* [24] also detect various sleep-related events. A number of commercial smartphone applications are also available which include: *Smart Alarm Clock*, *MotionX*, *Sleep Cycle*, *Sleep Bot*, *Sleep Cycle*, *Sleep Tracker*, *Sleep as Android*, *Sleep as Android Paid*. While smartphone applications are easily accessible and convenient for everyday users, they are infeasible as smartphone is required to be placed on the bed meaning one phone is required for each user. This would not be very economical when there are a lot of patients. Lastly, these require user intervention to start and stop the application.

Smartwatches are powerful devices in terms of the sensors that are embedded in it. Sleep sensing using these devices can lower the burden of manual sleep tracking and improve the accuracy of sleep inference at home. The *Fitbit Charge2* [25] and the *Jawbone UP3* [26] are popular commercially available wrist worn sleep trackers used for collecting data about sleep. They have limited functionality and can monitor only movement and heart rate, which can be used as the basis for tracking sleep, but their accuracy is questionable [27]. In addition, wrist worn devices are battery powered and often require Bluetooth connectivity to gather information meaning that it still requires the use of a smartphone for storing and analyzing data. This would result in extra tasks for the caregivers to complete within their daily routines. Lastly, wrist worn systems cannot detect sleep posture.

There are many alternative solutions that are non-intrusive in nature. They are based on pressure sensing or camera based visual data. Normally, these solutions make use of common digital 2D, 3D, and infrared cameras to acquire visual data and then apply image processing and machine learning techniques to recognize different postures [28-30]. For example, [28] used a single 2D camera to acquire image, applied the background subtraction to extract the foreground human body, used projection histogram, and applied support vector machine (SVM) algorithm for posture classification. Some researchers used multiple calibrated cameras camera to build a multi-view Eigen model of human body in terms of its constituent body part and then recognize the posture [30]. Versatility of the data captured is augmented by using different sensor in conjunction with the sensors [31-35]. Lee et [32] used Kinect camera hanged over the bed to classify six sleep positions. They extracted body joint positions using Kinect V2’s own libraries and used the relative position of hands and knees with respect to the spine for classification using a parametric approach. The patient was not allowed to use the blanket. Evaluation and results were not provided by the researcher. [29] used 3D camera together with Microsoft Kinect sensors for analyzing body positions and monitoring the posture of person in residential care. Torres et al. [33] used a combination of depth and infrared cameras together with a pressure mattress to classify among different sleeping postures. Only one scenario with a fixed camera above the bed is used, thus ignoring the alignment problems. Martinez et al. proposed “BAM” descriptor based on depth information collected from a Microsoft Kinect, which could monitor the sleeping posture and movement data [34]. This work is further extended to recognize high level activities such as removing bed covers [35]. [31] used pressure arrays and a single depth camera to build a bed aligned maps (BAMs) al. Although, these computer camera-based methods may appear to be suitable for posture recognition and fall detection field, several problems do exist. They are expensive, sensitive to light, requires installation, and infringement of personal privacy is a concerning issue for computer vision-based posture recognition systems and elderly people may worry that they are being “watched” by cameras.

Another approach exclude the use of cameras and instead use smart bed-type devices in the form of sensors installed on or near the mattress for sleep posture monitoring. These devices comprised Inertial Measurement and Unit (IMU) sensor, 2) wireless sensors (Wi-Fi and RFID), and 3) a dense array of the pressure sensor. Wireless identification and sensing platform (*WISP*) used the y-axis accelerometer [36] and *MediSense* [37] used z-axis gyroscope readings to infer body postures and movement of the patients. *Wi-Sleep* [38] classifies a person’s respiration, six sleep positions, and rollovers by leveraging Wi-Fi signals, i.e., channel state information (CSI), from a pair of TX-RX. *TagSheet* [39] used passive RFID tags taped under a bed sheet or on the surface of mattresses on a bedsheet. Passive tags were powered by radio frequency (RF) signals from an RFID reader, and they communicated with the reader by backscattering the RF signals. By observing the RF signal variance amongst all tags, the reader constructed a coarse-grained gray scale snapshot, analyzed it and could identify six sleep positions as well as estimate the respiration rate. *SMARS* [40] exploited ambient radio signals to recognize sleep stages and assess sleep quality. It used a statistical model that accounted for all reflecting and scattering multipath, allowing an accurate and instantaneous breathing estimation and sleep stages, including wake, rapid eye movement (REM), and non-REM (NREM). *SleepSense* [41] used a Doppler radar-based system that could monitor and classify the sleep-related events by detecting the on-bed movements during sleep based on the radar signal. The Doppler radar sensor is specialized radar that can measure target displacement remotely by using the Doppler Effect. Above mentioned techniques can detect the activities but do not possess the capability to recognize postures.

More recently, research has shifted to pressure sensing techniques as it leverages to not only identify sleep patterns but recognize postures as well. These make use of different types of pressure sensors that are unobtrusive and do not interfere in the comfort of users. One technique made us of fluid filled cells between the patient and a support for detecting motion via pressure fluctuations [42]. Another researcher used low-end load cells and placed them under each bed leg to classify 27 pre-defined movements by analyzing the computed forces [43]. A more popular approach is to place a small sensing mat between the mattress and bed sheet. The bedsheet deploys pressure sensors that can capture pressure mapping images and different postures can be recognized using classifiers. Alternatively, dispersed pressure sensors embedded in the mattress can record when changes in body posture occur. [44] used a non-invasive pressure-sensitive bedsheet to monitor different sleep postures by generating high-resolution pressure maps. [45] proposed pillow sensor system based on polysomnography. The pillow employed a 3x3 sensor array of FSR (force sensing resistor) based on polymer thick film device for classifying and recognizing sleep posture. However, this work were only useful for point-of-care applications. On the other hand, [46] used a bed pressure sensor array which could detected changes in the contact pressure between a subject and the bed. It automatically selected the sensor with the best respiratory signal, determined the respiratory rate, and counted number of sleep apneas and body position changes through the night. [47] used a fast responsive triboelectric active sensor (TEAS) with adjustable pressure measurement range allowing both gentle pressure detection and large scale pressure sensing. Through integrating multiple TEAS units into a sensor array, the as-fabricated TEAS matrix was capable of monitoring and mapping the local pressure distribution applied on the device with distinguishable spatial profiles.

The pressure sensitive mats manufactured by S4 sensors (formerly Tactex Sensors) recorded the patient’s movement between different postures [48]. These mats used photodiodes of connected to optical fiber for providing light. The light intensity of photodiodes would vary as pressure is applied which is translated to voltage signal indicating the pressure exerted on the mat. Data was transferred to a computer for processing via Bluetooth, and linear and SVM classifiers were used for categorizing data. Apart from being expensive, this system was not able to detect multiple postures and relay the recorded information to the user in real-time. Force Sensing Application pressure mattress [49] is a high resolution mattress that contains 2048 sensors. This system could identify only three different postures, namely “supine”, “right side” and “left side”. Similarly, [50] used a sensor mat comprising 1728 resistive sensors for identifying 13 different sleep postures using Gaussian Mixture Model. Image collected form the mat was processed by various filters for highlighting the pressure areas using a low pass Gaussian filter. For identifying the positions of a user’s limbs, pressure sensor data from specific regions on the mat were clustered together. This information was combined with the previously collected information from pressure sensors to obtain the posture classification. KNN linear classifier was used for supervised training using the collected datasets. The reported system was very efficient in terms of the posture classification given the high accuracy of 91.6%.



**Fig. 2** System Architecture

All the investigated solutions developed lack the capability of delivering processed data to the end user in real-time. Our proposed system overcomes this drawback by accompanying a smartphone application where the user or medical staff can visualize the data in real-time and can also access the previously collected for analyzing and diagnosing different medical conditions. Some of the solutions use mats that have a high resolution to only categorize a few postures. High-resolution mats are also expensive and not affordable to most consumers. The smartwatch and smartphone-based solutions are intrusive. Our developed solution is affordable, unobtrusive, has acceptable level of accuracy and takes the aspect of accessibility into focus. Accessibility is reflected by the developed Android application for our system.

# System Architecture

The system architecture shown given in Fig. 2 provides the conceptual model defining the structure of the system. It comprises a sensing mat made up of pressure sensors used to capture data related to the sleep position of the subject. The data acquisition module integrated into the mat collects the data from the pressure sensors providing the snapshot of the current posture, and transmits it to the cloud server using Wi-Fi. The data acquisition unit is implemented using the ATmega32u4. The firmware performs initialization, collects data from sensors, arranges data, and transmits the data to the cloud server using the ESP8266 Wi-Fi module. The cloud is set up using Amazon Elastic Compute Cloud (Amazon EC2) web service that provides secure and re-sizable compute capacity in the cloud. The reason for this selection was the availability of the simple and user-friendly web service interface that allows obtaining and configuring capacity with minimal friction. Data received by the cloud server is then stored in a *MySQL* server database. We use a central server design, which performs the data storage, data processing and user authentication. The server is written in *NodeJS* and *Express* framework allows forming the backbone of the server i.e. our server can send and receive data from clients. A request is made to the server using a *REST* (Representational State Transfer) API.

A python script running on the server can read the recently added data to the table in the *MySQL* server database for classification. We use machine learning algorithms to perform statistical analysis of the data obtained from the data acquisition unit and classify different postures. The python script runs continuously on server to receive and classify the data. We made use of Google's popular deep learning library called *TensorFlow* that incorporates different APIs to build at scale deep learning architectures like Convolution Neural Network (CNN). The data is first loaded into memory, a model is built, a machine learning algorithm is trained, and then posture is estimated.

The Android application is provided to the end user (subject or health professional) to interact with the system and retrieve information from the cloud. The information provided is the current sleep posture and statistical data for a specified period of the time. The statistical data contains the overall time in bed and the posture distribution over time. The application also generates fall warning alerts when the user is sleeping closer to the edge of the mat. The fall warning may help in preventing any potential fall injuries. If a user sleeps in one posture for a prolonged period, a bed sore alert generation option is also provided for the caregivers so that they can attend the patient and help change their posture. Bed unoccupied alert is generated when the user leaves the bed which is also helpful for caregivers.



**Fig. 4** Three layered FSR design

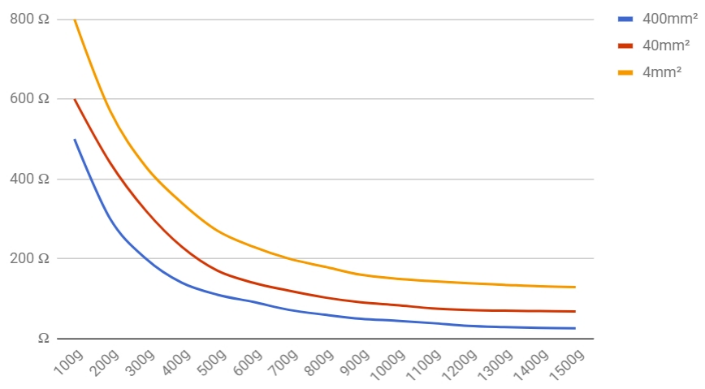
# Design and Implementation

The Sleep Mat-e system comprises sensors, mat, data acquisition system, and a mobile application.

## Sensor Design

Force sensitive resistors (FSR) are simple tactile sensors [51] that are used in applications where changes and differences in pressure need to be detected. These are constructed using conductive polymers, elastomers or semiconducting polymers, piezoresistive material, conductive wires, fibre-optical or fibre-gratting material. In our research, we implement an array of FSR’s to capture the pressure distribution of a person’s sleeping posture. Furthermore, they are cheap as they involve low cost electronic components and for these reasons they are widely used in such applications. For the construction of the sensor material, Velostat pressure sensitive material was used because it is inexpensive. The Velostat-based FSRs have an exponential decay resistance to pressure curve having a significant drop in the resistance of the material within a small region of the pressure range as shown in Fig. 3.

This high sensitivity helped us to distinguish between high and low pressure regions. An FSR sensor with the greater surface area has higher resistance, but it still has the same level of sensitivity. This is an important property as we can easily then have sensors designed for different pressure ranges with all of them having the same sensitivity. The square shaped sensor has dimensions of *2cm x 2cm* and contains three main layers which are a top electrode, Velostat, and bottom electrode, respectively as shown in Figure 4.



**Fig. 3** Velostat Resistance vs Pressure Graph

## Mat design

Our sensing mat is designed using an array of sensors attached to a thin plastic film under the sheet, making it easy to deploy on the mattress and unobtrusive to users. As shown in Fig. 5, a total of *171* sensors are placed in a *19x9* grid structure. The sensors are organized in rows and columns, forming an I-by-J rectangular matrix where denotes the pressure sensor at the row and column of the matrix, . The total number of sensors is . The dimensions of the mat are the same as that of a single mattress i.e., *100 cm by 200 cm*. The end-to-end clearance between two sensors is around *8 cm*. We use the equally spaced sensor topology as opposed to a few other sensor topologies such as the placement of sensors depending on the regions on the mat expected to have certain pressure values. We preferred this topology as it was more generic and would fit all the different types of major application without impose any restrictions on the user for the usability of the map.



**Fig. 5** Sensor topology with heat map

In Fig. 6, two different plastic layers can be seen, copper tapes applied on the bottom black plastic layer (B) of the mat run perpendicular to the copper tapes applied on the top transparent plastic layer (A). The Velostat sensor cutouts were placed on the copper tapes on the bottom plastic sheet that can be seen in Fig. 6 (B) as black dots along the entire stretch of each copper strip.



**Fig. 7** Connection diagram



**Fig. 6** Mat construction

## Data Acquisition

The data acquisition unit captures a snapshot of sensor mesh (the values of all the FSR’s on the mat at an instance) and sends it wirelessly to the cloud database. We use sensor matrix scanning strategy and this is done by pulling up one row, the analogue values outputted by all the columns fed to analog to digital converter (ADC) are captured by the controller. The same procedure is repeated for all the rows, and pressure values of all nodes are captured. This is used to construct the snapshot of the pressure profile of the person at a given instance. This sets a requirement of *19* digital outputs and *9* analogue input channels and low-end microcontrollers available in the market are not capable of meeting this requirement and others with higher IO count are expensive.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Algorithm 1:** *Sensor Scanning* | | | | | |
| 1: | ***procedure*** | | | | |
| 2:  3: |  | *clear shift register shift 1 into shift register* | | | |
| 4: |  |  | ***for row i*** *= 0 to* ***I-1*** | | |
| 5: |  |  |  | ***for column j*** *= 0 to* ***J-1*** | |
| 6: |  |  |  |  | *array[i][j] = ADCj value* |
| 7: |  |  |  | ***end*** *for;* | |
| 8: |  |  | *shift 0 into shift register* | | |
| 9: |  | ***end for****;* | | | |
| 10: | ***end procedure****;* | | | | |

We considered the option of using a multiplexer chip thus reducing the number of IOs required but multiplexers with 16 or more outputs per IC are expensive. The more economically feasible option is to use three eight-output multiplexers. This would require at least nine control pins from a microcontroller, which were too many. We opted to deploy a shift registers in a daisy-chain configuration, which essentially creates a single large shift register while using the same common control signals for each chip. This requires only five control signal lines for any number of shift registers in a daisy-chain configuration. Least significant bit asserted will shift and activate the column row in sequential fashion. Eventually, each of the nine columns was connected to voltage divider circuit. The layout of our connections to and from the sensing mat is shown in Fig. 7. A common eight output shift register, the Texas Instruments SN74HC595N was chosen for our application.

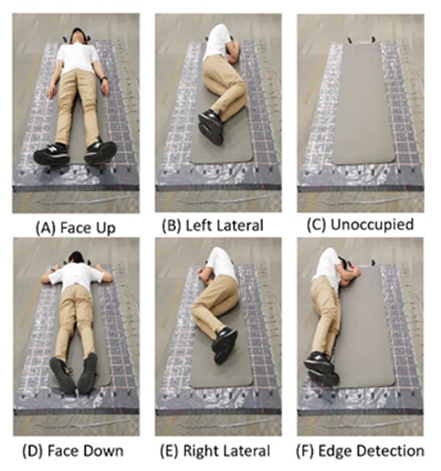
The three shift registers in Fig. 8A can be seen in the top middle of the breadboard connected to the 19 red cables on the top left. The diodes for all the 19 rows are connected at the outputs of the shift registers. The 9 red cables at the bottom left are connected to the 9 ADC input channels. These input channels were then connected to Arduino Leonardo development board using voltage dividers. Breadboard testing was a significant aspect in the development of design as it allowed us to verify our circuit schematic which was then finalized for printed circuit board (PCB) production.

The final completed PCB is presented in Fig. 8B has the dimensions of *7cm x 6.4cm*. The ATmega32u4 can be seen in the center of the PCB with a 5V regulators for a clean 5V supply on the right side as well as a 3.3V regulator for Wi-Fi module. The socket on the very top of the PCB is for the 5V connection to the 19 rows on the sleep mat, which are activated by the shift registers. Fig. 9 illustrates the completed mat with attached cables visible on the far left and the far top. The two plastic layers have been placed together to form a grid of sensors. Diodes are used to prevent the current flowing back into shift register outputs that are set to LOW. The voltage scale regarding the ADC value was now from 0V to 4.3V as there was a 0.7V drop.



Figure 8: Bread-boarding and final PCB

**Fig. 8** Bread boarding and PCB



**Fig. 10** Identifiable sleep postures



**Fig. 9** PressureSensor mat prototype

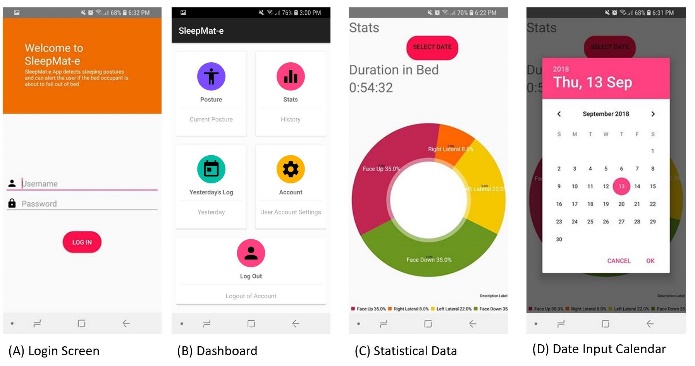
## Posture Recognition

We identify six different cases based on positions a user could be in when on the mat. These positions are identified as “Face Up”, “Facedown”, “Right Lateral”, “Left Lateral”, “Unoccupied” and “Closer to the Edge” as shown in Fig. 10. The closer to the edge case will alert the caregiver through the Android application that someone may fall off the bed.

Figure 11 shows the categorical heat map images generated from the pressure readings. Each colored square represents pressure sensor and it has color which is based on the magnitude of the pressure applied to the FSRs. The brighter colour (yellow) indicates the highest pressure. The Python script is used for the classification of the data stored in the database by NodeJS. Libraries used in the Python code are MySQL, *TensorFlow*, *Matplotlib* and *NumPy*. MySQL library allows us to establish a connection with the database from python and then access the most recent data. APIs provided by *TensorFlow* library were used to start the *TensorFlow* session, which was then used for classification of data. *Matplotlib* and *NumPy* are used for generating the categorical heat map images using a 2D array. A 2D array data structure is used for storing the values read from the MySQL query in the Python script.

The images shown in Fig. 11 were used by the *TensorFlow* session for sleep posture prediction. A new piece of data is classified when the python script reads a flag set in a text file that is edited by NodeJS. This was to ensure that python script was not continuously polling the database. A method that allows us to start the Python script from the NodeJS was also tested. However, it was found that it was not the optimal way of classifying data as the Python script will restart every time and was not able to classify data in the given time because the restart of the script will also restart the *TensorFlow* session which creates a significant delay to start. Whenever the server updates the table with new data, the Python script begins to classify it.

This is an image recognition problem and deep learning, specifically Convolutional Neural Networks (CNN), is an effective tool to solve this problem. We make us of *TensorFlow*, an open source artificial intelligence library which uses data flow graphs to build models. More precisely, it is an image classifier, type of image recognition algorithm that takes an image (or part of an image) as an input and predicts what the image contains. The output is a class label, which is one of the postures here. The dataset comprises 200 images for each of the six possible cases i.e. classes. Each image has three channels and all images have some aspect ratio. From the 200 collected images for each case, we filtered out the images that were either similar with other cases or were difficult to classify. This was due to the resolution of the mat. Instead of creating whole model again, we retrained existing model with our own data. We adapt a pre-trained network for other classification based on *TensorFlow* Hub module that computes image feature vectors. By default, it uses the feature vectors computed by Inception V3 (CNN) trained on ImageNet. The training usually took around 10 to 15 minutes depending on the size of the data. Graph file generated from the training session was then transferred to the server and used in a *TensorFlow* session for classifying postures.

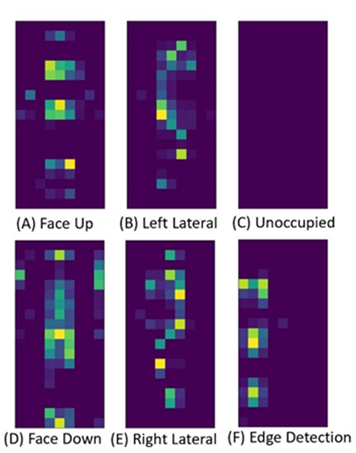


**Fig. 13** Mobile application user interface



**Fig. 12** CNN process in TensorFlow

The process image classification using *TensorFlow* is shown in Fig. 12. First, we pre-process data to generate the input of the neural network. Then, we reshape input and create a convolutional layer (using *tf.nn.conv2d()*), followed by the creation of a pooling layer. Above step is process is repeated multiple times to create the multiple convolution and pooling layers. The output of convolution and pooling layers is flattened before feeding it to the fully connected layer. A fully connected layer is created using *tf.matmul()* function and an activation is also added. Lastly, a final layer for class prediction is created and weights and biases are stored using *TensorFlow* variables.



**Fig. 11** Categorical heat map images generated from the pressure readings.

## Mobile Application

The final stage of our solution was to display the processed data to the user using a smartphone. The Android application then provides the processed information to the end user. The information provided is the current sleep posture and the statistical data for a specified date. The statistical data contains the overall time in bed and the posture distribution. The application also generates fall warning alert when the user is sleeping closer to the edge of the mat. The fall warning will help in preventing any potential fall injuries. If a user sleeps in one posture for a significant amount of time, a bed sore alert is generated for the caregiver so that they can attend the patient and help change their posture. Bed unoccupied alert is generated when the user leaves the bed which is also helpful for the caregivers.

Fig. 13 shows the screenshots of our Android app. The first screenshot is of the user login as shown in Fig. 13(A). The user login screen also provides a general description of the application. Once a user has successfully logged in, the user can then access the dashboard (Fig. 13 (B)) from where the user can check the current status of the mat of whether someone is on the mat or not. “Posture” option when clicked uses cartoon images as an indication of the current posture of the occupant. To get more details regarding the sleep posture for a given night, the user can select “Stats” option and then select a date through the calendar menu as shown in Fig. 13(D). The “Stats” option also provides information regarding overall time in bed (Fig. 13(C)). This time is measured from midday of the selected date to the midday of the next day; a complete day.



**Fig 14** (a) Live posture image (b) fall alert

# Results

The developed prototype could identify four different postures namely “Face up”, “Face Down”, “Right Lateral” and “Left Lateral” alongside generating fall warning, bed sore alerts and whether the bed is occupied or not. Our system also has an Android application, which allows a user to get statistical data regarding their sleep. *TensorFlow* machine learning library was used for classification of the pressure images that are generated from the pressure sensors information sent by the microcontroller. The average accuracy of the system from physical testing of the system after training the *TensorFlow* model was more than 90%. The system performed well for all the different cases with the highest for unoccupied and edge, as these cases were the easiset to classify.

**Table 1**: Accuracies of posture categories

|  |  |  |
| --- | --- | --- |
| **Category** |  | **Accuracy (%)** |
| *Unoccupied* |  | *100.0* |
| *Face up* |  | *92.5* |
| *Face down* |  | *90.0* |
| *Left Lateral* |  | *85.0* |
| *Right Lateral* |  | *80.0* |
| *Edge* |  | *95.0* |

The current posture is displayed on the app screen as shown in Fig. 14(a). Fall Alert is triggered when the system detects that the user is close to either the left or the right edge of the mat, which can be seen in Fig. 13 (b). When the user leaves the bed, the “Bed Alert” is triggered for the caregiver. This notifies the caregiver that the bed occupant has left the bed. Both alerts are intended to inform the android application user about the possibility that the user may fall or has fallen out of bed.

# Conclusion

Poor sleep and sleep postures poses a great threat to the health of elderly people living residential care. These risks can be reduced by effectively monitoring the pattern and posture of the sleep which ia a challenging task. In this paper, we presented a system that is unobtrusive, affordable and accessible through a smartphone. Our system can identify four different major sleep postures alongside generating fall warning, pressure sore and unoccupied bed alerts. A cloud server was used for collection and processing of the sensor data. Machine learning is used for the classification. A user-friendly Android application allows users to easily access the statistical data related to their sleep such as posture distribution and generates fall, bed sore and bed unoccupied alert warnings. The system has an average accuracy of 90% in identifying different cases. Further improvements can be made to the system to enhance the overall functionality.

We intend to increase the number of postures that can be detected easily and we also plan to develop the algorithm to measure the breathing rate. Development of an Android or iOS application for smartwatch will make the system more flexible, and the health care professionals will be able to view statistical data and get alerts on their smart watch.

**Compliance with ethical standards**

**Conflict of interest**

The authors declare that they have no conflict of interest.

**Ethical approval**

This article does not contain any studies with human participants or animals performed by any of the authors.

**Informed consent**

Informed consent was not necessary for this review.

# References

1. Population projections overview, Stats NZ, 8 March 2017. [Online]. Available: http://archive.stats.govt.nz/browse\_for\_stats/population/estimates\_and\_projections/projections-overview/nat-pop-proj.aspx. [Accessed: 28 April 2018].
2. Colten HR, Altevogt BM, Institute of Medicine (U.S.). *Committee on Sleep Medicine and Research*. Sleep disorders and sleep deprivation: an unmet public health problem. Washington, DC: Institute of Medicine, National Academies Press, 2006.
3. Harvey R Colten, Bruce M Altevogt, and Institute of Medicine (US) Committee on Sleep Medicine and Research. 2006. Sleep Disorders and Sleep Deprivation. National Academies Press (US).
4. Verhaert, Vincent, Bart Haex, Tom De Wilde, Daniel Berckmans, Marie Vandekerckhove, Johan Verbraecken, and Jos Vander Sloten. "Unobtrusive assessment of motor patterns during sleep based on mattress indentation measurements." *IEEE Transactions on Information Technology in Biomedicine* 15, no. 5 (2011): pp. 787-794.
5. Jean-Louis, G., Zizi, F., Brown, D., Ogedegbe, G., Borer, J., & McFarlane, S. (2009). Obstructive sleep apnea and cardiovascular disease: evidence and underlying mechanisms. Minerva pneumologica, 48(4), 277–293.
6. D. Seitz, N. Purandare, D. Conn, “Prevalence of psychiatric disorders among older adults in long-term care homes: A systematic review,” *International Psychogeriatrics*, vol. 22, no. 7, p.1025-1039, June 2010.
7. R. Catto, “The case for investment in: A quality improvement programme to reduce pressure injuries in New Zealand,” KPMG Advisory, New Zealand. Report. 19 Nov. 2015.
8. Ye, S., and Eum. S. 2017. Implement the system of the Position Change for Obstructive sleep apnea patient. Journal of the Korea Institute of Information and Communication Engineering. 21, 6 (Jun. 2017), 1231-1236.
9. Tangtrakulwanich B, Kapkird A. Analyses of possible risk factors for subacromial impingement syndrome. World J. Orthop. 2012;3(1):5–9.
10. Cheyne JA. Situational factors affecting sleep paralysis and associated hallucinations: position and timing effects. J Sleep Res. 2002;11(2):169–77.
11. Johnson DA, Orr WC, Crawley JA, Traxler B, McCullough J, Brown KA, Roth T. Effect of esomeprazole on nighttime heartburn and sleep quality in patients with GERD: a randomized, placebo-controlled trial. *Am J Gastroenterol*. 2005;100(9):1914–22.
12. "Bed Sore Lawyers | Pressure Sores | Queens, Long Island & NYC", Bed, Bedding, and Bedroom Decoration Ideas, 2018. [Online]. Available: http://www.homedesigndll.pw/photo/22043/bed-sore-lawyers-pressure-sores-queens-long-island-nyc.jpg. [Accessed: 08- Oct- 2018].
13. "Living outside the norm: An analysis of people living in temporary and communal dwellings, 2013 Census", Archive.stats.govt.nz, 2018. [Online]. Available: http://archive.stats.govt.nz/Census/2013-census/profile-and-summary-reports/outside-norm/residential-old.aspx. [Accessed: 08- Oct- 2018].
14. Ministry of Health, “DHB spending on services for older people,” 13 July 2016. [Online]. Available: https://www.health.govt.nz/nz-healthstatistics/health-statistics-and-data-sets/olderpeoples-health-data-and-stats/dhb-spending- 7 services-older-people. [Accessed 08- Oct- 2018]
15. "Residential care questions and answers", Ministry of Health NZ, 2018. [Online]. Available: https://www.health.govt.nz/our-work/life-stages/health-older-people/long-term-residential-care/residential-care-questions-and-answers. [Accessed: 08- Oct- 2018].
16. ACC, “Statistics on our claims,” 29 April 2017. [Online]. Available: <https://www.acc.co.nz/aboutus/> statistics/#injury-stats-nav. [Accessed 08- Oct- 2018]
17. Penzel, T., Schöbel, C., & Fietze, I. (2018). New technology to assess sleep apnea: wearables, smartphones, and accessories. F1000Research, 7.
18. Mayo Clinic, Polysomnography (sleep study). [Online]. Available: https://www.mayoclinic.org/tests-procedures/polysomnography/about/pac-20394877. [Accessed: 8 October 2018].
19. Itamar-medical, WatchPAT. [Online]. Available: https://www.itamar-medical.com/watchpat-home-sleep-testing-made-simple/. [Accessed: 8 October 2018].
20. Jun-ki Min, Afsaneh Doryab, Jason Wiese, Shahriyar Amini, John Zimmerman, and Jason I Hong. 2014. Toss “ N ” Turn : Smartphone as Sleep and Sleep Quality Detector. Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI ’14: 477–486.
21. N. Pombo and N. M. Garcia, “ubiSleep: An ubiquitous sensor system for sleep monitoring,” 2016 IEEE 12th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), 2016.
22. Google Play Store, “Sleep as Android: Sleep cycle tracker, smart alarm,” 2018. [Online]. Available: https://play.google.com/store/apps/details?id=com.urbandroid.sleep. [Accessed 28 April 2018].
23. Google Play Store, “Runtastic Sleep Better: Sleep Cycle \& Smart Alarm,” 2018. [Online]. Available: https://play.google.com/store/apps/details? id=com.runtastic.android.sleepbetter.lite. [Accessed 28 April 2018].
24. T. Hao, G. Xing, and G. Zhou, “iSleep: unobtrusive sleep quality monitoring using smartphones,” in Proc. of ACM Sensys, 2013, pp. 4:1–4:14.
25. Fitbit Inc., “Fitbit Charge 2,” 2018. [Online]. Available: https://www.fitbit.com/nz/charge2. [Accessed 28 April 2018].
26. [26] Jawbone, “Up3,” 2018. [Online]. Available: https://jawbone.com/up/trackers/up3. [Accessed 28 April 2018].
27. Jeon, L., and Joseph Finkelstein. "Consumer sleep tracking devices: a critical review." *In Proc. Stud. Health Technol. Inform.*, vol. 210, pp. 458-460. 2015.
28. Yu M, Rhuma A, Naqvi SM, Wang L, Chambers J. A posture recognition-based fall detection system for monitoring an elderly person in a smart home environment. *IEEE Trans Inf Technol Biomed*. 2012;16(6):1274–86.
29. M. Masek, C. P. Lam, C. T. Fryer, B. Jansen, K. Baptist, “Sleep monitor: A tool for monitoring and categorical scoring of lying position using 3D camera data,”
30. Bhatia S, Sigal L, Isard M, Black MJ. 3D human limb detection using space carving and multi-view eigen models. In: 2004 *IEEE conference on computer vision and pattern recognition workshop* (CVPRW’04). IEEE; 2004.
31. T. Grimm, M. Martinez, A. Benz, and R. Stiefelhagen, “Sleep position classification from a depth camera using bed aligned maps,” in *Proc. IEEE Int. Conf. Pattern Recog.*, 2016, pp. 319–324.
32. J. Lee, M. Hong, and S. Ryu, “Sleep monitoring system using Kinect sensor,” *International Journal of Distributed Sensor Networks*, 2015.
33. C. Torres, V. Fragoso, S. Hammond, J. Fried, and B. Manjunath, “Eye-CU: Sleep Pose Classification for Healthcare using Multimodal Multiview Data,” in *Winter Conference on Applications of Computer Vision* (WACV), 2016.
34. M. Martinez, B. Schauerte, R. Stiefelhagen, International Conference on Computer Analysis of Images and Patterns, pp. 465-472, 2013.
35. M. Martinez, L. Rybok, R. Stiefelhagen, "Action recognition in bed using bams for assisted living and elderly care", Machine Vision Applications (MVA) 2015 *14th IAPR International Conference* on, pp. 329-332, 2015.
36. E. Hoque, R. F. Dickerson, and J. A. Stankovic, ‘‘Monitoring body positions and movements during sleep using WISPs,’’ in Proc. Wireless Health, 2010, pp. 44–53.
37. J. Park, W. Nam, J. Choi, T. Kim, D. Yoon, S. Lee, J. Paek, and J. Ko, ‘‘Glasses for the third eye: Improving the quality of clinical data analysis with motion sensor-based data filtering,’’ in Proc. 15th Conf. Embedded Netw. Sensor Syst., 2017, p. 8.
38. X. Liu, J. Cao, S. Tang, and J. Wen, ‘‘Wi-sleep: Contactless sleep monitoring via WiFi signals,’’ in *Proc. IEEE Real-Time Syst. Symp*., Dec. 2014, pp. 346–355.
39. Liu, J., Chen, X., Chen, S., Liu, X., Wang, Y., & Chen, L. (2019, April). TagSheet: Sleeping Posture Recognition with an Unobtrusive Passive Tag Matrix. In IEEE INFOCOM 2019-IEEE Conference on Computer Communications (pp. 874-882). IEEE
40. Zhang, F., Wu, C., Wang, B., Wu, M., Bugos, D., Zhang, H., & Liu, K. R. (2019). Smars: sleep monitoring via ambient radio signals. *IEEE Transactions on Mobile Computing.*
41. Lin, F., Zhuang, Y., Song, C., Wang, A., Li, Y., Gu, C., & Xu, W. (2016). SleepSense: A noncontact and cost-effective sleep monitoring system. *IEEE transactions on biomedical circuits and systems*, 11(1), 189-202.
42. Toms M (2000) Patient movement detection. URL https://www.google.com/patents/US6036660, uS Patent 6,036,660
43. Alaziz M, Jia Z, Liu J, Howard R, Chen Y, Zhang Y (2016) Motion scale: A body motion monitoring system using bed-mounted wireless load cells. In: 2016 *IEEE First International Conference on Connected Health: Applications, Systems and Engineering Technologies* (CHASE), pp 183–192, DOI 10.1109/CHASE.2016.13
44. J. J. Liu, W. Xu, M.-C. Huang, N. Alshurafa, M. Sarrafzadeh, N. Raut, and B. Yadegar, “A dense pressure sensitive bedsheet design for unobtrusive sleep posture monitoring,” in *Proc. IEEE Int. Conf. Pervasive Computing and Communications*, 2013, pp. 207–215.
45. S. Lokavee, N. Watthanawisuth, J. P. Mensing, and T. Kerdcharoen, “Sensor pillow system: Monitoring cardio-respiratory and posture movements during sleep,” in *Proceedings of the 4th Biomedical Engineering International Conference*, BMEiCON-2011, pp. 71–75, Thailand, January 2012.
46. E. J. Pino, A. Dorner de la Paz, P. Aqueveque, J. A. Chavez, and A. A. Moran, “Contact pressure monitoring device for sleep studies,” in *Proceedings of the 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (EMBC), pp. 4160–4163, Osaka, Japan, July 2013.
47. L. Lin, Y. N. Xie, S. H. Wang et al., “Triboelectric active sensor array for self-powered static and dynamic pressure detection and tactile imaging,” *ACS Nano*, vol. 7, no. 9, pp. 8266–8274, 2013.
48. S. Bennett, Zhaofen Ren, R. Goubran, K. Rockwood and F. Knoefel, "In-Bed Mobility Monitoring Using Pressure Sensors", *IEEE Transactions on Instrumentation and Measurement*, vol. 64, no. 8, pp. 2110-2120, 2015.
49. M. B. Pouyan, J. Birjandtalab, M. Heydarzadeh, M. Nourani, and S. Ostadabbas, “A pressure map dataset for posture and subject analytics,” 2017 *IEEE EMBS International Conference on Biomedical & Health Informatics (BHI)*, 2017.
50. S. Ostadabbas, M. B. Pouyan, M. Nourani, and N. Kehtarnavaz, “In-bed posture classification and limb identification,” *2014 IEEE Biomedical Circuits and Systems Conference (BioCAS) Proceedings*, 2014.
51. N. Ida, Sensors, Actuators, and their Interfaces: A Multidisciplinary Introduction. Edison, NJ: SciTech Publishing, 2014.