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Assistive multi-sensor framework for prevention and monitoring of pressure ulcers

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Abstract

Pressure ulcers (PU) are injuries to the skin and soft tissues due to prolonged pressure and have a significant impact on the quality of a patient's life. The common risk factors of PU are pressure, shearing forces, friction, moisture, temperature, and immobility. The use of low-tech and high-tech devices is effective in distributing the high pressure exerted on the patient's body. However, patients can still develop PU because these devices do not provide any real-time information about the risk factors of PU development. With the help of sensors, smart beds are effective to monitor and prevent the development of PU but the prevalence of PU around the globe is still high due to the aging population.

In this thesis, a multi-sensor framework is developed and tested to aid in the monitoring and prevention of PU. The proposed system is able to measure, process, and store real-time information about the numerous risk factors of PU. In addition, the framework does not need to be attached to the patient's body in order to provide extra comfort. Different experiments are conducted to test the reliability and effectiveness of the proposed system. Experimental results indicate that the system is capable to provide the rate of repositioning, temperature, and pressure distribution.

Keywords: Pressure ulcers; repositioning; temperature; pressure distribution; LabVIEW

Contents

Preface

First of all, I would like to thank my supervisor Dr. Ivan Vujaklija, who provided me an opportunity to work on this project and guided me throughout the thesis. I would also like to thank my advisor Dr. Ramyah Gowrishankar, who aid in the writing of my thesis.

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Shah Fahad Farooqi

Symbols and abbreviations

Symbols

°C	Unit of temperature on the Celsius scale
kg	Unit of mass
m	Unit of distance
mmHg	Manometric unit of pressure
V	Unit of electric potential difference

Abbreviations

3D	Three Dimensional
AFB	Air-Fluidised Bed
APAM	Alternating Pressure Air Mattress
CSV	Comma Separated Values
DAQ	Data Acquisition
DMUX	Demultiplexer
FBG	Fiber Bragg Grating
FSA	Force Sensing Array
FSR	Force Sensing Resistor
I2C	Inter-Integrated Circuit
I/O	Input/Output
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
MUX	Multiplexer
NI	National Instruments
PU	Pressure Ulcers
SPI	Serial Peripheral Interface
SVM	Support Vector Machine
UART	Universal Asynchronous Receiver Transmitter
UI	User Interface
USB	Universal Serial Bus
VI	Virtual Instrument

1 Introduction

Pressure ulcers also known as bed sores are skin and soft tissue injuries caused by sustained pressure on the area for an extended period of time [1]. Mostly, PU occurs over bony prominences such as elbows, shoulders, sacrum, and trochanters [2]. The main cause of PU is pressure applied over a long interval of time. Other factors that contribute in the development of PU are shearing forces, friction, moisture, temperature, and immobility [3].

Bed sores are painful and difficult to cure [4]. They are associated with physical and mental problems and have a negative effect on the quality of life [5]–[7]. The supervision of PU is very demanding for clinicians and usually support surfaces are used to prevent PU. These support surfaces redistribute the applied pressure to reduce its magnitude [8]. They can be categorized either as low-tech devices which easily mould to the shape of the human body or high-tech devices that use inflatable cells which alternately inflate and deflate [9].

Although support surfaces aid to decrease the exerted pressure on the human body, patients are still at the risk to develop PU. It is because these surfaces do not provide real-time information about the factors of PU development [8]. Research studies suggest that smart beds are an effective solution to prevent PU. With the help of sensors, these beds can monitor the factors of PU development [10]. Moreover, based on these sensor data, machine learning algorithms have been developed to detect the position of the patient and also suggest the next suitable positions [11]. This allows nurses to spend more time on patient care instead of rotating them every moment.

The figures for PU patients are still high due to the aging population [12]. Throughout the world, the prevalence of PU ranges from 0% to 72.5% in healthcare centers [13], while it varies from 6% to 18.5% in acute care facilities [14], [15]. The high prevalence of PU has increased the use of healthcare resources and costs. In Finland, around 55,000 to 80,000 PU patients are treated every year. This costs around 2% to 3% (Between 350 and 520 million euros) of the annual health expenditure. Moreover, PU is detected in 5% to 25% of patients in various healthcare units [16].

This thesis aims to develop a system to monitor and assist in the prevention of pressure ulcers. The scope of the project is to build and test a multi-sensor framework that does not require any attachment to the patient's body so that patient can change its position easily. The proposed system provides real-time information about the rate of repositioning, temperature around the patient's body, and pressure distribution over the patient's body. Moreover, the system is tested to ensure its feasibility and reliability for the monitoring and prevention of PU.

The rest of the thesis is organized as follows: Chapter 2 briefly explains the main factors of PU development and their measurement techniques. In chapter 3, research material and methods are discussed to fulfil the objective of this thesis. In chapter 4, experimental results are presented and discussed. Finally, chapter 5 concludes the thesis work.

2 Literature review

2.1 Pressure ulcers

Pressure ulcers are injuries to the skin and underlying tissues due to persistent pressure on a specific area of the skin [1]. In the normal human body, tissue is capable to bear a pressure of approximately 30 to 32 mmHg for a short interval of time on the arterial side. When the pressure goes beyond this capillary filling pressure, it obstructs the blood vessel and the underlying tissues become anoxic (greatly deficient in oxygen). If the pressure remains for a significant amount of time, it can lead to pressure ulcers [17], [18].

Usually, when a person is sitting or lying for a long time, the soft tissues between the human skeleton and support (bed or chair) are compressed and tissue deformation happens. Blood vessels inside these tissues may be stretched out, compressed, or angulated from their normal shape. As a result, blood is not capable to pass through them and causes tissue ischemia, which leads to pressure ulcers. Depending on the health condition of a person, PU can be developed even when a small quantity of pressure is applied to the skin over a long period. They can also occur when an ample amount of pressure is applied for a short duration [17].

People who are limited to a bed or chair for a long interval of time and discouraged mobility, are vulnerable to bedsores. Usually, PU occurs over bony prominences such as occiput, shoulders, trochanters, ear lobes, sacrum, and elbows depending on the position of the patient [2]. Age is another key aspect that's why the majority of PU occurs in old people [12]. In other words, any individual who is unable to avoid sustained intervals of continuous compression is at risk of PU [17].

2.1.1 Factors of pressure ulcers development

Research indicates several factors that can contribute in the development of pressure ulcers [3]. For instance, when constant pressure is retained on the skin, soft tissues try to adjust it, known as tissue creep. It may reduce the applied pressure, but the supply of blood will also decrease to that area due to further deformation of those tissues [17]. If this tissue ischemia remains for as little as two hours, it will cause PU [18]. Generally, PU is worse than what they appear on the skin surface because muscles and tissues are more prone to pressure injury than the skin [19].

Similarly, shear is also an important factor in PU development. When a bed is lifted at the head, the human body can slide down on the bed due to gravity. In such a scenario, underlying tissue moves down but the top layers of the skin remain stationary. As a result, this shearing reduces the blood supply to the affected area of the skin and causes tissue ischemia [19]. Shear has a huge impact on PU development and in addition to pressure, it causes an additional destructive impact on skin viability [20].

Apart from pressure and shear, a rise in skin temperature due to low exposure to air also causes PU. In general, a 1 °C increase in skin temperature causes an approximately 10% increase in tissue metabolism. As a result, it reduces the tolerance of tissue to ischemia and makes it more susceptible to PU at lower pressure levels [21].

Friction is also commonly cited as a cause of PU. It happens when the skin of a human body rubs against the bed or clothes. It can develop PU both directly and indirectly. In the indirect perception, friction is essential to produce shear forces to develop PU [17]. Research suggests that frequent friction may result in deeper injury [19].

Similarly, moisture is another important factor that contributes to the formation of PU. Moisture from sweat and urine causes softening of the skin surface which forms sores and is susceptible to breakdown. Moreover, unnecessary moisture on the skin makes it prone to pressure, friction, and shear, which stimulates the occurrence of PU [19], [22].

Additionally, immobility which is linked with the position of the patient also causes PU. Normal people can change their posture regularly due to the sensorimotor feedback system. However, patients who have received prolonged anesthesia, and those who are neurologically impaired, their feedback system works inadequately. As a result, such patients are more vulnerable to develop PU because they are unable to make postural alterations in response to persistent pressure [19].

Pressure is the most important factor in PU development, however, other factors such as shear, temperature, friction, moisture, and immobility also significantly contribute to the formation of PU [3], [17], [19].

2.1.2 Stages of pressure ulcers

According to research studies, pressure ulcers can be classified into six categories based on the extent of injury as shown in Fig. 2.1. For instance, stage I is the mildest phase of PU in which skin has no tears, but it may be painful and change its colour. In this stage, sores are not open wounds, but they can be stiff or soft as compared to their surrounding area [23]. On the other hand, stage II happens when the skin breaks down and develops an ulcer, which expands into the thicker layer of the skin. The sores in this stage are usually painful, and the skin may be scratched beyond repair [23].

In contrast, stage III ulcers expand into the tissue under the skin and create a tiny crater. In this phase, fat tissue appears in the sore, but bone or muscle is still invisible [23]. However, bed sores at stage IV are very complicated to cure and in this stage, the damage is very intense, and its reaches into bone and muscle easily [23]. Apart from the four main stages, there are two other categories of PU. For instance, an unstageable is a category that refers to injury with an unknown stage. In such cases, the base of the wound is obscured by slough or eschar and the stage of PU cannot be determined [24]. In contrast, deep tissue injury is a type that indicates injury that is hidden beneath undamaged skin. This sort of wound has a high potential to transform into a high stage PU [24].

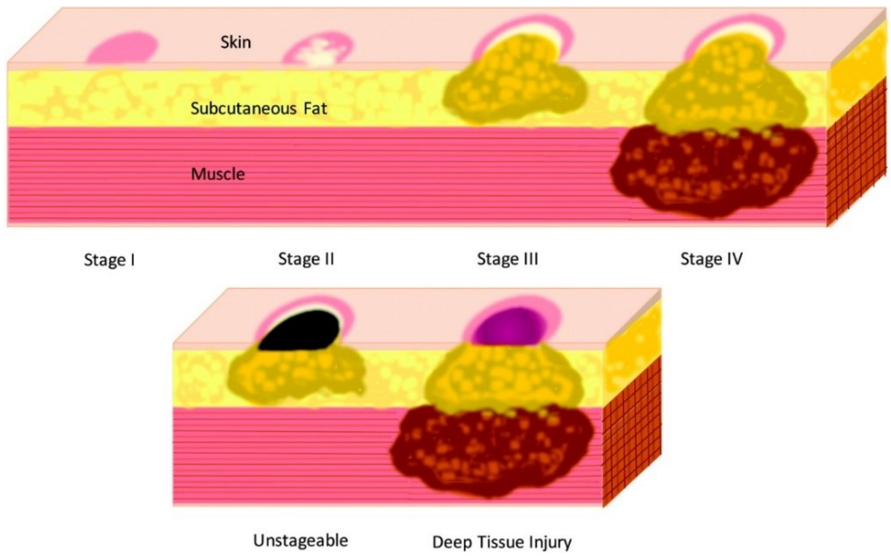

Figure 2.1: Illustration of different categories of pressure ulcers. From left to right, the top diagram shows stage I, II, III, and IV of PU respectively. The bottom diagram shows the unstageable and deep tissue pressure injury respectively, adopted from [24].

2.2 Measurement techniques of pressure ulcers factors

In hospitals and health centers, different approaches are used to monitor the risk factors of PU development. These approaches allow acquiring data to identify risky situations that can be used to assist caregivers in the prevention of PU [10]. For instance, pressure can be evaluated in different ways. Usually, the common sign of continuous pressure on the normal human body is frequent body movements [25]. In hospitals, the rate of repositioning can be observed through rounds of nurses. Moreover, it can be monitored continuously with the help of accelerometers [26]–[28]. To avoid PU, these accelerometers must be capable to measure the dynamic acceleration due to motion and have high resolution (±16 g) to effectively detect human body movements [28]. Patients who are vulnerable to bedsores need special attention and the pressure on their bodies must be monitored continuously. Smart beds [10] are a feasible solution to provide real-time pressure distribution over the human body by using pressure sensors [29]–[32]. Moreover, commercial pressure mats could also be used to get the pressure map of the human body [33]–[35]. However, these pressure sensors are required to provide pressure distribution over a wide range of applied weights (up to a few kilograms) to prevent the development of PU [17], [35], [36]. On the other hand, nurses used the Braden scale [37] to calculate friction and shear in hospitals. It is determined by the level of assistance required to move the patient, the frequency with which the patient is slide on the bed or chair, and the existence of agitation that causes friction.

Touching the forehead with a hand is the simplest way to check the temperature of a person. Generally, nurses used a thermometer to measure the temperature of a patient body. Although these techniques are easy and inexpensive, they are not efficient to avoid PU [25]. On the other hand, nurses examine the skin of the patient, dress, and bed to check for moisture. They also used the Braden scale [37] to calculate the degree to which the skin is exposed to moisture. These methods are efficient, but they are not suitable for patients who are vulnerable to PU [25]. Smart beds [10] assist to address these concerns because they used temperature and humidity sensors [38]–[41] to provide continuous monitoring of these risk factors. To avoid PU, previous studies suggest that the accuracy of these sensors is required up to ±1 °C and ±3% respectively [39], [41].

In hospitals, nurses' rounds are planned to frequently check the bedridden patient's posture. However, it is important to continuously keep eye on the posture of the unconscious or paralyzed patients. Smart beds [10] with machine learning algorithms aid to detect the posture as well as suggest the next possible suitable positions for such patients to provide extra comfort [11].

2.3 Prevention of pressure ulcers

PU is a common healthcare problem [13]–[15], therefore it is necessary to prevent its development to reduce the use of healthcare expenditures [16] and improve the quality of patient's life [5]–[7]. In traditional hospital mattresses [42], a waterproof cover is used to offer a tight and wrinkle-free surface. This allows nurses to reposition the patient easily to minimize the risk of PU. The main drawback of these mattresses is their design which provides an environment for tissue injury. It is because, they are comparatively rigid, and their tight cover produces a non-uniform weight distribution arrangement. As a result, high pressures can be produced, especially over the bony regions [2]. These contact pressures can vary from 50 to 150 mmHg [42], which is unsuitable for patients at risk of developing bed sores [17], [18]. The probability of PU development can be reduced by changing the position of the patient every two hours [25]. On the other hand, a suitable support surface can also reduce the risk of PU and would be beneficial for patients and people restricted to bed [8]. These surfaces reduce the magnitude of high pressure by redistributing it over a large area. They can be categorized as low-tech and high-tech devices [9].

Low-tech is also known as non-powered devices. Memory foams [43] are a common type of low-tech device that can be made from various materials such as petrochemical-based materials and natural rubber latex. Memory foams use the body heat to become soft and mould to the body shape. They remember the body shape and as a result, when the high pressure is removed, they return gradually to their original shape. This property provides support to the natural curved of the human body as well as prevents the development of PU. Similarly, gel cushions [44] are also pressure relief surfaces. Gel beads or spinning liquid gels are used in their construction. Due to the viscosity of the gel, they can easily mould to the shape of the human body and increased the surface area of the body in contact with them. As a result, they distribute the magnitude of the pressure and provide extra comfort. Moreover, these gel-based cushions also provide cool to the user by conducting body heat away. Air-filled mattresses [45], also known as static air mattresses are preferred over traditional hospital mattresses because they prevent bedsores. Due to their static surface, they reduce the exerted pressure by uniformly distributing it at a constant low pressure over a large surface. On the other hand, sheepskin-based support surfaces [46] are also effective to reduce the magnitude of extreme pressure by increasing the contact area. These surfaces can be used in the usual clinical care to reduce high-pressure points to avoid bedsores.

In contrast, high-tech is also known as powered devices. Alternating pressure air mattresses (APAMs) [47] are a well-known type of high-tech device. They are made of several air-filled cells, which are inflated and deflated with the help of a pump. Inflation and deflation of these cells vary the region under high pressure, which aid to redistribute the pressure. APAMs are very useful to prevent PU because they help to restore the supply of blood to tissues. Similarly, air-fluidised beds (AFBs) [48] are also commonly used in hospitals to avoid PU. In these beds, a mattress is filled with small ceramic beads. When the warm air is passed through the beads inside, they adopt the properties of a fluid. The movement of beads allows to redistribute the exerted pressure on the patient body.

2.3.1 Smart beds as a complete solution of pressure ulcers

Although low-tech and high-tech devices are efficient to distribute pressure, patients can still develop PU [8]. It is because they do not provide any information about the risk factors of bed sores. Smart beds are an appropriate solution to prevent PU [10]. They range from simple devices that only monitor risk factors of PU to autonomous beds that automatically reposition the patients.

To avoid PU, researchers have used different approaches to monitor the pressure distribution over the human body. Manohar and Bhatia [29] used resistive bend sensors on the flocked single chamber air bed to monitor the pressure points. The low-cost pressure detection system was successfully tested by dividing the bed into small sections, each with a bend sensor in the center. Yip et al. [30] have presented capacitive-based pressure sensitive sheet to determine the location and magnitude of the applied pressure. Experimental results showed that the relaxation time of these sensors is a few minutes due to hysteresis. Another research team, Chung et al. [31] proposed a fabric-based pressure sensor array to capture pressure maps of high-risk body areas. The technology was meant to be integrated into a wound dressing to reduce friction. For wheelchair users, FBG (Fiber Bragg grating) based real-time pressure monitoring solution was proposed by Tavares et al. [32]. The results revealed that FBG technology is immune to electromagnetic interferences and can be used in wet areas.

Prior studies suggest that monitoring other risk factors in addition to pressure is valuable to avoid PU. Fard et al. [38] demonstrated a pressure and temperature monitoring system based on FSR (force sensing resistor) and digital temperature sensors. The proposed system can generate alerts by specifying the threshold and duration of the pressure intensity. McNeill et al. [39] proposed a wireless sensor patch that monitors temperature, pressure, and relative humidity to prevent PU. An assessment of the design showed that the patch can be worn for up to seven days. Agueda et al. [41] designed a prototype of an electronic layer with pressure, temperature, and humidity sensors. The layer can be placed on the top of the patch to monitor the environment of the wound. The study aimed to improve the supervision of PU patients.

The posture of bedridden patients is a critical factor in the development of PU. Monitoring the patient's posture allows caregivers to reposition the patient in time to reduce the risk of PU. Yousefi et al. [33] proposed an image-based processing algorithm to predict the posture of the patient's bed. FSA (Force Sensing Array) based commercial mat was used to get a pressure map of the subjects. Experimental results indicated that the developed algorithm could classify five different postures with 97.7% of average accuracy. Hsia et al. [49] explained the design of a pressure sensitive mattress based on FSR (force sensing resistor) and the algorithms used to classify the sleeping positions. Experimental results showed that SVM (Support vector machine) is more complicated to deal with non-linear separable classification than Bayesian classification. Ahmad et al. [50] presented a pressure sensing system for a wheelchair and an algorithm to classify sitting postures. The developed algorithm can classify four different sitting postures with more than 80% accuracy. Ostadabbas et al. [51] proposed an algorithm that uses a commercial pressure mat to monitor the pressure data using various postures. Based on the current position, the algorithm recommends several next optimal postures for the patient. The goal of the study was to reduce nurses' efforts and the risk of PU.

Intelligent beds with a control system reduce the probability of PU development because they automatically redistribute the exerted pressure. Moon et al. [34] proposed an air mattress (KOREC_mat) and its pressure control technique. The human body was split into four segments and the pressure of each segment was calculated using an approximate anthropometric model. Experimental results showed that the KOREC_mat is effective for the prevention of PU. Elfehri et al. [52] proposed a control algorithm for mattress to keep the pressure under threshold values on different body parts. The experimental results revealed that the algorithm's convergence results in patient comfort and prevention of PU. Raeisinezhad et al. [53] presented the development of a robotic pad system that consists of multiple domes. Air chambers allow to independently actuate and control each dome in the vertical and horizontal directions. The assessment of the study demonstrated that the proposed system could redistribute the applied normal and shear loads. Zhang et al. [40] developed a flexible turning and sensing system for bedridden patients as shown in Fig. 2.2. The system includes infrared temperature sensors to monitor the patient's status and turning process. Turning and supporting airbags are used with the turnover mattress to lessen the shear during repositioning of the patient to prevent PU.

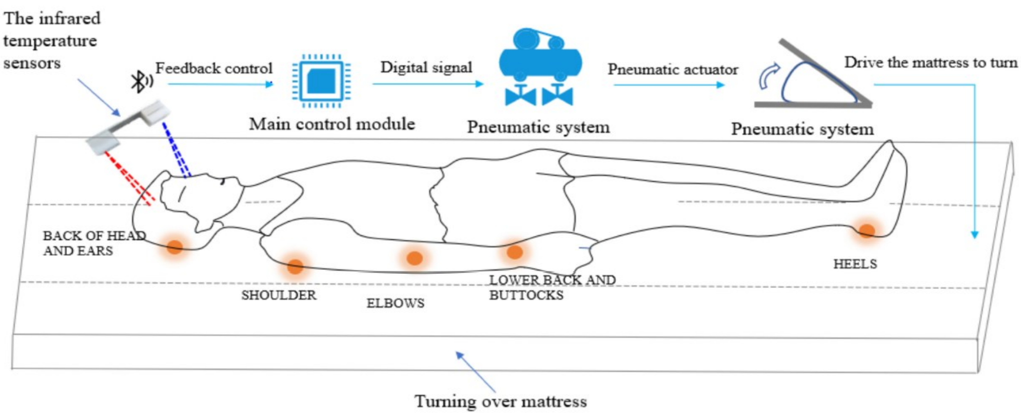

Figure 2.2: Flexible turning and sensing system for the prevention of PU. The system consists of a turnover mattress and non-contact temperature sensors to monitor the patient's body temperature, getting out of a bed, and the process of turning, adopted from [40].

3 Research material and methods

The probability of PU development can be reduced by continuously monitoring its risk factors [10]. For this, a multi-sensor framework is developed as shown in Fig. 3.1, that can measure, process, and record the risk factors of PU in real-time. The proposed system mainly consists of three components: sensors, Arduino Mega, and LabVIEW (Laboratory Virtual Instrument Engineering Workbench). It is capable to measure the rate of repositioning, temperature, and pressure distribution. Other risk factors are not monitored because the system needs to be isolated from the patient's body to provide extra comfort. The framework is tested in a real-time environment to validate its feasibility for the monitoring and prevention of PU.

Figure 3.1: Block diagram of a multi-sensor framework. The system consists of three essential components. The sensors are used to acquire data regarding the risk factors of PU. Arduino Mega is used as a data acquisition (DAQ) device to process this data. Finally, LabVIEW runs on the PC to display and record this data.

3.1 Key components

3.1.1 Sensors

To measure the risk factors of PU, the most popular technology used is sensors [10]. For instance, research studies suggest that accelerometers are useful to track the frequency of repositioning [26]–[28]. Similarly, ADXL345 is used to detect the position changed by the patient over the mattress. It is a low-power, 3-axis accelerometer with a measurement range of ±2 g, ±4 g, ±8 g, or ±16 g. It can measure static as well as dynamic acceleration and can be accessible through I2C or SPI communication protocol.

Past studies suggest that pressure sensors are capable to provide pressure distribution [10] [29]–[32]. In this project, textile-based resistive pressure sensors as shown in Fig. 3.3 are used to monitor the exerted pressure on the human body. From Fig. 3.2, it can be seen that the sensor consists of three layers: the top and bottom layers consist of conductive fabric while the middle layer is piezoresistive fabric. When pressure is applied to the sensor, the resistance of the piezoresistive material decreases. In other words, the pressure sensor behaves like a variable resistor.

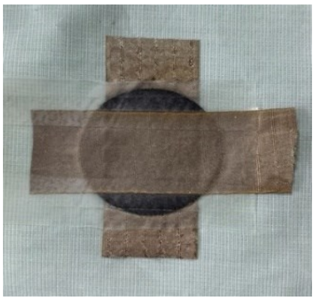

Figure 3.2: Textile-based resistive pressure sensor, manufactured by Aalto University. The top and bottom rectangle layers are conductive fabric while the middle layer is piezoresistive fabric.

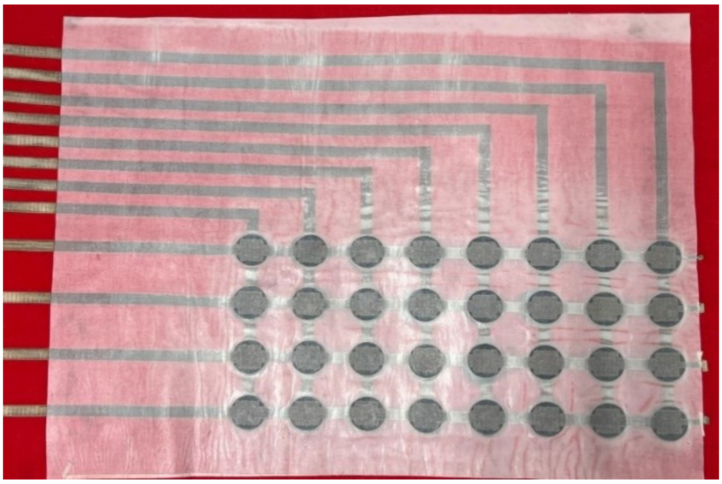

Figure 3.3: Textile-based resistive 4x8 pressure sensor matrix, manufactured by Aalto University.

Table 3.1: I2C slave addresses of Digilent PmodTMP3 to connect eight temperature sensors with a single I2C channel of a master device, adopted from [54].

JP3	JP2	JP1	Address
GND	GND	GND	0x48 (0b1001000)
GND	GND	3V3	0x49 (0b1001001)
GND	3V3	GND	0x4A (0b1001010)
GND	3V3	3V3	0x4B (0b1001011)
3V3	GND	GND	0x4C (0b1001100)
3V3	GND	3V3	0x4D (0b1001101)
3V3	3V3	GND	0x4E (0b1001110)
3V3	3V3	3V3	0x4F (0b1001111)

On the other hand, temperature sensors are used to monitor the intensity of temperature around the patient's body [10], [38]–[41]. In this project, Digilent PmodTMP3 is used which is a digital temperature sensor with an accuracy of ±1 °C. It is built around the microchip TCN75AVUA and accessible via I2C serial communication. At the same time, eight sensors can be connected to a master device by changing their address as shown in Tab. 3.1. To choose one of the eight valid addresses, JP1, JP2, and JP3 pins can be connected to the ground or 3V3 pin.

3.1.2 Hardware setup

The hardware of the proposed system mainly consists of Arduino Mega, six accelerometers, three temperature sensors, and a 4x8 pressure sensor matrix. In this project, Arduino Mega is used as a DAQ device because it is easily compatible with LabVIEW and sensors. It processes the data acquired by the sensors regarding the risk factors of PU and sends it to LabVIEW. Arduino Mega is an open-source development board based on the ATmega2560 microcontroller. It has 54 digital I/O pins, a 16 MHz oscillator, 16 analog pins, and a USB (Universal Serial Bus) connection. The board can be powered by connecting it to a laptop or personal computer via a USB cable.

Moreover, the development board supports various communication protocols. For instance, the communication between LabVIEW and Arduino Mega is done using UART (Universal Asynchronous Receiver Transmitter) as shown in Fig. 3.4. UART is an asynchronous communication protocol that used two lines, TX, and RX for transmitting and receiving data respectively. It does not have its own clock, so transmitting UART add up start, parity, and stop bits with the data. Start and stop bits assist receiving UART to read data, while the parity bit is used for error checking.

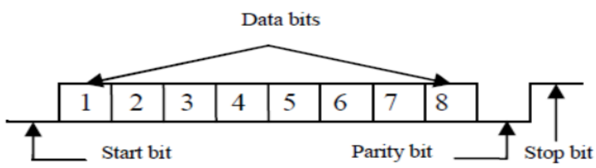

Figure 3.4: Illustration of UART data frame, adapted from [55].

On the other hand, Arduino Mega communicates with accelerometers and temperature sensors through I2C (Inter-Integrated Circuit) as shown in Fig. 3.5. I2C is a bi-directional and synchronous communication protocol that support multiple master and slaves. It has two lines SDA (Serial Data) and SCL (Serial Clock). To start communication, the master sends a start bit, the address of the slave, and a R/W bit, respectively. The slave receives the start bit and its address and sends an acknowledgement bit to the master. When the master receives this bit, it sends the address of the specific register to the slave. The slave receives this address and sends another acknowledgement bit to the master. Upon receiving this bit, the master can send or receive data from that register of the slave. Once the data has been transferred, the receiver sends a final acknowledgement bit to the transmitter. Finally, the master sends a stop bit to the slave to stop the data transfer.

START	Slave address	Rd/nWr	ACK	Data	ACK	Data	ACK	STOP
1 bit	7 bits	1 bit	1 bit	8 bits	1 bit	8 bits	1 bit	1 bit

Figure 3.5: A simple I2C communication protocol, adapted from [56].

Furthermore, Arduino Mega supports SPI (Serial Peripheral Interface) as shown in Fig. 3.6, which can be used to communicate with accelerometers. SPI is also a synchronous communication protocol that operates in full duplex mode, and it is faster than I2C. In this protocol, multiple slaves can be controlled by a single master. It has four wires, namely MOSI (Master Out Slave In), MISO (Master In Slave Out), SCLK (Serial Clock), and SS/CS (Slave/Chip Select). To start communication, the master selects the specific slave device by lowering its SS/CS signal. When the slave is ready, it starts to pay attention to both the MOSI and SCK. Then the master sends a start bit before sending the data. In SPI, both MISO and MOSI can send and receive data simultaneously.

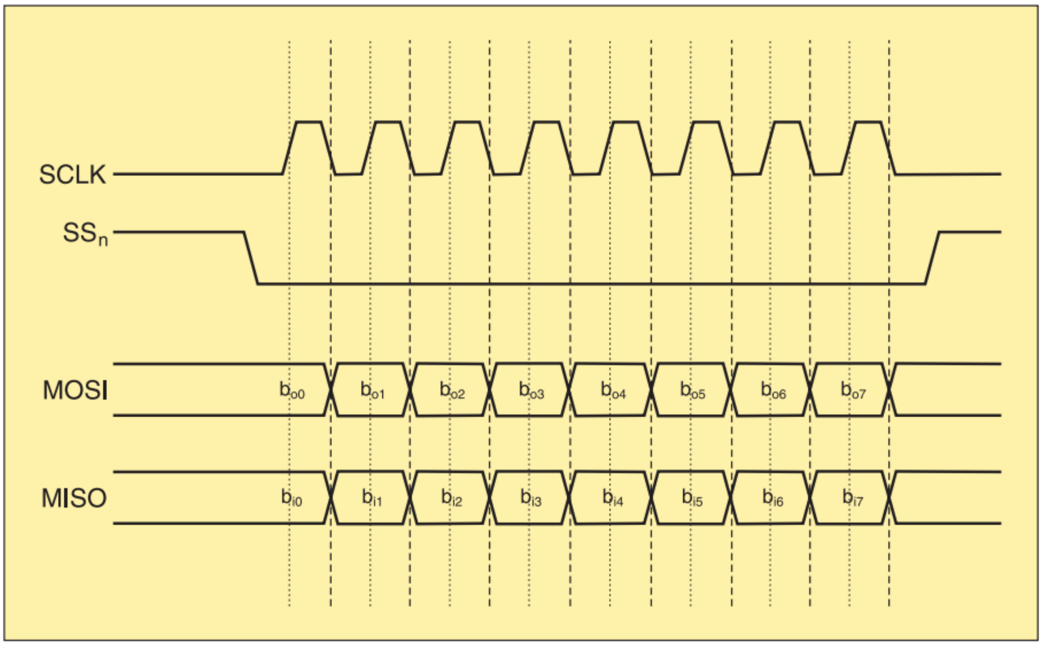

Figure 3.6: A simple SPI communication protocol, adopted from [56].

Apart from the main hardware, additional electronic components such as an I2C multiplexer, multiplexer (MUX), and demultiplexer (DMUX) are required to establish communication between the development board and sensors as shown in Fig. 3.7.

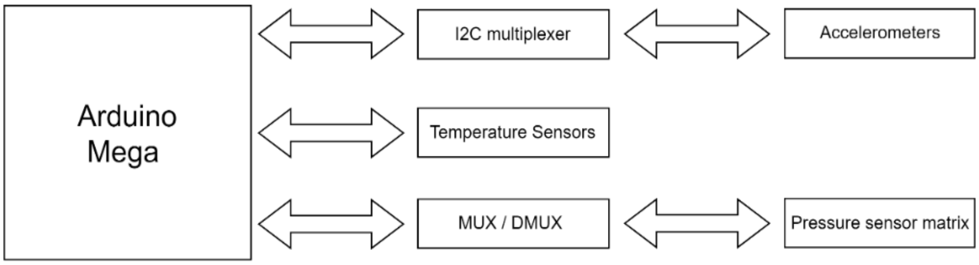

Figure 3.7: Block diagram of a hardware implementation for a multi-sensor framework. Arduino Mega communicates with the accelerometers and temperature sensors through its I2C channel. On the other hand, data from a 4x8 pressure sensor matrix is acquired through an analog channel of the board.

In I2C communication, multiple slaves having different addresses can be connected with the same I2C bus of the master. However, the TCA9548A I2C multiplexer allows Arduino Mega to communicate with accelerometers having the same I2C slave addresses as shown in fig. 3.7. The I2C address of the multiplexer can be configured as shown in Tab. 3.2, to connect 64 sensors having the same I2C addresses with a single I2C bus of the master. On the other hand, temperature sensors have also the same I2C addresses but their addresses are configured using their JP1, JP2, and JP3 pins to optimize the hardware. In this way, all the accelerometers and temperature sensors are interfaced with a single I2C channel of the development board.

Table 3.2: I2C slave addresses of TCA9548A I2C multiplexer to interface 64 sensors having identical I2C addresses with a single I2C bus of a master, adopted from [57].

INPUTS			I^2C BUS SLAVE ADDRESS
A2	A1	A0	
L	L	L	112 (decimal), 70 (hexadecimal)
L	L	H	113 (decimal), 71 (hexadecimal)
L	H	L	114 (decimal), 72 (hexadecimal)
L	H	H	115 (decimal), 73 (hexadecimal)
H	L	L	116 (decimal), 74 (hexadecimal)
H	L	H	117 (decimal), 75 (hexadecimal)
H	H	L	118 (decimal), 76 (hexadecimal)
H	H	H	119 (decimal), 77 (hexadecimal)

In contrast, 74HC4051 is used to acquire data from the 4x8 pressure sensor matrix. It is a single-pole octal-throw analog switch that can be used either 8:1 MUX or 1:8 DMUX. Two DMUXs are used to control the rows and columns of the pressure sensor matrix as shown in Fig. 3.8. In this way, one sensor is selected sequentially, and the matrix becomes a voltage divider circuit as shown in Fig. 3.9. MUX is used to acquire data from the chosen sensor.

This technique optimizes the hardware of the proposed system because the data from 32 pressure sensors is acquired through a single analog channel of Arduino Mega.

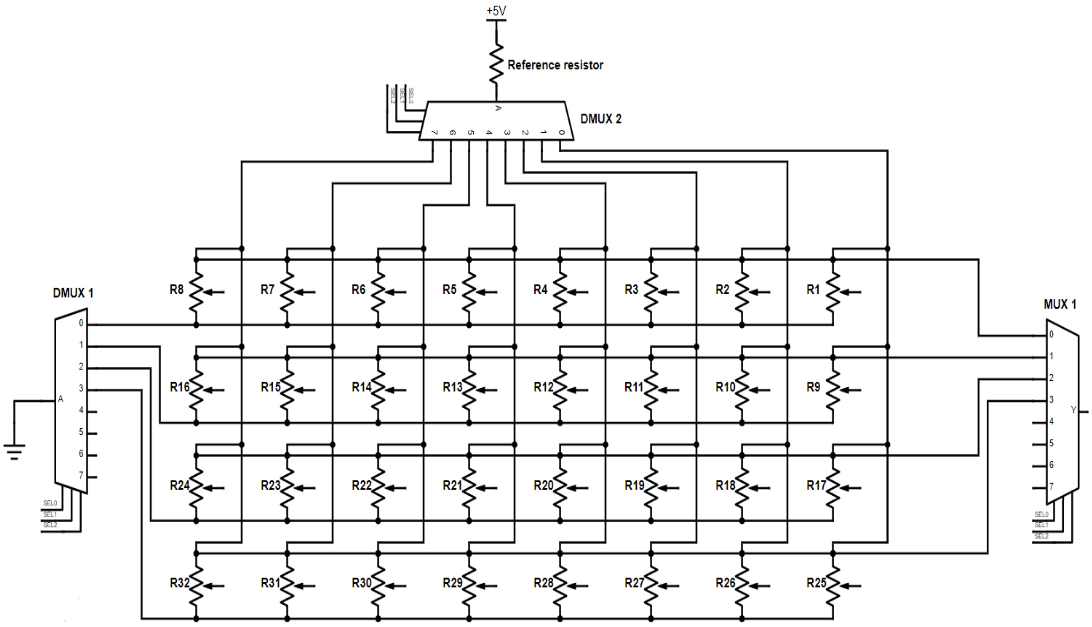

Figure 3.8: Schematic of hardware to acquire data from 4x8 pressure sensor matrix. Variable resistors represent pressure sensors because their resistance changes when pressure is applied.

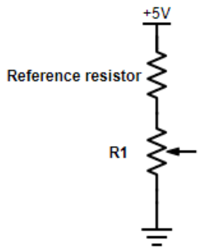

Figure 3.9: Schematic of 4x8 pressure sensor matrix when all the select lines of a multiplexer and demultiplexers are set to boolean zero.

3.1.3 Data acquisition software

To monitor and record real-time information about the risk factors of PU, data acquisition software is required. For this purpose, LabVIEW 2020 Community Edition is used as a development environment due to its several features. First of all, LabVIEW provides extensive hardware access support. Apart from National Instruments (NI) hardware, it can be easily interfaced with third-party instruments such as Arduino Mega. Moreover, its data flow programming model, and modularity nature makes it suitable for the proposed multi-sensor-based system. The interfacing between Arduino Mega and LabVIEW is done through LINX Toolkit. It allows to access the digital I/O, analog I/O, I2C, UART, and SPI of the board.

LabVIEW programs are called virtual instruments (VIs) which consist of two components: block diagram, and front panel. The main programming is done in the block diagram to acquire data from the sensors through the DAQ device. First of all, the initialization of accelerometers and temperature sensors is done to bring them out of sleep mode. Moreover, the resolution of accelerometers is set to maximum (±16 g) to effectively detect the rate of repositioning. The main loop is then used to continuously acquire data from the sensors. Inside this loop, a sequencer is used to control the data execution because all accelerometers and temperature sensors communicate with LabVIEW through a single I2C channel of Arduino Mega. Additionally, a nested loop is implemented inside the main loop to control the select lines of MUX and DMUXs. LabVIEW acquires the voltage values from a 4x8 pressure sensor matrix which is converted into resistance by implementing a voltage divider formula.

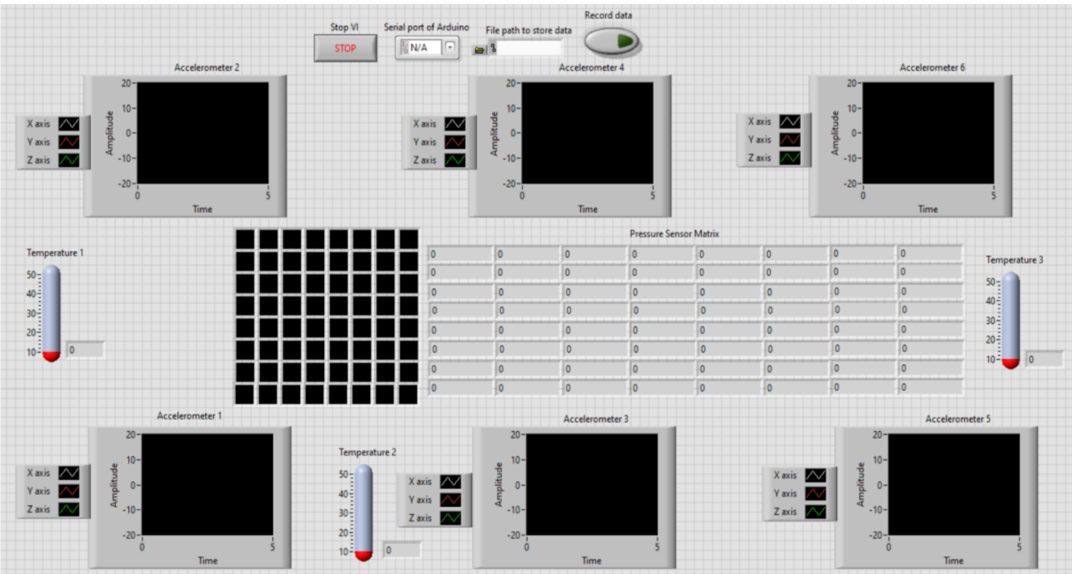

Figure 3.10: The user interface of a multi-sensor framework to monitor and record the data of accelerometers, temperature sensors, and pressure sensor matrix using LabVIEW.

On the other hand, user interface (UI) is developed on the front panel to display the real-time information acquired by the sensors as shown in Fig. 3.10. It also allows the user to start/stop the VI, change the serial port of Arduino Mega, and store the information at the desired location. In the UI, waveform charts are used to display the measurements of accelerometers because they keep the history of data which allows monitoring the rate of repositioning. Next, thermometers with digital displays are used to present the reading of temperature sensors in Centigrade. Finally, the data acquired by the pressure sensor matrix is shown using numeric indicators and RGB colours. Numeric indicators show the resistance values of the pressure sensors while RGB colours map these values into specific colours.

3.2 Complete workflow of a multi-sensor framework

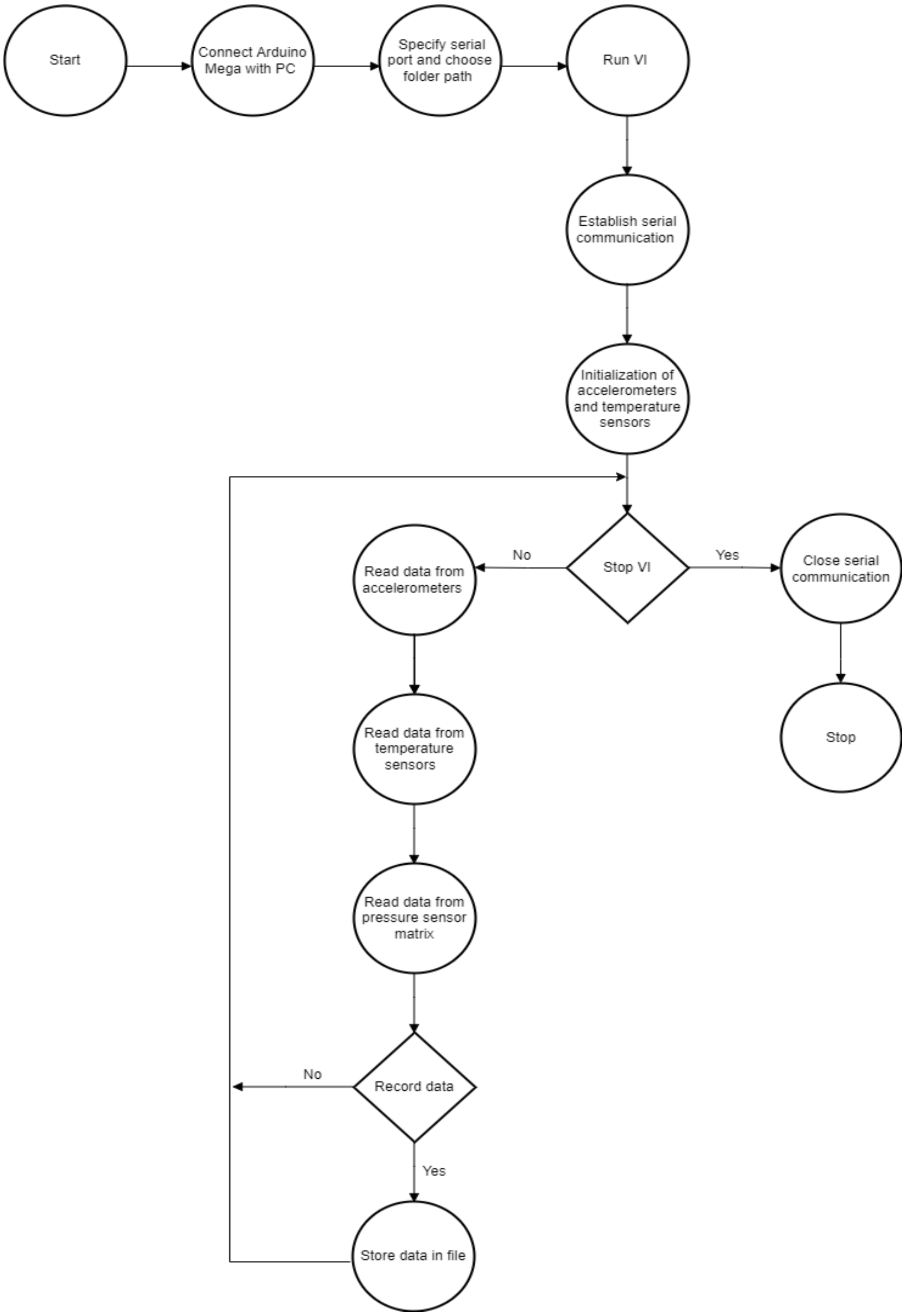

Figure 3.11: Demonstration of a multi-sensor-based system using a state diagram.

The working of the multi-sensor framework is shown in Fig. 3.11. First, Arduino Mega is connected to a computer using a USB cable. Then, the serial port of Arduino Mega and the file path to save data of the sensors is provided on the UI. After that, the family and type of the development board are specified using LINX Firmware Wizard. When the VI started, LINX established a serial communication between LabVIEW and Arduino Mega with a baud rate of 9600. However, the communication is then re-established at the maximum baud rate supported by the board. Next, LabVIEW initialized the accelerometers and temperature sensors using the I2C communication to bring them out of sleep. After that, LabVIEW begins the data acquisition from the sensors via Arduino Mega.

First of all, it acquired the data sequentially from accelerometers using I2C communication. Each accelerometer data consists of X, Y, and Z components of the acceleration which are displayed on the UI using a waveform chart. Then, using the same communication protocol, the data is acquired sequentially from the temperature sensors and displayed on UI in Centigrade. Finally, data acquisition from a 4x8 pressure sensor matrix is started. In this phase, LabVIEW controls the select lines of DMUXs and chooses one pressure sensor sequentially. The voltage across the chosen sensor is acquired through an analog channel of Arduino Mega and converted into resistance. The result is then displayed on the UI using a numeric indicator and RGB colours. The whole sequence of data acquisition is repeated until the user stops it.

During the execution of VI, the user can record the data of sensors in a comma-separated values (.csv) file at a sampling rate of approximately one Hz. The data acquisition is controlled by LabVIEW and the user can start/stop it. When the user terminated the VI, LINX immediately closed a serial communication between LabVIEW and Arduino Mega, and the data acquisition stopped.

3.3 Experimental setup

The proposed system is tested in a real-time environment. Based on the functional requirement of sensors, different tests are performed to verify their reliability and effectiveness in the prevention of PU. In each experiment, the real-time data is recorded in a .csv file using LabVIEW. Following that, MATLAB is used to plot the data for analysis.

3.3.1 Experiment 1:

In the first experiment, a hospital mattress is used, and it is divided into three sections: top, middle, and bottom. An accelerometer is placed on the left and right sides of each section to evaluate their effectiveness in the detection of the position change. For testing, a subject (male, age 31 years, weight 79 kg) lay down on his right side over the mattress for 15 seconds and then changed his position to the left side. The position is then maintained for 15 seconds. The subject performed six repetitions of the position changing. During testing, the measurements of each accelerometer are recorded continuously in three directions (X, Y, and Z). To estimate the rate of repositioning, spikes in the data are considered.

3.3.2 Experiment 2:

In this experiment, a temperature sensor is placed on the top and bottom sides of the mattress to monitor the temperature around the subject's body. Moreover, one sensor is placed on the side of the mattress to monitor the room temperature. For testing, a subject (female, age 26 years, weight 85 kg) lay down on the mattress and her body is covered with a blanket for 15 minutes, then the data is recorded for 25 seconds. Following that, the blanket is removed for 15 minutes, and the data is recorded again for 25 seconds. This experiment is repeated three times and the temperature data is recorded in Centigrade. For analysis of the experimental results, variation between temperature values with respect to covering and uncovering of the subject's body is studied.

3.3.3 Experiment 3:

In order to investigate the effectiveness of textile-based resistive pressure sensors, two tests are performed. In the first test, two different weights (weight 1 = 0.05 kg, weight 2 = 0.25 kg) are applied to each sensor of a 4x8 pressure sensor matrix sequentially as shown in Fig. 3.12. First of all, weight 1 is applied for three seconds and then removed for the same time period. This process is repeated ten times. Following that, the same steps are repeated for weight 2.

Figure 3.12: Testing of the 4x8 pressure sensor matrix with two different weights.

In the second test, a cylindrical object (weight = 1 kg, height = 0.6 m, diameter = 0.08 m) is rolled over the pressure sensor matrix. The horizontal and vertical rolling is done in five and ten seconds respectively and both rolling is repeated ten times. During both tests, the resistance of each pressure sensor is recorded continuously. Moreover, the data of the second test is normalized and then plotted in 3D for better visualization. Experimental results are evaluated based on the decrease in the resistance of the pressure sensors with respect to applied weight.

4 Results and discussion

4.1 Accelerometers results

The effect on the output of accelerometers due to repositioning of the subject over the mattress examined in experiment 1 is shown in Fig. 4.1. The output of each accelerometer is displayed individually using three different graphs representing the X, Y, and Z components of the acceleration. The experimental results indicate that repositioning of the subject produces spikes in the X, Y, and Z-axis.

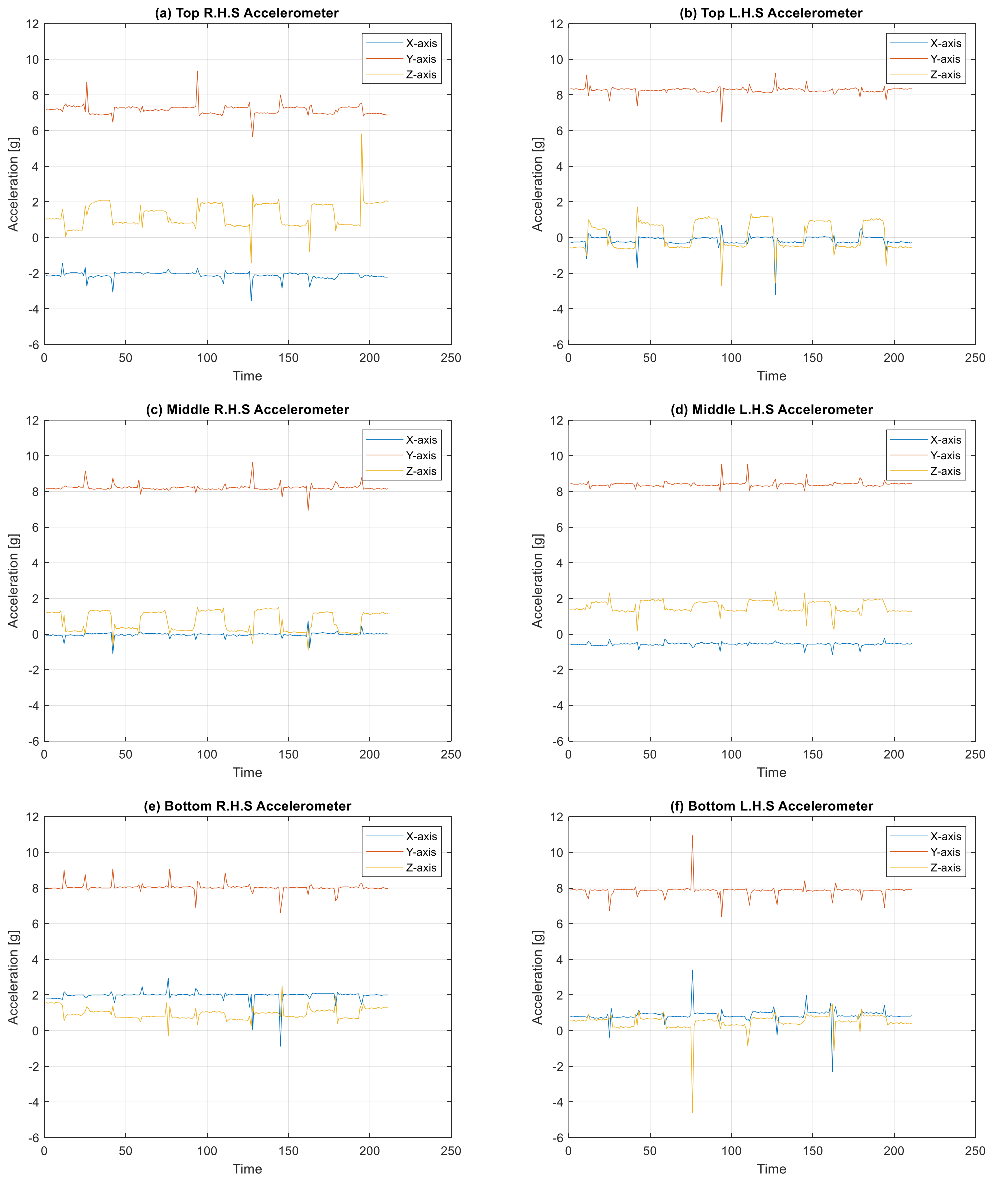

Figure 4.1: Measurements of the accelerometers with a maximum resolution (±16 g) due to repositioning of the subject.

4.2 Temperature sensors results

The results of the temperature sensor around the head and feet of the subject investigated in experiment 2 are shown in Fig. 4.2. When the subject's body is covered with a blanket, it is observed that the temperature around it rises significantly. In contrast, when the blanket is removed, the temperature values decreased. During the experiment, room temperature is recorded around 22 °C.

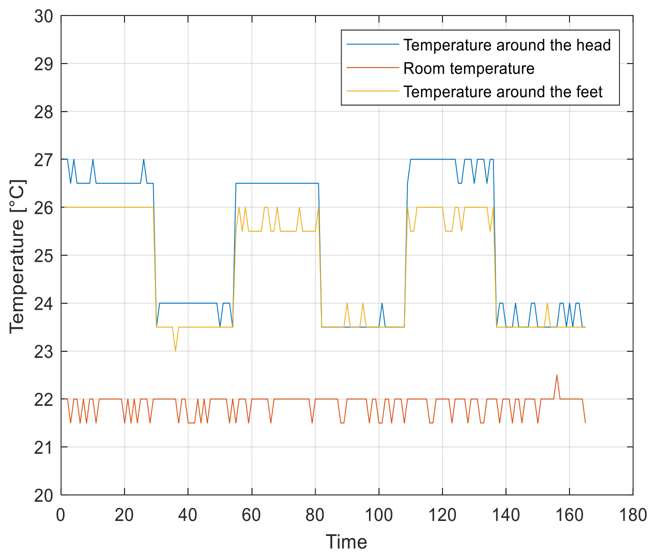

Figure 4.2: Overview of the temperature in a room and acquired around the subject's body during testing. The temperature sensor on the top and bottom sides of the mattress recorded the temperature around the head and feet of the subject respectively.

4.3 Pressure sensor matrix results

The performance of the individual pressure sensors with two different weights studied in experiment 3 is shown in Fig. 4.3. During the experiment, each sensor of the 4x8 pressure sensor matrix is tested. However, the results of the three sensors are presented for analysis. These particular sensors are chosen based on the variation in their baseline resistance due to the manufacturing process. In each graph, the response of a sensor with weights 1 and 2 is represented by a dash and dot lines respectively.

On the other hand, the behaviour of a row and column of the 4x8 pressure sensor matrix due to the rolling of a cylindrical object examined in experiment 3 is shown in Fig. 4.4. The results of both experiments indicate that when weight is applied to the sensors, their resistance significantly decreased. However, the values of sensors return to their baseline resistance after the weight removal.

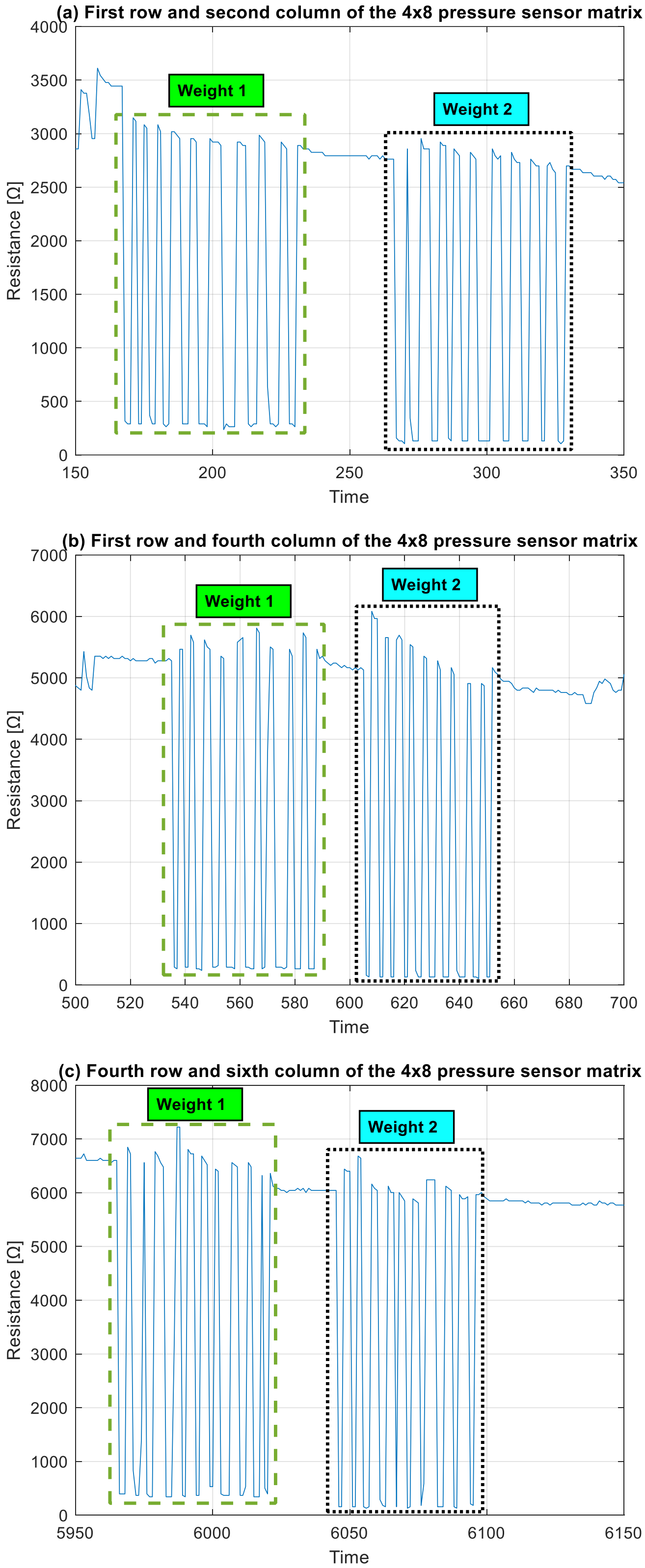

Figure 4.3: From top to bottom, the results of the three individual sensors of a 4x8 pressure sensor matrix with two different weights (weight 1 = 0.05 kg, weight 2 = 0.25 kg).

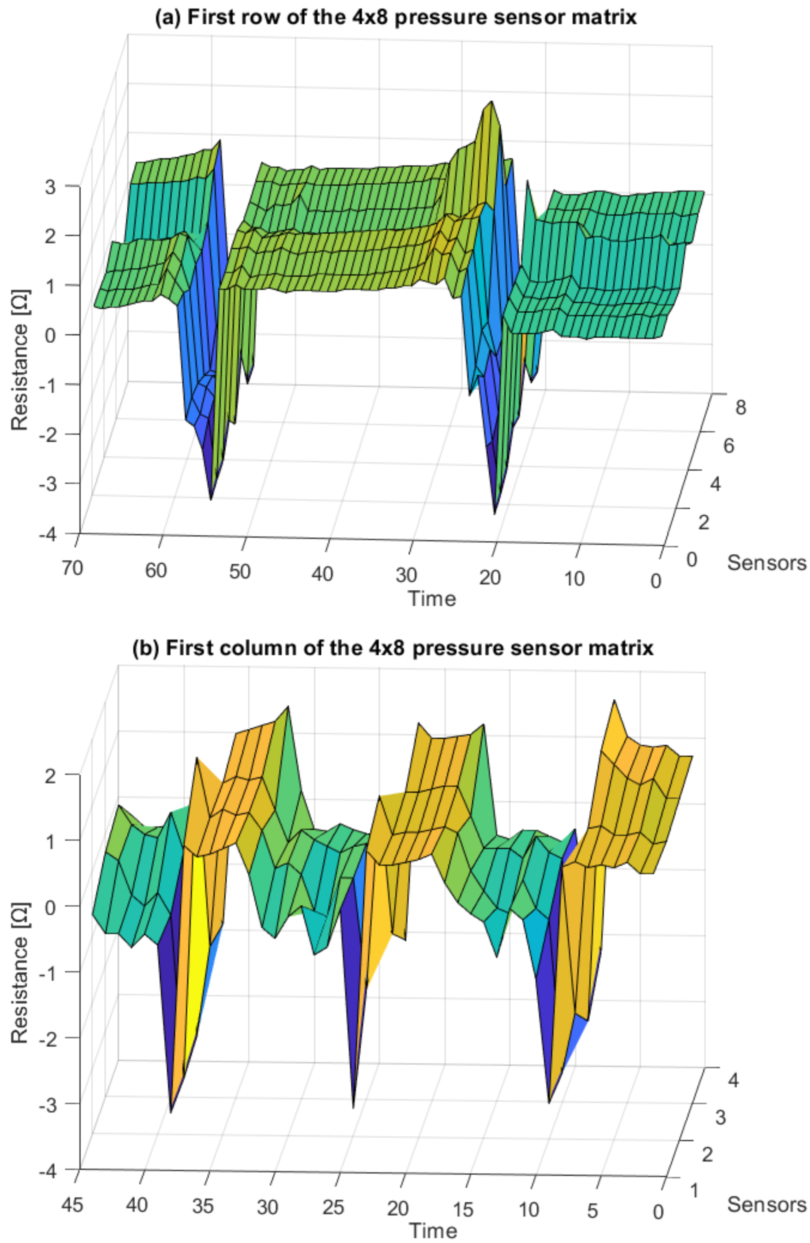

Figure 4.4: Results of rolling a cylindrical object (weight = 1 kg, height = 0.6 m, diameter = 0.08 m) over 4x8 pressure sensor matrix. The top and bottom diagrams represent the effect of horizontal and vertical rolling respectively.

4.4 Discussion

The feasibility and reliability of the proposed multi-sensor-based system to monitor and prevent the development of PU have been tested in real-time. From the analysis of the experimental results, several findings highlight the significance and shortcomings of the system.

First, the proposed system is able to detect the rate of repositioning of the subject over the mattress. The recognition of the movement patterns using accelerometers has been investigated in previous studies due to several reasons [26], [58], [59]. However, in these studies, the proposed system required physical attachment to the human body. In contrast, Hayn et al. [28] developed a system to detect the movements of a person by putting accelerometers on the mattress. However, the placement of these sensors required a special belt system. Our intended system neither needs an attachment to the subject's body nor a belt for the detection of movements. From Fig. 4.1, it can be seen that each time the subject changes its position, it generates spikes in the X, Y, and Z components of the acceleration. The magnitude of these spikes is directly proportional to the intensity of the movement. The baseline values of each accelerometer depend on its alignment with respect to gravity and are expected to unchanged as long as there is no movement on the mattress. The placement and resolution of accelerometers are appropriate to effectively detect the whole-body movements over the mattress as shown in Fig. 4.1 and thus have the potential to be used for the monitoring and prevention of PU. However, it seemed challenging to detect small movements due to noise. This concern can be solved by defining the threshold value of the X, Y, and Z components of the acceleration and filtering the data of sensors [28]. The optimal threshold values could be chosen by testing the system with subjects having different weights.

Second, the proposed framework is capable to provide real-time temperature around the human body. In previous studies [39], [41], a temperature sensor is embedded in a wearable electronic patch to detect the temperature around the high-risk location to aid in the prevention of PU. In contrast, the temperature sensors in our system don't need to be placed on the subject's body and can detect a rise in temperature around the body due to less air exposure as shown in Fig. 4.2. A similar trend has been noted earlier [38], however, the abrupt changes in our temperature values happened because the data is recorded with a 15-minute time off. However, the sensors are capable to provide real-time temperature data with a sampling rate of one Hz. In addition, the sensors are able to monitor the temperature with an accuracy of ±1 °C around the subject's uncovered body as shown in Fig. 4.2 and therefore can aid in the monitoring and prevention of PU. The significance of the system can be improved by adding more sensors to monitor the temperature around the areas at high risk of developing PU [2]. However, a previous study [38] and results investigated in experiment 2 suggest that the addition of one sensor per risky area could be beneficial.

Third, the textile-based resistive pressure sensors in our system can detect applied weight. Unlike capacitive pressure sensors [30], it is noticed that the response and relaxation times of these sensors are less than one second. It indicates the sensors are effective to detect pressure changes instantly and could be valuable when a patient is at high risk of developing PU [17]. From

Fig. 4.3, it can be seen that the pressure sensors have good stability under constant weight. However, a small variation in their baseline resistance is observed under no weight or when weight is applied to an adjacent sensor. On the other hand, deviation in the response of individual sensors is observed as shown in Fig. 4.4 during cylindrical object rolling. It occurred because each time the object is rolled with a different force. The main advantage of these sensors is that they can be placed on the lying surface to get pressure distribution without any physical attachment to the human body. However, the main constraint of these pressure sensors is that they can only provide pressure distribution at small weights because unlike previous studies [35], [36], the resistance of these sensors becomes less than 200 Ω at 0.25 kg as shown in Fig. 4.3. To be effective in the prevention of PU, these textile-based resistive pressure sensors are required to provide pressure distribution at higher weights as well [17], [35], [36].

5 Conclusions

In this thesis report, a multi-sensor framework for the prevention and monitoring of PU in bedridden patients is presented. It is designed in such a way as to provide minimal discomfort to the patients and cause only limited change in the standard operating procedures of the relevant medical staff. The intended framework comprises of sensors that acquire information regarding several primary risk factors of PU, most notably flexible textile-based pressure sensors. The entire system is built around modular control unit that handles data manipulation and storage, and an informative graphical user interface that visualizes all acquired signals and helps in the assessment of relevant PU risk factors. Preliminary experimental evaluation indicates that the system is capable to robustly provide real-time information about the subject's full body movements, temperature around their body, and finally the pressure distribution over their body segments during sitting or lying. Moreover, the system is able to indicate the usability of the selected sensors for the given PU detection applications. For instance, it has been determined that the used pressure sensors would require some improvement in order to prevent saturation under higher anticipated loads.

In the future, the performance of the proposed system should be improved by extending the signal processing capabilities of the system for more informative observation of all PU associated risks.

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