EPILLOW: A FABRIC-BASED PRESSURE SENSOR ARRAY FOR TETRAPLEGIC PATIENT CALL DETECTION SYSTEM

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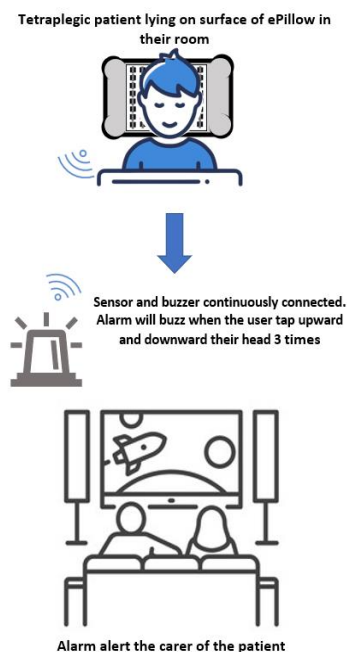[b]Biosensor and Embedded Systems Laboratory, Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
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Graphical abstract

Tetraplegic patient lying on surface of ePillow in their room

Sensor and buzzer continuously connected. Alarm will buzz when the user tap upward and downward their head 3 times

Alarm alert the carer of the patient

Abstract

Call bell systems play an essential role in patient and nurse interaction in hospitals and at homes. However, many hospitalized patients, especially patients with tetraplegia, cannot press a call bell button for assistance due to hand weakness or paralysis from the neck down. This problem has motivated developing a fabric-based multi-array pressure sensor as a call bell garment, named ePillow, that works by detecting the pressure pattern on a pillow surface where the patient is lying down. In this study, off-the-shelf materials were utilized to form: i) a fabric-based multi-array pressure sensor system, ii) an acquisition circuit along with an interface, and iii) a signal processing algorithm to acquire and interpret the sensor data. To ensure the functionality of the proposed ePillow, a color-coded mesh plot was developed to visualize the sensor data. The reliability of the system was tested with two individuals. The pressure profile of the proposed ePillow shows a comparable profile to that of the commercialized pressure sensor. Findings from this case study have demonstrated the ability to map the force on the surface of the pillow and subsequently the location of the force applied with 71% accuracy and 70% sensitivity.

Keywords: Call Bell System, Fabric Based Pressure Sensor, Patient Assistance System, Pressure Mapping, Smart Pillow, Smart Sensor Array

Abstrak

Sistem loceng panggilan memainkan peranan penting bagi interaksi pesakit dan jururawat di hospital dan di rumah. Namun, sebilangan besar pesakit yang dirawat di hospital, terutama pesakit tetraplegia, tidak dapat menekan butang loceng panggilan untuk mendapatkan bantuan kerana ketidakupayaan tangan atau lumpuh dari leher ke bawah. Masalah ini telah mendorong penciptaan sensor berasaskan kain sebagai loceng panggilan, bernama ePillow, yang berfungsi mengesan corak tekanan pada permukaan bantal pesakit sebagai alatan panggilan. Dalam kajian ini, alatan komersial digunakan untuk membentuk: i) sistem sensor berasaskan kain, ii) litar algoritma pemprosesan isyarat dan iii) penafsirkan maklumat sensor. Untuk memastikan fungsi ePillow yang dicadangkan,

plot mesh berkod warna dikembangkan untuk memvisualisasikan maklumat sensor. Kebolehpercayaan sistem diuji dengan dua individu. Profil tekanan dari ePillow yang dicadangkan menunjukkan profil setanding dengan sensor tekanan yang dikomersialkan. ePillow, ini mampu mengenalpasti kedudukan tekanan dengan ketepatan 71% dan 70 % kepekaan.

Kata kunci: Sistem Loceng Panggilan, Sensor Tekanan Berasaskan Kain, Sistem Bantuan Pesakit, Pemetaan Tekanan, Bantal Pintar, Array Sensor Pintar

1.0 INTRODUCTION

Tetraplegia is a condition where motor and sensory function in the cervical segment of the spinal cord is lost due to damage of neural elements within the spinal canal. Tetraplegia results in impairment of function in the arms as well as the trunk, legs, and pelvic organs [1]. Herrmann *et al.*, 2011 indicated that the majority (97.3 %) of tetraplegia patients had a loss of every system of the body, including bladder functions, muscle tone, motor reflex functions, and respiratory system. There is no movement ability or sensations from the neck down, requiring the patients to be assisted most of the time. Due to paralysis of the abdominal muscles, the voice and speech is also affected. Tetraplegic patients cannot do most of daily life activities such as bathing, toileting, eating and drinking independently thus they need full assistance [2]. A call bell is one of the most important tools for tetraplegic patients to signal the nursing staff or health attendants to attend to their daily needs. Traditionally the calling device was made to be activated by the upper limb or the patient's head. A large bell and cross-pieces of pipe were invented so that the patient can use it by bending his head or by blowing the 'bell' to produce sound [3]. However, in general, this method is only applicable for those who had a lower neck injury. When there is a higher level of neck injury, the head movement is limited [4]. To make matters worse, tetraplegic patients mostly experience paralysis of the abdominal muscle, thus have weak expiration and limited voice production ability. This, in turn, makes it more difficult for them to call the nurse using conventional methods[5]. This paper, therefore, aims to address this limitation through utilization of a novel ePillow system.

The fabric-based pressure sensor is gaining research interest in the field of biomedical engineering [6]. This is due to the practicality of wearable technology for a wide range of biomedical applications such as gait investigations, bed sores monitoring, and anti-fall alert system [7]. The need for integrated sensors that are wearable, comfortable, and straightforward to be used is increasingly demanded[8]. Thus, integrating fabric-based pressure sensors into a body measurement system might be a better option. A piezoresistive fabric-based pressure sensor is the most popular fabric sensor due to its simplicity, low cost, and reliable performance [9]. The sensor properties can be manipulated by altering the combination of conductive fabric and piezoresistive layers, from which the combination forms pressure sensing elements [10]. A piezoresistive fabric-based pressure sensor is configured into a single unit sensor of a multi-array depending on the measurement requirements [11]. In rehabilitation, surface pressure measurement is used to monitor and control the development of pressure ulcers in paralyzed patients, diabetic foot patients, and for prosthetic users, it is used to monitor their residual limbs[12]–[15]. In the field of biomechanics, surface pressure sensors are used to measure athlete performance normally by using fabric sensors in the form of socks for better gait and comfort [16]. Apart from these, surface pressure measurements are increasingly being considered in wearable devices such as data gloves [17] and heart rate breathing jackets [18]. For these reasons, surface pressure measurement is becoming important, which has triggered diverse investigations to further improving its functionalities and system performances suitable for various biomedical applications.

In this paper, we proposed a smart call detection system, called ePillow, to detect the pressure from the tetraplegic patient's head position and use it to activate the alarm system. The proposed approach is different from the other pressure sensors available in the market. Our ePillow is capable of measuring localized pressure produced by the patients in real-time, and more importantly, it is based on fabric materials, thus provide comfort to the user. In this paper, the design of the proposed fabric sensor array is discussed, and its working framework is proposed to address the challenges in determining the tetraplegic person's head position and pressure pattern.

The contribution in this paper is three folds. Firstly, a fabric-based pillow system was developed to detect the pressure exerted by a tetraplegic patient to activate the alarm at the nurse counter. The system consists of a fabric-based pressure sensor array, a conditioning circuit, a processing unit, a display unit, and a wireless alarm system. Secondly, various methods of constructing fabric-based sensor arrays were evaluated. The effect of utilization of mesh layers and type of piezoresistive material was analyzed in

terms of its multi-array sensor performance. Thirdly, an algorithm for position pressure mapping recognition was presented in order to differentiate the head movement pattern. The ePillow system performance was then evaluated. The experimental results showed that the system was able to differentiate between the pressure patterns produced by the user's head for buzzer activation in lying down conditions with 71% accuracy and 70% sensitivity. This method is also applicable for other applications that demand flexible pressure sensing platforms.

2.0 METHODOLOGY

In this project, a fabric sensor system was developed to be used in hospital settings and could also be extended for home users. Therefore, the essential problem is on how to make the system straightforward to be deployed, convenient to access, and simple to be used. More importantly, it should be flexible and comfortable for the users. In addition, the system should also be affordable and compatible with existing call bell systems. Figure 1. shows the architecture of the proposed ePillow system. Basically,
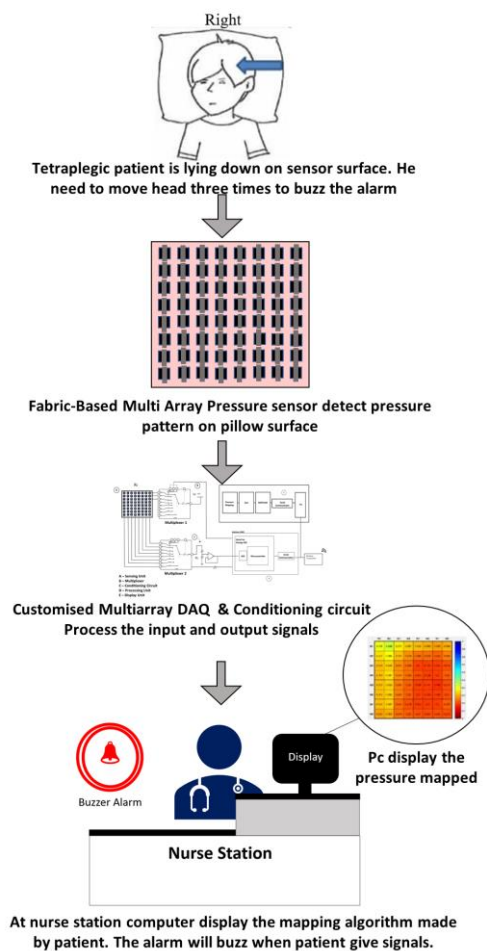
the system was constructed using five main components: a fabric-based sensor array, a signal conditioning circuit, a processor unit, a wireless buzzer alarm, and a customizable data acquisition unit.

The fabric-based sensor array captures the head pressure distribution produced by the user while laying their head down on the ePillow. Then, the data sampling unit acquires the sensor values and transmits the data wirelessly to the processor unit. The processor unit analyzes the sensed data and maps it according to the patient's intention, which then triggers a notification at the nurse's table. Figure 2. shows the implementation of the proposed fabric-based sensor array in ePillow. The total sensor surface is 0.3 x 0.3 m^2, where the area of each square sensing area is 0.02 x 0.02 m^2 as each row, and the column bus is 0.02m wide, and the space between the sensors is 0.01m.

Figure 2 Fabric-Based pressure sensor array in ePillow system

The construction and the design structure of the sensor array are presented in Figure 3. The construction of a piezoresistive fabric-based pressure sensor is the simplest architecture as compared to the other related fabric-based sensors[19], [20].
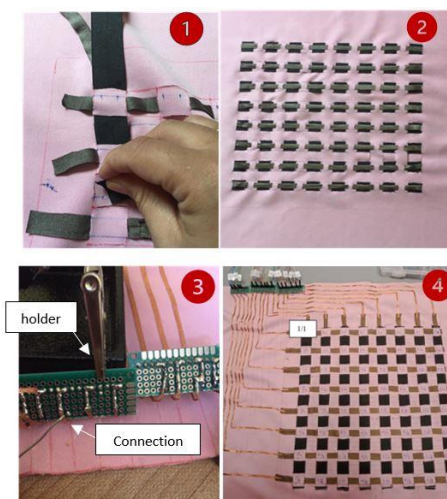

Figure 3 Procedure to construct multi-array fabric-based pressure sensor using weft and waft technique.1: Wrapped piezoresistive materials on top of wafted conductive materials. 2: wraps horizontally conductive materials on top of piezoresistive material until complete 64 cells. 3: Circuit board was placed at the edges of the sensor and rows are linked in array manner. 4: completed Multi-array Fabric Based Pressure Sensor

Figure 1 ePillow architecture

The proposed sensor can be constructed by sandwiching three basic materials as illustrated in [21] and combine all the materials into a multi-array sensor using the weft and wraps technique. A conductive material is on the topmost layer and the bottommost layer, while the piezoresistive material is positioned in the middle. To protect the circuit from a short circuit, a non-conductive fabric was used as a protection layer. In this case, a conductive fabric (MedTex130, Shieldex Trading, USA) [22] was chosen. The conductive knit fabric was made up of 78% Nylon, 22% elastomer, and 99% pure silver with surface resistivity of less than $5\Omega/m^2$. The conductive fabric was constructed with 0.45mm thickness and $140g/m^2$ density. The conductive fabric was used as a conductor to transport current in and out from the sensor and was sandwiched onto and bottom of the piezoresistive material. A non-conductive fabric (Neoprene) was used as a protective layer.

The data sampling and conditioning circuit was designed based on an Automatic Voltage Regulation (AVR) microcontroller platform with a multiplexing technique. A wireless module was built on the board to enable wireless data transmission. The wireless board was paired with a receiver unit on the nurse station that consisted of a buzzer alarm and a computer for data processing and real-time position mapping. Data storage and analysis were performed in a processor unit, including the head pressure analysis, pressure mapping, and alarm activation. Considering high potential use in the hospital and for further data analytics, a user-friendly mapping application was developed for computers or laptops, which can conveniently display real-time feedback of laying down head pressure distribution and facilitated continuous visualization of the head position.

For the data acquisition system, three important elements are involved in this ePillow system hardware system, software system, buzzer alarm system. The Hardware system was build using commercially available electronics tools, which are: AVR based as processing unit, two units of CD4051B Analog Multiplexor, a unit of LM324 op-amp, and 10KΩ resistor (Figure 4). The build-in ADC within the microcontroller can read analog signals at a certain voltage range; for this case, the signal from the sensor needs to be conditioned to the 0-5V range. To achieve this, a conditioning circuit is required. In this study, a voltage divider technique was employed. Each sensing unit is configured to be connected to a fixed 10kΩ resistor with multiplexing techniques. The output voltage terminal is connected to the analog input pin of the microcontroller. The equation of voltage output is as follows:

Where R1 is the fixed resistor and R2 is the resistance of the selected sensing unit. The Output voltage is, therefore, a function of force or pressures due to changes of the R2 sensing element.

Reading sensor data needs to be acquired one at a time. Since the sensor is arranged In a matrix array configuration, it is important to used n analog switch that can act as a multiplexer that connects only to one selected analog or digital input at a time and forward it into a single connection. For the 8 × 8 array sensor, IC CD2051B was chosen as the multiplexor unit, which acted as a solid-state switch with a rapid switching frequency. This property enabled the microcontroller to read signals from all the sensing elements. A voltage follower constructed using LM324 op-amp was used to ensure stable voltage at the ADC input terminal.

The software system-pressure mapping recognition, a microcontroller, was programmed using a standard integrated development environment (AVR IDE) software. The serial monitor displays the analog signal in the form of digital representation in real-time from one output channel at a time. Due to the abundance of data from a multi-array fabric-based pressure system, mapping algorithms were created using the MATLAB program. Visualization of sensor data was done using MATLAB by constructing a color-coded mesh plot. This plot is collated with the amount of force applied to each individual sensor. The scale color ranges from dark blue, light blue, green, yellow, orange, and red. The colormap response changed in accordance with the amount of force applied to each sensing element. When a greater amount of force was applied, the acquisition system detected a decrease in voltage at the sensor cell. The cell on the pressure mapping screen that represented the location of applied force would change in color according to the magnitude of force applied on the sensor cell. At the freeloading condition, the sensor value displayed on pressure mapping was dark blue. When slight force is applied, the pressure mapping cell will change color to light blue, green, yellow, orange, and red, corresponds to the increased force application.

The buzzer alarm system consisted of a transmitter and receiver circuit boards. The transmitter circuit was attached to the sensor reading hardware presented earlier. Additional components were the NRF24L0 module as the wireless transmitter and a pair of red and white LED. or the receiver circuit board; NRF24L0 was used to capture the transmitted wireless signal containing sensor data. An AVR-based microcontroller is employed as the processing unit along with a buzzer to alert the caregiver. The receiver is located at the hospital's counter or near the caregiver. An algorithm was formulated to classify the force pattern and then inform the caregiver if the signal matched the preprogrammed pattern. The buzzer would be activated when the user taps the sensor three times.
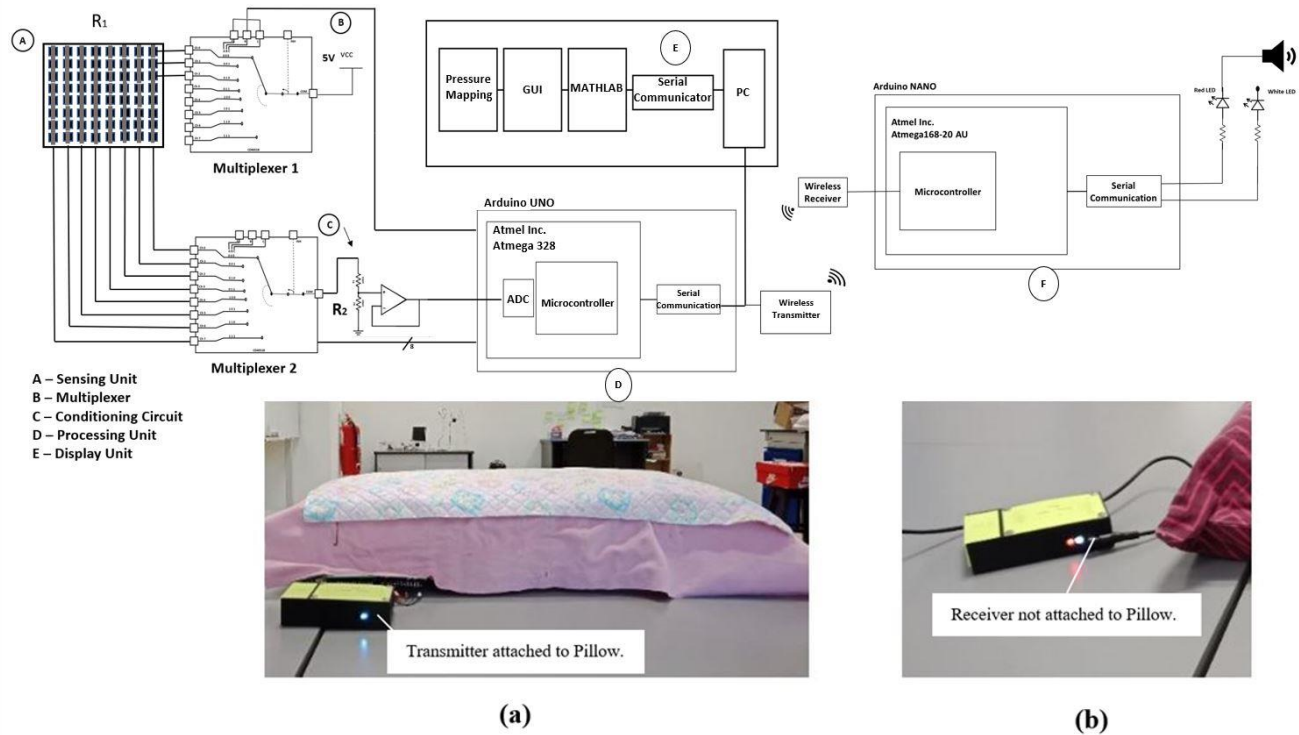
$$V_{Out} = V_{In} \frac{R1}{R2+R1} \quad (1)$$

Figure 4 ePillow Hardware system (a) Processing Unit (b) Buzzer Alarm Circuit

3.0 RESULTS AND DISCUSSION

There are four experiments reported in this section, respectively. The first experiment is the reports of factors that influence the fabric-based pressure sensor performance. In these experiments, 14 designs had been developed that are fall under these three categories; type of piezoresistive materials, type of non-conductive materials, and sewing technique. The second experiment was to investigate the effect of multi-array fabric-based pressure sensors with different internal layers, and four designs were developed in this experiment. The third experiment was done to investigate the ability of the ePillow system to locate the position of force on a multi-array fabric sensor on a flat surface in real-time. Meanwhile, the fourth experiment was done to investigate the performance of the ePillow system on pillow surfaces using two subjects, one healthy subject, and one tetraplegia subject.

In this study, it was found that piezoresistive fabric-based pressure sensor performance was highly affected by three main factors, namely, the type of piezoresistive materials, the choice of non-conductive materials, and the sewing technique. These properties were investigated and reported as follows. Piezoresistive materials are the core structure of piezoresistive fabric-based sensor that influences the resistance properties of the sensor. It was reported that Velostat and Eeontex[23] are the most popular piezoresistive materials used in fabric-based pressure sensor construction. Velostat is made from carbon that is fused into the plastic sheet, while

Eeontex is made from carbon fused into the fabric sheet. The properties of the materials are shown in Table 1.

Table 1 The properties of piezoresistive material

Material Properties	Velostat	Eeontex
Part Number	Velostat	EeontexNW170SLPA2K
Surface resistivity	<31,000Ω/sq.cm	2000Ω/sq.cm
Density	17g/m^2	18.66 g/m^2
Thickness	0.2mm	0.80mm
Material	PLA Plastic	Nylon Fabric

*The properties are adapted from the datasheet of Velostat and Eeontex, which can be downloaded from [24]

From this datasheet, it stated that at zero force, Velostat has higher surface resistivity compared to Eeontex. In terms of texture, due to different types of material, Eeontex does not easily crumple compared to Velostat because it is made out of fabric. An experiment was conducted to compare the properties between Velostat and Eeontex in a real situation when being folded. This experiment is very important because it will affect the performance of ePillow when being exposed to head pressure movement. Samples from each Velostat and Eeontex were prepared into 5 x 5 cm^2 square-shaped pieces. The resistance between two endpoints of the diagonal line on the sample was measured and recorded. It should be noted that the distance of the measurement would influence the resistivity values. A

Proskit MT-182 multimeter was used to measure resistance. The samples were then folded 1-fold, and measurement was taken during the folded condition. The folding and measurement procedure was repeated until the maximum possible folding, which was 5-fold. Folding is a technique used to understand does the material being affected by crumpling since the application was mean to be as a pillow garment. The experiment was illustrated in Figure 5. The collected data were recorded and plotted as in Figure 6.
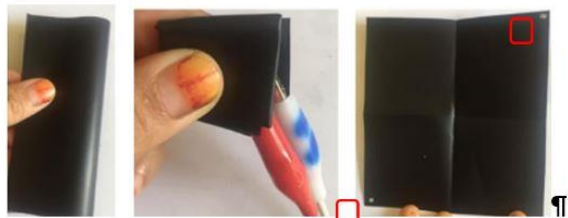

Figure 5 Experiment on piezoresistive materials Velostat and Eeontex. The resistance between two endpoints of the diagonal line on the sample (red square) was measured and recorded. Both materials were fold from 1 until 5 maximum folds. The experiment were repeated for 3 times
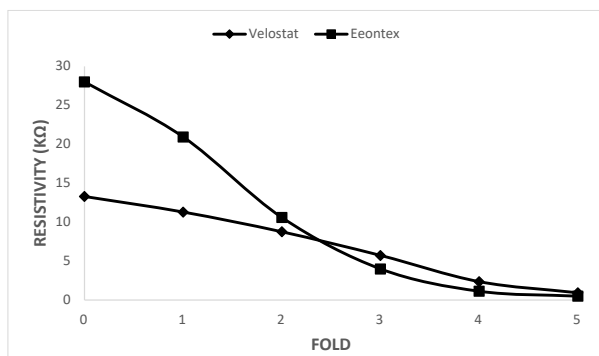

Figure 6 Graph performance of Velostat and Eeontex

From this data, before the experiment started at zero fold, there are clear differences of initial resistivity values between Velostat and Eeontex. Eeontex has 30 KΩ resistivities while Velostat has 15 KΩ initial resistivities. The obtained values are comparable as reported from the published datasheet [24]. Velostat had a sharper decrease of resistivity as compared to Eeontex with an increased number of folds. Both materials showed resistance saturation when folded into 4 and 5-fold resulting 0KΩ resistivity. From observation, when Velostat was being folded, folding marks were left on its surface and cannot return to its original smooth texture, while Eeontex does not leave any folding marks on its surface. When we unfold Eeontex, it returns to its original smooth texture. From this experiment, it was concluded that the type of materials, either Velostat or Eeontex, will have a different response and resistivity changes when in pressed or folded condition. From this experiment,

Eeontex is better to be used in the ePillow system based on its' response and resistivity change when in pressed or folded condition.

The choice of non-conductive fabric plays an important role in ensuring all the components of the sensor are intact and properly isolated. The sensor should not easily crumple and maintain its position on the pillow surface, even with the person lying down on it. The fabric should not absorb too much water, is smooth enough, and not too rough that might cause irritation to the skin. For this experiment, comfortability was defined as in Table 2, while Table 3 described the performance of non-conductive materials.

Table 2 The definition of comfort for ePillow

Comfort Parameter	Definition
Soft next to skin	The fabric should be soft, not causing irritation to the skin, such as rashes or redness in contact.
Moisture permeability	When perspiration, the fabric allows moisture vapor to pass through its structure.
Thermal conductivity	From body heat, the fabric able to conduct heat on the area.
Stretch Recovery	The fabric is able to stretch under deformation and recover to its original position after removal of deformation.
Dimensional stability	The fabric is able to remain stable without change in its dimension after being crumpled or washed.

Table 3 Performance of non-conductive materials

Types of Fabric	Material Performance				
	A	B	C	D	E
Lycra	No	Yes	No	Yes	No
Felt	Yes	No	Yes	No	Yes
Rubber	No	Yes	No	No	No
Sports Knit	No	Yes	No	Yes	No
Neoprene	Yes	Yes	Yes	Yes	Yes

A: Non-wrinkle   C: Easy to sew   E: Stable
B: Slightly flexible   D: Comfortable

In this investigation, it was found that Lycra, Sports knit, and rubber is a very flexible and stretchy fabric. This makes them very difficult to sew. As time goes by, the materials become easily wrinkled and not stable when we put them on the surface of a pillow. Meanwhile, felt and Neoprene is both easy to sew and non-wrinkle. When being squeezed and being put on the pillow surface, both fabric surfaces were still stable. However, between Felt and Neoprene in terms of comfortability, Neoprene is more comfortable to the skin. In conclusion, Lycra, Sports knit, and rubber is not the best choices, as it is

relatively more difficult to sew and put all the sandwich materials together due to their highly stretchable properties. The best non-conductive fabric among these materials is Neoprene, as it is flat and stable on the surface, not too stretchy, easier to sew, and not easily wrinkled. The neoprene material is the most suitable protective layer for multi-array fabric-based pressure sensors.

Sewing is the third category as a contributing factor that influences fabric-based sensor performance. Sewing was done mainly to ensure the electrical connectivity of the sensor, alignment of the sensing elements, and all the sandwiching layers are in place for effective multi-array design. Throughout the sensor development, 7 designs had been developed using a different method of sewing. It was found that the sewing technique affects the performance of the sensors. Conductive fabric cannot be directly sewn on the surface of piezoresistive materials as it caused micro-contact between two conductive fabrics on the top and bottom layers, which in turn causes a short circuit. The wefts and warps technique (Figure 3.) showed positive results, whereby all units were able to detect individual pressure as well as multiple applied forces. The technique was simple to be sewn, stable on any surface, and comfortable when one lays down on it. In conclusion, for experiment one, there are three factors that influence the fabric-based pressure sensor performance; the first one is the type of piezoresistive material, secondly types of non-conductive material, and lastly, sewing technique. From the investigation, it can be concluded that for

an effective multi-array fabric-based pressure sensor to be implemented, the best piezoresistive material is Eeontex. In comparison, Neoprene is the best intact fabric for ePillow. Wefts and warps sewing technique for its stability and non-wrinkle properties.

Now, let's shift to the second experiment. This experiment was to investigate the effect of a multi-array fabric-based pressure sensor with different internal layers. Bianchi *et al.* had applied multiple layering techniques using mesh fabric, multi-layer of piezoresistive fabric, and spacer layer [25]. Any changes of the basic layer would affect the sensor properties, whereby changing the number of piezoresistive materials and geometry of the conducting electrode on piezoresistive materials did affect the range and sensitivity [26]. Thus, another experiment was conducted to investigate which layering technique is most suitable for the ePillow system. Four sets of sensors designed as in Figure 7 were constructed and investigated. The sensor was constructed using MedTex 130 as the conductive fabric, Velostat, and Eeontex NW170SLPA2K as piezoresistive fabric, and Nylon meshes with 0.3mm openings as mesh layer. The use of MedTex130 conductive fabric was maintained throughout all four constructed sensors and sandwiched as top and bottom layers. The only change made was on the middle layer construction, labeled as set A, set B, set C and set D. The middle layer of set A consisted of Velostat only, middle layer of set B were made of Velostat and mesh layer, set C made of Eeontex only, while set D consisted of Eeontex and mesh layer.
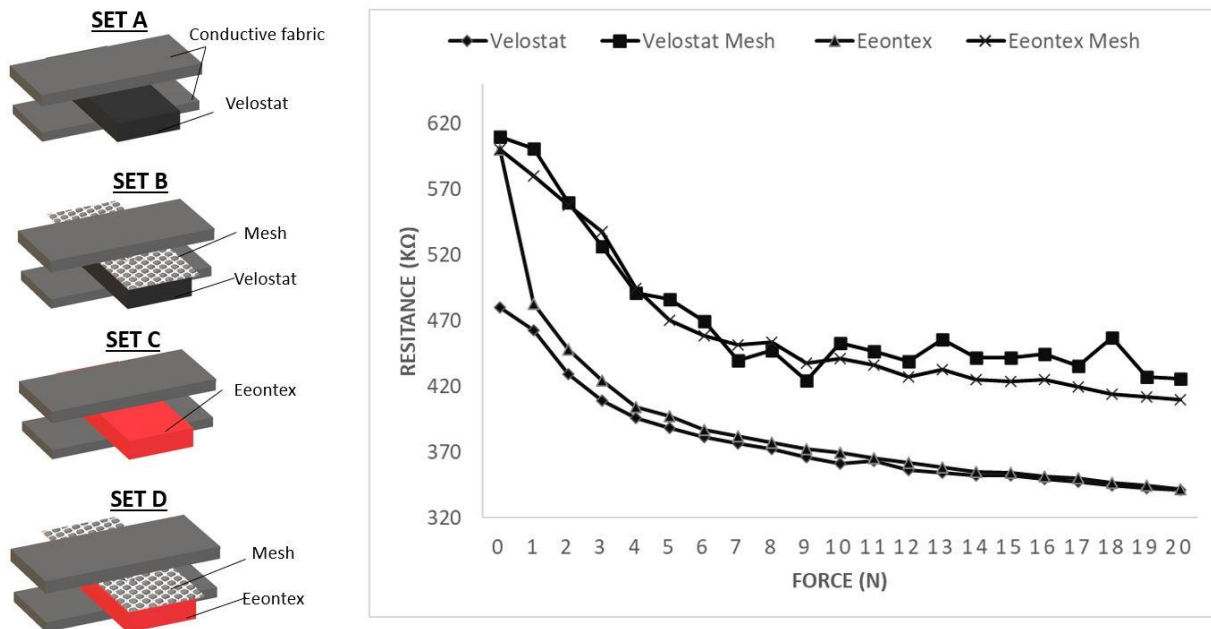

Figure 7 Multi-array Fabric Based sensor performance with different type of internal layer . The grey block represented the conductive fabric (MedTex 130) that is used throughout all design. The black block the Velostat, while the red block illustrates the Eeontex. The white block represented the mesh layer. The graph is the result of the overall sensor performance. Set A is Velostat , Set B is Velostat & Mesh , Set C is Eeontex and finally Set D is Eeontex & Mesh

Advance Force Gauge (AFG 500,850-419) was used to measure force onto each set from 0N until maximum 22N. All the external factors such as temperature, table, wires, humidity and tools were maintained throughout the experiment. All experiment procedure was repeated three times for all changes of force. The data was recorded and draw as shown in Figure 7. The graph in Figure 7 proves that , changes of materials inside the fabric sensor resulted in significant differences in term of sensitivity , consistency and resistivity. At zero force, Eeontex and sensor with additional mesh layer had high initial resistivity at 600 KΩ while Velostat only are the lowest initial resistivity at 470 KΩ. With the presence of mesh layer, the ability of the sensor to detect higher force was increased, however the captured data showed relatively higher inconsistency especially when Velostat mixed with mesh layer. In essence, the best combination for this experiment is conductive fabric and Eeontex, where the sensor manage to have high initial resistivity , the resistivity gradually decrease with additional force and not quickly saturated when higher forces was applied.

Next, a third experiment was done to investigate the ability of the ePillow system to locate the position of force on a multi-array fabric sensor on a flat surface in real-time. The developed mapping system was tested using an Advanced Force Gauge (AFG 500, 850-419) to collect pressure data reading and mapping images in real-time. The AFG end extension was loaded on the pressure sensor units' cells, and a steady force was gradually applied until the gauge force measurement was at 1N. The customized data acquisition board acquired the signal produced by the sensing element and fetched the data to a computer running pressure mapping algorithm. Pressure data in the form of an array of voltage potentials color-coded are displayed on the computer's screen. Using Ohm's law, voltage value can be converted into the resistance of the sensing element and subsequently correlated with the applied force. The procedure was repeated up to 20N of force applied to the sensor. The system showed successfully prove that the mapping algorithm could detect force and the location of the applied force.
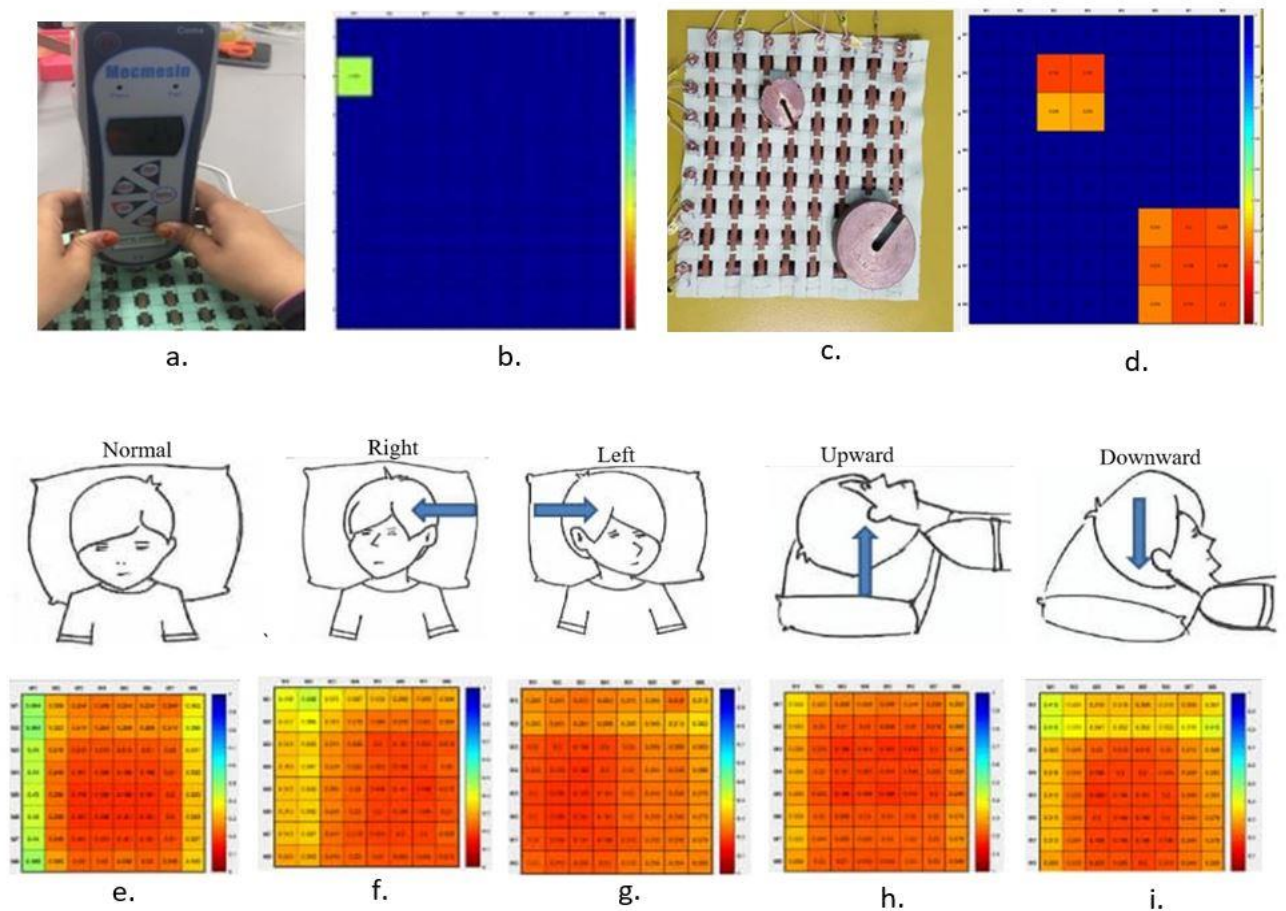

Figure 8 (a) Using AFG load and circular metal block (b-d), force is applied on sensor surface to test the ability of the sensor system to map forces on real time and the mapping image capture using pressure mapping system that successfully locate the position of the force given .(e-i) Lie down pressure sensing analysis: five lie down positioning on top are evaluated and each ePillow pressure map on bottom

Another simple test to indicate force localization capability was performed by placing standard sloted weight on the sensor array, as illustrated in Figure 8**.** The captured mapping data indicates the ability of the system to locate the location of the applied pressure.

Finally, the last experiment was done to investigate the performance of the ePillow system on pillow surfaces using real human subjects, one normal person and another one is a tetraplegia patient. Informed consent was given by patient both subject. For tetraplegia patient , investigation were done just as a limited primary subject trial with physician observation as shown in figure 9. Firstly, to avoid perspiration of the subject fall on the ePillow, the sensor was covered by the waterproof fabric. The fabric-based multi-array sensor was placed on the surface of a pillow (the setup already shown in Figure 4). The normal person placed her head in the middle of the sensing area of the sensor. She moved her head to a different position, upward, downward, left, and right. The data were recorded and analyzed as shown in Figure 8 (e-i)**,** whereby the mapping system successfully differentiated the pressure given with the head movement. This action was important for calibration and as a method to differentiate between real intended calls and false alarms. From these findings, an algorithm was improved by setting the alarm to only buzz when the head was lifted upward and down three times. This technique was found to be an effective method to eliminate false alarms. The circuit was also upgraded with simple calibration hardware by adding an LED light. The red LED would turn on to indicate that the user had put their head in the right position and would turn off when the user applied three times pressure on the ePillow system. The next stage of this project is a final validation phase through testing with real users in order to provide some data on the reliability of the system with real-world users in the hospital setting. The experiment was closely monitored by six doctors in the patient room (Figure 9), and clinical test approval was approved before conducting this trial. By repeating the same procedure on the mentioned experiment to a normal person before, the tetraplegia patient was required to test the device. This Tetraplegia patient was paralyzed all over their body except their upper neck and breathing using a supported breathing machine, making them unable to shout for help. During this experiment, this user manages to move their head upward and downward three times and successfully trigger the alarm. After resting for a while, another head movement was made by this patient and managed to successfully trigger the alarm. Whit these findings, it is proved that ePillow was successfully fulfilling the purposed of the invention. The next experiment was done to determine the accuracy and sensitivity of ePillow when the buzzer is activated. The tetraplegic patients were required to do head tapping three times to activate the alarm. Ten trials were done for system activation. The frequency of successfully and unsuccessfully activated alarms was recorded as successful alarms and unsuccessful alarms, respectively. Any alarms activated out of ten trials was considered as a false alarm and was also recorded. The experiment was conducted with the monitoring of doctors in the hospital, and all attempts were made through instructions from an investigator. The purpose of making it done through instructions is to see how effective the activation methods are when attempting under the full intention to activate a call. Table 4 illustrates the results of the experiment. The experiment was also done during the user was sleeping. This is to investigate how accurate and sensitive the sensor during unintentional head movement. The data was tabulated in Table 5, showing average values of the ePillow system is 71% accurate and 70% sensitive and is suitable to be used as a tetraplegic in-ward call bell system.

Figure 9 Limited prelimiry test on tetraplegic patient in ward under the supervision of medical doctor

Table 4 Total frequency of the head tap

Alarm	Total Frequency
Successful alarm	53/60
Unsuccessful alarm	7/60
False Alarm	7

Table 5 Accuracy and sensitivity of ePillow in percentages

Observation	Accuracy	Sensitivity
Awake	88%	89%
Sleeping	54%	52%
Average	71%	70%

In summary, weft and wasp are the best techniques used to develop multi-array fabric-based pressure sensors on the Neoprene surface. Eeontex is less affected by folding compared to Velostat. By adding a mesh layer with Velostat and Eeontex, the ability of the sensor to detect higher force will increase. In this system, the pressure mapping algorithm, which runs on AVR based platform and MATLAB, is able to map and locate the position of the applied force on any surface and sensor condition. The system has successfully differentiated between a false alarm and a true alarm when the user lies down on the system with 71% accuracy and 70% sensitivity, respectively. This shows that the method is highly potential to be used as a tetraplegic in-ward call detecting system.

4.0 CONCLUSION

A new technique of fabricating a fabric-based sensor array was developed and investigated. An ePillow system was designed, fabricated, and tested based on the new technique. The pressure sensor array was entirely customized from off-the-shelf conductive and piezoresistive fabric and designed with a weft and warped woven form. A data acquisition system was specially designed to read and visualize real-time pressure data from an array of the piezoresistive fabric-based pressure sensor. In addition, a pressure mapping algorithm that runs on AVR based platform and MATLAB was developed to continuously read and visualize the pressure profile from the fabric pressure sensor. The system has successfully differentiated between a false alarm and a true alarm when the user lies down on the system.

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