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Design and Development of a Pressure Monitoring System to Prevent Bedsores in Immobile Patients

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ABSTRACT

Pressure ulcers, commonly known as bedsores, are localized injuries to the skin and underlying tissue caused by prolonged pressure, which restricts or entirely halts blood circulation. These ulcers typically develop in bony prominences such as the sacrum, heels, elbows, and hips due to the limited cushioning provided by subcutaneous fat in these areas. Immobile patients, particularly the elderly and individuals with chronic illnesses, are at a heightened risk of developing pressure ulcers, necessitating continuous monitoring and effective preventive measures. Traditional prevention methods involve regular patient repositioning, but manual monitoring is often inconsistent and labor-intensive. In response to this challenge, this paper presents the design and implementation of a smart mattress system capable of detecting and predicting the onset of pressure ulcers. The system utilizes an array of pressure sensors embedded beneath the mattress surface to continuously measure and analyze the distribution of pressure exerted on different body regions. By leveraging real-time data processing, the system can identify prolonged pressure points and issue timely alerts to caregivers or nursing staff, prompting necessary repositioning interventions. The proposed smart mattress aims to enhance patient care by automating pressure ulcer prevention, reducing the burden on healthcare personnel, and improving overall patient outcomes. The study explores the technical aspects of sensor integration, data analysis algorithms, and alert mechanisms to ensure the system's reliability and effectiveness in clinical settings.

1. INTRODUCTION

Pressure ulcers represent a significant challenge in healthcare settings [1-10]. They are considered a patient safety threat [11] and the third most costly condition globally, following cancer and cardiovascular diseases [12]. Pressure ulcers vary in size and severity, affecting layers of tissue from the skin to the muscles and bones [13].

Individuals at risk of pressure ulcers include those who are bedridden for extended periods, immobile patients, unconscious individuals, and those with impaired pain sensation [14]. The prevalence of this condition is 25.1% in

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Canada, between 14% and 17% in the United States, and approximately 18.1% in European countries such as Portugal, Belgium, and Sweden [11]. In Iran, systematic reviews and meta-analyses estimate a prevalence of about 19% [12]. In the United States, it is estimated that approximately 2.2 billion dollars are spent annually on treating pressure ulcers [15]. Nurses' knowledge and biomedical engineering equipment play crucial roles in the incidence and prevalence of pressure ulcers in healthcare settings [16].

Two primary methods exist for preventing pressure ulcers: continuous and regular care by nurses who reposition patients according to a fixed schedule, and the use of electro-mechanical devices that monitor pressure levels and durations on body areas, adjusting the patient's mattress and bed position mechanically. The first method is prone to errors and often imposes significant costs on patients and their families. Various studies have been conducted on the second method. One of the earliest examples is the device designed by Yousfi et al. in 2011, which uses pressure sensor arrays to initially detect the patient's position and then, based on predicted pressure levels on body areas, mechanically reposition the patient's body using actuators if a warning threshold is reached [17]. Similarly, Brosch et al. in 2013 developed a device using actuators and air cushions to reposition patients [18]. In 2013, the American company Wellsense designed hardware and software for hospital beds that continuously provides a color-coded map of pressure areas on the body via a wireless display for caregivers [19]. In 2016, the German company INSIDE developed a device that, in addition to providing a color-coded map, mechanically repositions the patient's body areas using a flexible and bending system upon reaching warning thresholds [20]. In 2018, Hong designed an intelligent system that uses pressure sensor arrays and load cells on four sides of the bed to continuously monitor the patient's body areas, accurately predicting the approach to semi-critical and critical pressure areas [21].

Designing and developing mechanical devices to reposition patients is both costly and, in the long term, can pose risks to patients due to potential technical issues. This research presents a system designed and implemented to continuously process pressure sensor data and identify body areas at risk, issuing appropriate alerts to inform caregivers or nurses in hospitals or homes to reposition the patient.

2. DESIGN AND METHODOLOGY

Initially, a standard mattress with dimensions 189.5 cm by 85 cm was prepared, and the entire body was divided into five regions using eight sensors, as illustrated in Figure 1, based on the patient's body position:

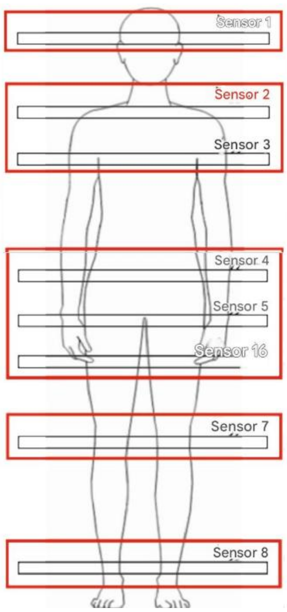

Fig.1. Sensor layout design in five regions on the mattress, marked in red.

The sensors were assigned as follows: sensor 1 for region 1, sensors 2 and 3 for region 2, sensors 4, 5, and 6 for region 3, sensor 7 for region 4, and sensor 8 for region 5.

2.1. Hardware Desig

For the hardware design of the smart mattress, an Arduino Uno board based on the powerful Atmega328 microcontroller was used to collect data from the pressure sensors. This board has eight analog-to-digital converter channels. Due to the presence of eight pressure sensors, all eight channels named a_1 to a_8 were utilized. Given a 10 millisecond delay in the analog-to-digital data acquisition program for each channel, the sampling rate (Fs) for each channel was set to 100 samples per sensor. The digital data obtained from the pressure sensors was transmitted using the serial port of the Arduino board, with a data transmission rate set at 9600 bits per second by the board's software. The data from each sensor ranges between 0 and 5 volts, and since the analog-to-digital converter channels of the microcontroller are 10-bit, the digital values range from 0 to 1023. The eight analog sensor voltages are converted to these digital values and transmitted to a computer via the serial port at the specified rate.

2.2. Software Design

The control and monitoring software for the system was designed using LabVIEW. LabVIEW consists of two parts: the Front Panel and the Block Diagram. The Front Panel handles control and monitoring, while the Block Diagram is used for coding the Front Panel, typically involving block diagrams and wiring.

In this project, the Front Panel includes two main sections. The first section is for configuring the serial port parameters, which must match the serial port settings in the Arduino code. Initially, the COM port matching the recognized serial port in Windows is selected, for example, COM1 on the computer used in this research. The second step involves selecting the Baud Rate, which is the data transmission rate from the microcontroller to LabVIEW via the serial port, set at 9600 in this study:

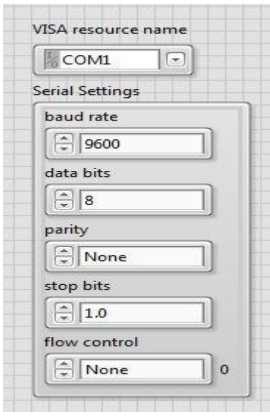

Fig.2. Serial port settings in the Front Panel.

In the second main section of the software, the program can be started or stopped using the start and stop buttons. User inputs such as name, surname, weight, height, and age are entered in designated fields. The Calibrate Threshold button is then pressed to determine the initial pressure threshold based on the age, as will be explained later. The software displays the pressure values from each sensor in Newtons in the monitoring section. Below each bar graph, two LEDs indicate semi-critical and critical pressure levels, flashing at a frequency of 1 Hz when these levels are reached. Additionally, five message boxes at the bottom of the screen provide explanations of the condition of each body region, displaying appropriate messages for the caregiver based on the conditions mentioned.

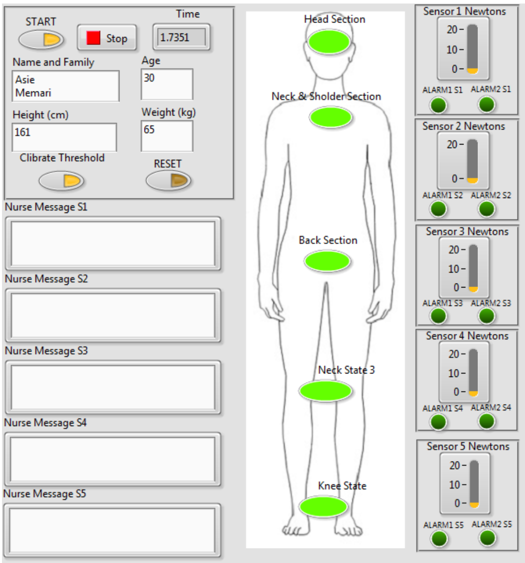

Fig.3. Main control and monitoring section of the program.

The display on the body shows the pressure status on sensor-equipped regions in three colors: green for normal, yellow for semi-critical, and red for critical, according to the device's software algorithm.

In the Block Diagram, two main sections are designed for coding. The first section applies the user's serial port parameter settings from the Serial Setting section to the Visa serial block, allowing LabVIEW to communicate with the serial port and the microcontroller. The second section contains the main body of the software, coded within a While loop connected to the Visa read section. The raw data from the eight sensors is continuously read every 10 milliseconds from the microcontroller. Through mathematical operations mentioned in the sensor calibration section, the raw sensor data is scaled to Newtons due to their nonlinear output. In this part of the software coding, two crucial conditions are checked for reaching the semi-critical and critical time thresholds, and the changes to these conditions affect the threshold adjustments accordingly.

By entering the patient's age and pressing the calibration key, the threshold for entering the semi-critical and critical states, considering the patient's age according to the information in Table 2, is determined based on the total time under pressure for the specified area. This will be referred to as the first condition in this study. Additionally, in the second condition, all five areas continuously influence the time to reach the semi-critical and critical states according to Table 3.

2.3. Sensor Calibration

To calibrate the conversion of each sensor's voltage readings to Newtons, due to the non-linear output of the FSR sensor and the use of a 10k ohm resistor in series with the sensor, we refer to the datasheet [22] of the FSR 402 sensor, which provides the non-linear graph in Figure 4.

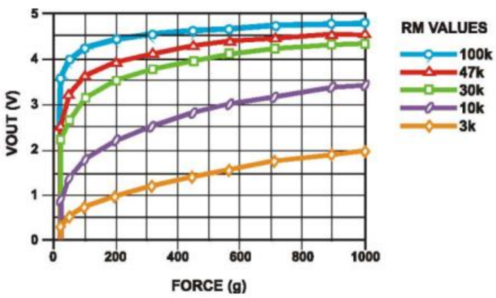

Fig.4. Non-linear output graph of the pressure sensor as per the manufacturer's datasheet.

To implement the non-linear sensor output in LabVIEW software, the polynomial equation of the seventh degree was implemented in MATLAB as follows:

$$y(x) = ax^7 + bx^6 + cx^5 + dx^4 + ex^3 + fx^2 + gx^1 + h \quad (1)$$

The coefficients of Equation (1) are listed in the following table:

Table 1. Coefficients of the seventh-degree polynomial equation.

Coefficient 1	**31.2806**
Coefficient 2	-392.9015
Coefficient 3	$1.9814 \times 10^{+3}$
Coefficient 4	$-5.1163 \times 10^{+3}$
Coefficient 5	$7.1485 \times 10^{+3}$
Coefficient 6	$-5.0941 \times 10^{+3}$
Coefficient 7	$1.4396 \times 10^{+3}$
Coefficient 8	39.9978

The fitted sensor graph in MATLAB using the coefficients in Table 1 is shown in Figure 5.

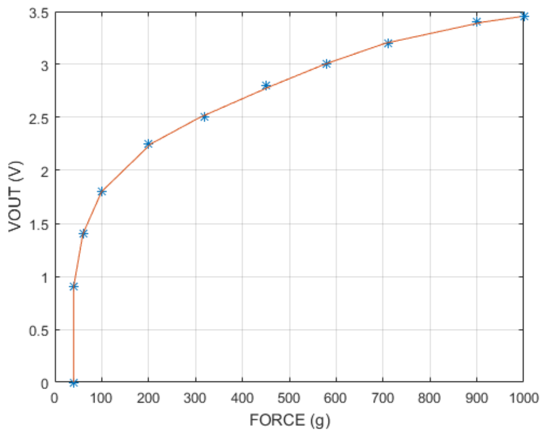

Fig.5. Fitted sensor graph with the sensor datasheet data, where blue data points correspond to the datasheet and red data points correspond to the fitted output.

To convert the sensor output to Newtons, the following equation was used in the software:

$$F = m \times a \quad (2)$$

According to equation (2), to convert the sensor output from grams to Newtons, assuming a constant acceleration a = 9.8 , the sensor outputs are scaled from voltage to Newtons using the implemented formula and the line equation derived from fitting in MATLAB.

2.4. Determining Sensor Thresholds

By applying force to different areas of the patient's body on the sensors and exceeding the 3 Newton threshold, the software applies conditions 1 and 2, which will be explained further, and calculates times T1 and T2 to determine the total time to reach the semi-critical and critical areas. It is essential to note that in this study, the time to reach the semi-critical and critical thresholds has been scaled from 2 and 4 hours to 5 and 10 minutes respectively to facilitate easier testing of the research results.

2.4.1. Condition 1

For implementing the first condition, three age ranges were considered. As the patient's age increases, the impact of each age range on reaching the semi-critical and critical areas is calculated using equation (3) and Table 2, which provides the value of T_1 for each age range:

$$y - y_0 = m \times (x - x_0) \tag{3}$$

In equation (3), known as the linear equation, m is the slope, x_0 is the intercept on the x-axis, and y_0 is the intercept on the y-axis.

Table 2. Determining the parameters of the linear equation for different age ranges for Condition 1

Age Range	y_0	x_0	m
10-50	0	10	1
51-70	31	51	3
71-100	89	71	5

As observed, with increasing age range, the slope of the equation increases by two units compared to the previous range, thereby reducing the time to reach the threshold according to equations (4) and (5), which will be explained subsequently.

2.4.2. Condition 2

In Condition 2, unlike Condition 1, which is applied at the start of the program, the time T2 is continuously calculated during the device's operation, according to Table 3, based on the applied force on each area using equation (3):

Table 3. Determining the parameters of the linear equation for each sensor for Condition 2

Pressure Range (N)	y_0	x_0	m
3-20	0	3	3

When the software is executed, initial calculations for Condition 1 are performed. When the sensors in each area exceed the 3 N threshold, calculations for Condition 2 are performed. Finally, the times to enter the semi-critical and critical states, T_{total2} and T_{total1}, are calculated using equations (4) and (5):

$$T_{total1} = 300 - (T1 + T2) \tag{4}$$

$$T_{total2} = 600 - (T1 + T2) \tag{5}$$

According to the above calculations, the maximum time to reach the semi-critical state after exceeding the 3 Newton threshold is 5 minutes (300 seconds). However, this time can be less than 300 seconds depending on the patient's age and the applied force on each area's sensors. Similarly, for reaching the critical state, the maximum time is considered to be 10 minutes (600 seconds), which can also be less than 600 seconds based on the patient's age and the applied force. Overall, applying these conditions according to the patient's status can optimize the device's performance in timely alerting the nurse.

3. RESULTS

This section thoroughly examines the program's execution stages from the beginning and the obtained results.

3.1. Starting the Device and Entering Patient's Age

In the control section of the software, the patient's age is first entered. According to the explanations in previous sections, one of the three age ranges implemented in the LabVIEW software algorithm of the device is applied by pressing the Calibrate button. For instance, in Figure 6, the test subject's age is 30 years. Upon pressing the START button, the software begins operation. In this state, the pressure applied to the sensors is displayed in Newtons both digitally and as a bar graph on the right side of the human body figure continuously. Below each pressure display section, there are two indicators that start flashing at a frequency of 1 Hz if any body area enters the semi-critical or critical state. In the middle of the software interface, a schematic of the human body with five indicators for each area individually displays the status of each body area in three colors: green (normal), yellow (semi-critical), and red (critical). Additionally, at the bottom left of the software screen, five boxes are provided to display messages to the caregiver or nurse, showing appropriate messages in semi-critical and critical situations.

3.2. Semi-Critical State

As explained in the previous section, after the program execution, the sensors of each area individually start sampling the pressure applied to the respective areas. For each area, the times T1 and T2 are calculated continuously and individually based on the two conditions explained earlier, determining the time to reach the semi-critical state. In Figure 7, due to the pressure exceeding the 3 Newton threshold and applying conditions 1 and 2, the areas corresponding to the buttocks, pelvis, and ankle have entered the semi-critical state. Additionally, in this test, it is observed that the relevant indicators below the bar graph for each area on the left side, which belongs to the semi-critical state, have started flashing. Finally, in the message boxes for the two areas that have entered the semi-critical stage, a message indicating entry into the semi-critical stage and a warning to change the patient's position are displayed.

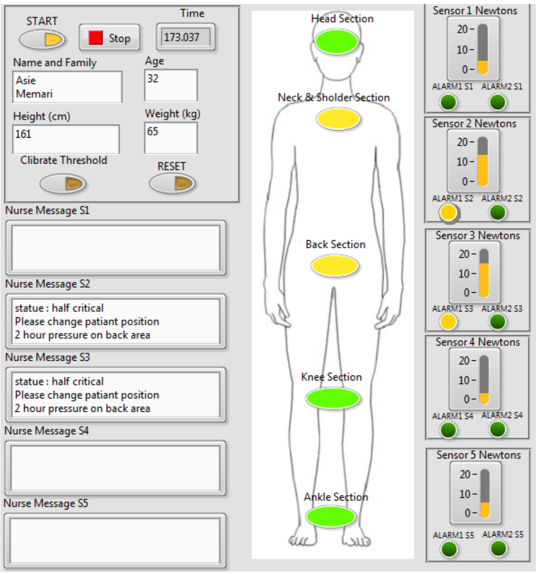

Fig.6. An example of the device's operation in the LabVIEW environment, showing two areas entering the semi-critical state.

3.3. Critical State

In this state, after applying a force higher than the permissible limit and exceeding the critical time threshold for all five areas, depending on the pressure applied to each sensor and the age parameter mentioned earlier, if the caregiver does not reposition the patient, the area under pressure can individually enter the critical state. In Figure 7, due to greater force applied to the second area, this area entered the critical state sooner than the third area. As shown in the figure, the critical state indicator for the second area has switched to a flashing mode, and a critical state warning message is displayed for the nurse or caregiver.

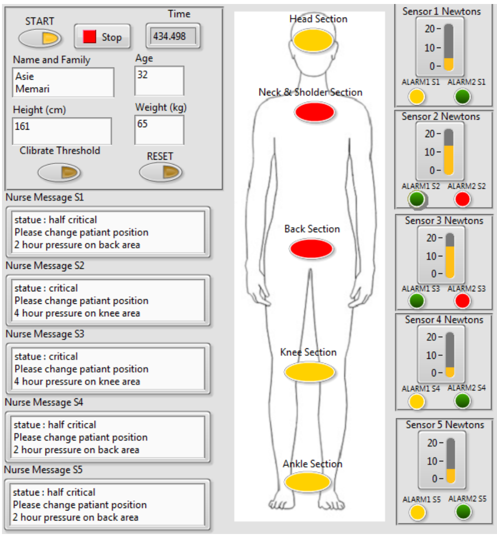

Fig.7. An example of the device's operation in the LabVIEW environment, showing one sensor in the critical state and one sensor in the semi-critical state.

As explained in previous sections, to construct the device, an Arduino Uno board, 8 FSR sensors, and a standard mattress with different body areas for a person of average height and build were used, as shown in Figure 8, which presents an overview of the device and its components.

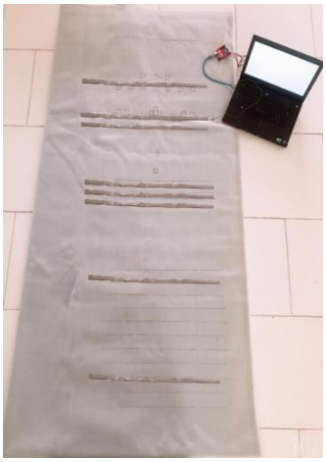

Fig.8. An overview of the device.

4. DISCUSSION AND CONCLUSION

By applying various pressures and testing the sensors, all implemented states in the software were tested, and all expected results were observed in the software's output displays. The explained conditions positively impacted the sensors' output for alerting the nurse or caregiver, which can be further improved by applying additional conditions, to be examined in future research.

Developing and enhancing a smart mattress for preventing pressure ulcers in patients at risk, as well as improving the quality of care for immobile patients and accelerating the response time of nurses, represents a significant advancement. Our intelligent system can continuously calculate the pressure in five body areas of an immobile patient through the efficient deployment of sensors. This system can detect potential pressure ulcer sites and, according to the algorithm implemented in the software, individually inform the nurse or caregiver about the conditions of different body areas via appropriate messages and visual warnings to prevent pressure ulcers.

Furthermore, with adequate funding for future research, additional areas at risk of pressure ulcers can easily be added to the constructed device, and all algorithms implemented for the five areas in this study can be extended to sensors for other areas. Ultimately, upgrading the software and hardware of this research can result in an industrial device for use by all low-mobility patients and the elderly.

Transparency Statement

The data supporting this study are available upon reasonable request to the corresponding author, subject to ethical and confidentiality considerations.

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Declaration of Interest

The authors declare that they have no competing interests.

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