MULTI-ARRAY SENSORISED PILLOWCASE AS CALL DETECTION ALARM SYSTEM FOR IN WARD TETRAPLEGIC PATIENT

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FACULTY OF ENGINEERING
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ABSTRACT

Call bell systems play an important role for patients and nurse interaction in hospitals and at homes. Conventionally, when in danger or in need, a patient would press a call bell button for assistance. However, a large percentage of hospitalized patients are unable to use such device due to hand weakness or the device is unreachable to the patient when positioned away, especially for patients with tetraplegia. This problem has motivated the development of a fabric-based multi-array pressure sensor as a call bell garment that works by detecting the pressure pattern on a pillow surface where the patient is lying down. In this study, we utilized off-the-shelf materials to form: i) a fabric-based multi-array pressure sensor system, ii) an acquisition circuit along with interface and signal processing algorithms to acquire and interpret the sensor data. To ensure the functionality of the proposed fabric-based pressure sensor, a colour-coded mesh plot was developed to visualise the sensor data. The reliability of the sensor was tested using a portable load cell. Pressure profile of the proposed multi-array fabric-based pressure sensor shows comparable profile to that of the commercialized pressure sensor. The main advantage of the proposed sensor is that it is flexible and adaptable making it suitable to be interfaced with the human body. A case study was performed on an able-bodied person and two tetraplegic patients who used the sensor as the pillow cover. 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. This feature makes it suitable to detect the pattern of head movement and hence a call bell for patients with special needs.

ABSTRAK

Sistem panggilan loceng memainkan peranan penting untuk pesakit dan interaksi jururawat di hospital dan di rumah. Dengan cara konvensional, apabila dalam keadaan berbahaya atau memerlukan, pesakit akan menekan butang loceng panggilan untuk meminta bantuan. Walau bagaimanapun, peratusan besar pesakit yang dimasukkan ke hospital tidak dapat menggunakan alat tersebut kerana kelemahan tangan atau peranti itu diletakkan jauh dari pesakit sehingga tidak dapat dicapai, terutamanya bagi pesakit tetraplegia. Masalah ini telah mendorong perkembangan sensor pelbagai tekanan berasaskan fabrik sebagai sarung loceng panggilan yang berfungsi dengan mengesan corak tekanan pada permukaan bantal di mana pesakit berbaring. Dalam kajian ini, kami menggunakan bahan-bahan sedia ada digunakan untuk membentuk: i) sistem penderia tekanan pelbagai berasaskan fabrik, ii) litar perolehan berserta dengan algoritma pemprosesan antara muka dan algoritma untuk memperoleh dan mentafsir data sensor. Untuk memastikan fungsi sensor tekanan berasaskan fabrik yang dicadangkan, plot mesh berkod warna dibangunkan untuk menggambarkan data sensor. Kebolehpercayaan sensor diuji menggunakan sel beban mudah alih. Profil tekanan dari sensor tekanan berasaskan fabrik pelbagai yang dicadangkan menunjukkan profil yang setara dengan sensor tekanan komersil. Kelebihan utama sensor yang dicadangkan ialah ia adalah fleksibel dan boleh disesuaikan oleh itu sesuai untuk dihubungkan dengan tubuh manusia. Satu kajian kes dilakukan pada orang yang bertubuh sihat dan dua pesakit tetraplegic yang menggunakan sensor sebagai alas bantal Penemuan dari kajian kes ini telah membuktikan keupayaan untuk memetakan kekuatan pada permukaan bantal dan dengan itu lokasi tekanan yang dikenakan oleh kepala pesakit dengan ketepatan 71% dan kepekaan 70%. Ciri ini menjadikannya sesuai untuk mengesan corak pergerakan kepala dan membolehkan loceng panggilan untuk pesakit dengan keperluan khusus.

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LIST OF SYMBOLS AND ABBREVIATIONS

SCI	:	Spinal Cord Injury
ICF	:	Internal Classification of Functions, Disability and Health
IoT	:	Internet of Things
FBPS	:	Fabric Based Pressure Sensor
EIT	:	Electrical Impedance Tomography
MASP	:	Multi-Array Sensorised Pillowcase
AFG	:	Advance Force Gauge

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CHAPTER 1: INTRODUCTION

This chapter discusses the general idea of the study in brief. This chapter is divided into 8 sections. Section 1 describes the background of the study. Section 2 and 3 explain the motivation and problem statement for the study, respectively. Section 4 lists the objectives of the study. Section 5 and 6 highlight the hypothesis and aim of the study, respectively. Section 7 explains the scope of the study. The last section of this chapter describes the dissertation organisation in brief.

1.1 Background of the Study

The purpose of this work is to describe the development, fabrication and validation of a novel multi-array sensorised pillowcase as call detection alarm system for in ward tetraplegic patient. This was carried out with a multi-array fabric piezoresistive materials that are comfortable, simple to fabricate and sensitive to detect pressure on a soft surface and to be used as a call bell alarm system. This study was inspired by spinal cord injury patients who suffer paralysis on all four limbs of the body causing the patients to have limited mobility known as tetraplegia. Since the condition of tetraplegia patients is complicated to understand, this chapter will hence provide a brief summary of the literature about tetraplegia patients and importance of this innovation for its target user is presented.

Tetraplegia is a condition impairment of function in the arms as well as the trunk, legs and pelvic organs due to spinal cord injury in the neck area (Saleh Velez et al., 2018). Herrmann et al., 2011 state that majority (97.3 %) of tetraplegia patients had lose 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 are also affected. Tetraplegic patients cannot do most of the daily life activities such as bathing, toileting, eating and drinking "independently", thus they need full assistance (Herrmann et al., 2011). 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 (Floris et al., 2010). However, in general, this method is only applicable to those who had a lower neck injury. When there is a higher level of neck injury, the head movement is limited (E.Berard et al., 1979). To make matters worse, tetraplegic patients mostly experience paralysis of the abdominal muscle, thus having weak expiration and limited voice production ability. This, in turn, makes it more difficult for them to call the nurse (Aminian, 2013). This thesis, therefore, aims to address this limitation through the utilization of a novel multi-array sensorised pillowcase call detection alarm system.

1.2 The Motivation for the Study

Multi-array pressure mapping system is an important technology in biomedical devices that are widely used in various applications. The high demand for pressure mapping system triggers diverse investigations to further improve the system. Most developed sensors have a common problem which is the inadaptability towards complex surfaces. Often scientists used multiple pressure sensor to map the whole targeted area. Due to lack of flexibility, scalability, and difficulty to interpret mass collected data, direct acquisition system requires large space and energy consumption and can cause inconvenience to system users.

Therefore, to overcome these problems, a flexible comfortable pressure sensor array along with an effective and scalable data acquisition system needs to be developed.

Over time, the textile industry has developed conductive materials into a fabric which can be manipulated into various electronic and wearable applications (Ogando, 2006). The fabric can be manipulated to become a simple sensing element by adjusting the layer between conductive materials and the degree of conductivity on its surface. Thus, developing this sensor can be applied to solve problems related to call bell system for in ward tetraplegic patients.

The aim of this study is to develop a surface pressure sensor that is wearable, comfortable and straightforward to use. Thus, various fabric-based based pressure sensors designs were investigated. Then, the developed sensor was evaluated based on its pressure measurement on pressure and position mapping. Once the sensor successfully maps the pressure position, an algorithm was developed for inward call bell system for tetraplegic patients. Therefore, the specific objectives of this study are:

i. To develop a multi-array fabric-based pressure sensor that can map the location of pressure applied on its surface.
ii. To require pressure mapping recognition system
iii. To perform a case study to validate the sensitivity and accuracy of the call bell system when real tetraplegic patient uses the system.

1.3 Problem Statement

In the ward or at home, nurse-patient communication is very crucial, where the nurse call system would be able to ensure effective communication with patients. Unfortunately, tetraplegic patients are unable to use the current call bell system due to the limitation of their hand movement and weak voice production to activate the system. The current call bell systems in hospital in Malaysia require the patient to push or press the call button to activate the call before the nurse gets notified and only then would be able to come and help immediately. A major consideration should be taken for in ward patients where they are physically unstable and need thorough medical supervision. Being refrained from asking for help or assistance when they are in pain or in need cause more damage to their current condition not only physically but also mentally. Hence, an effective solution needs to be developed and investigate.

Tetraplegic patients suffer paralysis to all four limbs and their voice production is very low. Fortunately, when the spinal cord injury is not too high, some head movement can be made by this patient. This very weak movement can be used as a trigger for call bell alarm system.

Nowadays, a fabric-based pressure sensor is gaining research interest in the field of biomedical engineering (Castano & Flatau, 2014; Jeong, Lee, & Kim, 2011; Stoppa & Chiolerio, 2014). 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 (Leong et al., 2016). The need for integrated sensors that are wearable, comfortable and straightforward to use are increasingly in demand (Capineri, 2014).

Thus, integrating fabric-based pressure sensors into a body measurement system might be a better option. The piezoresistive fabric-based pressure sensor is the most popular fabric sensor due to its simplicity, low in cost and reliable performance. The sensor properties can be manipulated by altering the combination of conductive fabric and piezoresistive layers, from which the combination forms pressure sensing elements (Dinparast Tohidi et al., 2018). The piezoresistive fabric-based pressure sensor is configured into a single unit sensor of a multi-array depending on the measurements requirement (Salibindla et al., 2013).

In rehabilitation, surface pressure measurement is used to monitor and control the development of pressure ulcer in paralyzed patients, diabetic foot patients, and for prosthetic users as it is used to monitor their residual limbs (Baldoli et al., 2017). In the field of biomechanics, surface pressure sensors are used to measure athlete performance normally by using a fabric sensor in the form of socks for better gait and comfort level measurement. Apart from these, surface pressure measurements are increasingly being considered in wearable devices such as data gloves (Liu et al., 2017) and heart rate breathing jackets (Ehrmann et al., 2014). For these reasons, surface pressure measurement is becoming important which has triggered diverse investigations to further improve its functionalities and system performances.

1.4 Hypothesis of the study

It was hypothesized that the multi-array fabric-based pressure sensor call bell alarm system is a feasible/optimal solution for in ward call bell system for in ward tetraplegic patients.

1.5 Significance of the Study

The significance of the study:

i. The study provides the framework of multi-array fabric-based pressure sensor design and development up to pressure mapping algorithms.
ii. This study would serve as a reference for future wearable fabric-based biomedical applications
iii. The study creates a smart wearable system, to detect pressure from the tetraplegic patients head position and use it to activate the alarm system in the hospital

1.6 Scope of the Study

The scope of the study was divided into three parts. The first part was the development of a hardware system, which includes the development of a multi-array fabric-based pressure sensor and the electronic circuit. The second part focused on the software system where the mapping algorithm was developed and tested. The last part was the buzzer alarm system development and case study on real tetraplegic patients.

1.7 Dissertation Organisation

This dissertation consists of five chapters, which are Introduction, Literature Review, Methodology, Results & discussion, and Conclusion.

Chapter 1 is the Introduction. It explains the general idea of the study in brief. This chapter also contains the motivation of the study, research objective, research significance, research scope, and dissertation organisation.

Chapter 2 is the Literature Review. It mainly addresses the critical analysis of previous relevant studies to the present study.

Chapter 3 is the Methodology. This chapter describes the research and development that have been used in the study.

Chapter 4 is the Results and Discussion. It contains all the findings of the current study. This chapter records all the sensor performance and case study results. This chapter also discusses the findings of the current study. This chapter clarifies the performance of the sensor and the effectiveness of the call bell system.

Chapter 5 is the Conclusion. This chapter summarises the findings of the current study. In addition, a few suggestions and recommendations were made to develop a better approach to achieve the goals of call detection alarm system for in ward tetraplegic patients.

CHAPTER 2: LITERATURE REVIEW

This chapter contains a critical study of currently available literature related to the study. This chapter is divided into three sections. The first section describes the conditions of tetraplegia patients. The second section explains the fundamental working of the conventional call bell system in hospitals. The third section introduced fabric-based pressure sensors in general and their potential applications for this study.

2.1 Tetraplegia

Spinal cord injury (SCI) is the most devastating experience that might cause permanent disability to a person, while tetraplegia is one of the side effects of SCI. Tetraplegia happens when the spinal cord is injured at the level of C1 to C5, mainly at the neck area as shown in **Figure 2.1**. This injury will cause paralysis of the whole body including the limbs, cardiovascular system, endocrine system, gastrointestinal system, renal system and respiratory system (Saleh Velez et al., 2018).

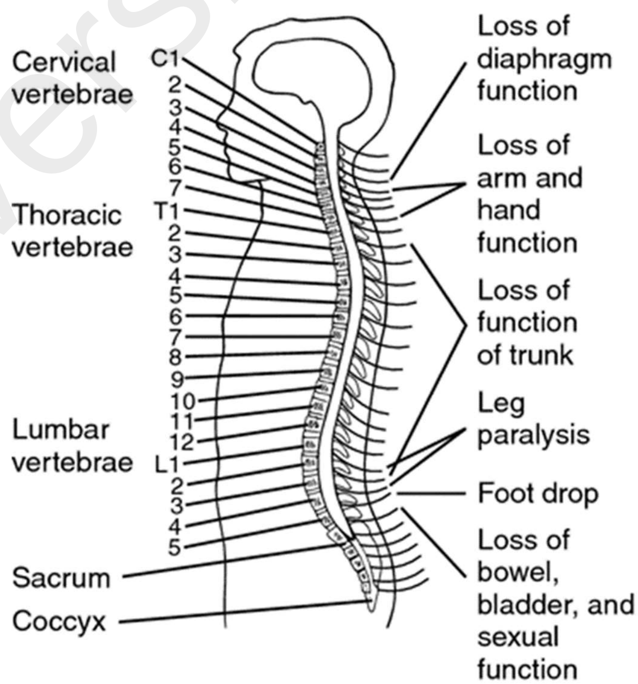


Figure 2.1: Area of injury and disability of SCI Patient (Saleh Velez et al., 2018)

For higher level injury (C1-C2), tetraplegic patients are most likely dependent on the ventilator for respiration due to absent diaphragm movement and non-functional cough (Gibson, 2003). Herrmann et al., 2011 used the International Classification of Functioning, Disability and Health (ICF) as a reference (**Table 2.1)** as it provides a comprehensive framework and common language. From his research, the majority of (97.3 %) tetraplegia patients had a loss every system of the body which include bladder functions, muscle tone, motor reflex functions and respiratory system. There was no movement or feelings from neck down causing the patients to be requiring assistance all the time. Due to paralysis of the abdominal muscles, assistive ventilation system is used to assist breathing thus it is affecting the voice and speech. For tetraplegic patients they cannot do any daily life activities such as bathing, toileting, eating and drinking, requiring them to need full assistance. A call bell is the most important tools for tetraplegic patients to signal the nursing staff or attendants which strengthens the patient's sense of security.

Table 2.1 : ICF Category of the Component Body Function In Persons With Tetraplegia (Herrmann et al., 2011)

Body Functions	**Descriptive analysis: Prevalence of Problems % Tetraplegia (n=475) (%)**
Touch Function	89.3
Sensory functions related to temperature and other stimuli	91.7
Voice function	12.2
Blood pressure function	33.8
Respiratory function	18.3
Respiratory muscle functions	62.2
Exercise tolerance function	57.2
Thermoregulatory functions	61.8
Mobility of joint functions	73.7
Muscle tone functions	95.4
Motor reflex functions	97.3

2.2 Call bell system

In hospitals, the call bell system plays important roles for patients and nurse interaction. When there is danger or need, patients are required to press the call bell for nurse assistance (Queensland Health, 2019) . There are three categories of call bell system that are commonly used in the hospital, which are: 1) Conventional call bell system, 2) Adaptive call bell system and 3) Smart call bell system. All the three main categories will be discussed in this chapter.

2.2.1 Conventional Call Bell System

In Malaysia, most of the call bell system are of the conventional type due to its lower cost, easy to use and low in maintenance. The conventional call system in hospitals requires patients to push or press the call button to activate the call before the nurse gets notified and only then be able to come and help immediately. Hospital call bell system consists of pushing two sets of push buttons, an LCD display and a buzzer **Figure 2.2**. Both push button sets are located at the patient's bed, one to activate the alarm and another one is to deactivate the alarm. Activation push button is in the form of wired handle while the off button is plugged onto the wall. Once the push button is activated continuous alarm would buzz and only stop once the nurse comes to turn off the deactivation button. The LCD and the buzzer are located at the nurse counter to alert the nurse when and which patient made the call.

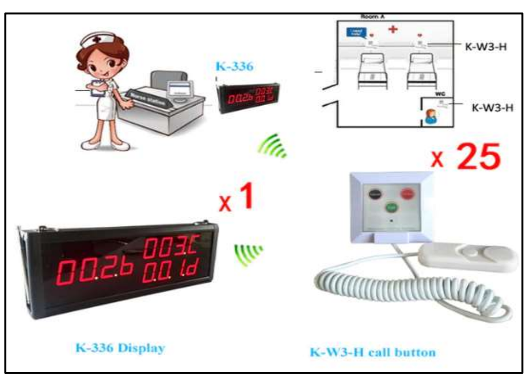


Figure 2.2: Call bell system architecture (Dhgate, 2020)

The present call bell system in the hospitals is based on the assumption that patients are able to get help by pressing the bell and activating the call bell. However, a large percentage of hospitalized patients are unable to use this device due to hand weakness or position of the device is not within the reach of patients(Duffy et al., 2005). The call bell was on average 82 cm away from bed are more alarmingly, over one third (38.1%) of all patients were unable to understand independently the roles of the call bell and how to use it (Chadwick & Hearn, 2014). Patients who lost their hand functions such as tetraplegic patients has no means of using this call system. This situation causes some concerns as patients with tetraplegia do need medical attention regularly and are at risk of medical emergencies. A major consideration should be taken for newly injured patient where they are physically unstable and need thorough medical supervision.

Figure 2.3 : Conventional Call Bell System (Schnaak, 2020)

2.2.2 Adaptive Call Bell System

This call bell system is made for patients who are unable to press the call bell using conventional method. Usually, this device adapts to any minimal movement that can be done by user either blowing air, tapping their head, using their chin or any adaptive movement. Basically, the device works the same as the conventional call bell system, it is just the activation method that is different . In **Figure 2.4**, upper limbs of patients are not functional, hence the adaptive call bell was used (E.Berard et al., 1979).

Figure 2.4: A call-button on flexible support to alert the nurse; controlled by head (L Floris et al., 2010)

2.2.3 Smart Call Bell System

With the advancement of Internet of Things (IoT) in this era, many researchers have developed the conventional call bell system into a more advanced system . This was done to ensure more effective patient-nurse interaction and communication for better and safer health service. The simplest system that is recently being used is the nurse call system with a mobile device and a smart watch (Ali & Li, 2016; Lu et al., 2018; Oren et al., 2017) . The smart device monitors the pulse of the heart and updates the nurse the condition of the patients in real time. This device is also used in the form of a wireless necklace button and is usually used for older patients. The wireless alarm system will turn on the mobile apps and alert the nurse when in emergency as shown in **Figure 2.5.**

Figure 2.5 : Mobile apps for call bell system (Ali & Li, 2016)

2.3 Fabric-Based Pressure Sensor

The Fabric Based Pressure Sensor (FBPS) system is considered to be a promising measurement tool in surface pressure sensing in a wide variety biomedical engineering applications. Therefore, the design of FBPS system for surface pressure applications has drown tremendous attentions in current research (Harris, 2014). In this section we will discuss the general types of developed FBPS. Then, we will focus the discussion on piezoresistive FBPS in term of development and applications.

2.3.1 General types of developed FBPS

The properties of pressure sensor developed using fabric are usually influenced by the properties of electronic functional ink used on the surface of the fabric. Electronic functional ink is defined as a solution that has the ability to carry electrical properties and is made into the form of ink to be printed on the surface of plastic film, paper, rubber and textiles (S.Cruz & N.J.Vieira, 2004). The ink plays important role in development of fabric pressure sensor. With different formulation, the ink can be manipulated into different properties ranging from conductors, insulators and semiconductors with organic or inorganic materials (Matsuhisa et al., 2015). There are several basic ink that usually are used as fabric coating such as polyethylene terephthalate (PET), polyimide, and poly-dimethysiloxane (PDMS), Sulphur containing aromatic such as polythiophene (PT) and poly (3,4-ethylenedioxythiophene) (PEDOT), Nitrogen containing aromatic such as polypro (PPY) and polyanilines (PANI) (Xiaomei et al., 2012). Using die coating approach (Takamatsu et al., 2014), even and uniform layer of electronic functional ink are coated on the surface of non-conductive thread (such as nylon) and woven together to form flexible cloth and sheet(Atalay et al., 2013) as shown in **Figure 2.6**.

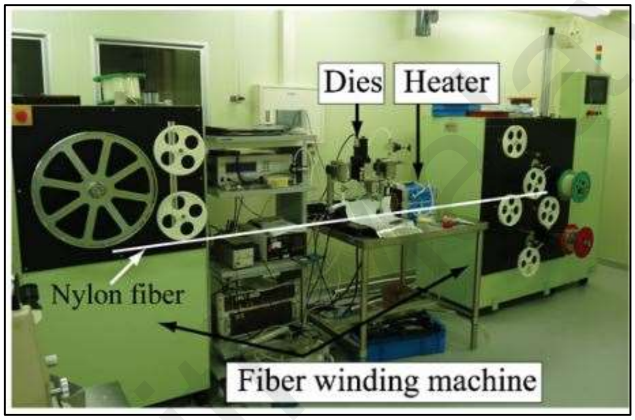


Figure 2.6 : Die coating technique on fabric surface (Takamatsu et al., 2012)

The presence of doping agent improves the electrical conductivity of the layer itself, the innovations of the textile materials has improvised the properties of the textile sheet, making it able to conduct electricity (Lee et al., 2014). Combinations of different textile sheet had verified the properties of the pressure sensor (Pacelli et al., 2013). Basically, the fabrication technique is usually done as summarised in **Table 2.2,** has concluded four major techniques in fabric pressure sensor development which are capacitive, piezoresistive, piezoelectric and electrical impedance tomography. The development of fabric pressure sensor includes parameters such as adaptability to body surface, flexibility, ability to stretch, low development cost, minimally disturb body motion and reliable performance (Pang et al., 2012).

Table 2.2: Summary of fabric pressure sensor fabrications techniques

Fabric Pressure sensor approach	Investigations	References
Piezoresistive	Tactile sensor	Büscher, et al., 2015
	Wearable Yarn	Huang, et al., 2008
	Robot skin	Lacasse, et al., 2010
	Wearable	J. Li & Xu., 2015
	Parallel woven structure	L. Li & Ding, 2009
	Linear wide range textile sensor	Lin, et al., 2015
	Robot skin	Masayuki Inaba, et al., 1996
	Musical controller	Roh et al., 2011
	Body sensor	Samy, et al., 2014
	Conductive rubber	Shimojo, et al.,2004
	Diabetic footwear system	Shu et al., 2012
	Socks for gait analysis	Tirosh, et al., 2013
	Clothing against impact loading	F. Wang, et al., 2014
	Physical abuse detection	Whiton & Nugent, 2007
	Ergonomic analysis	Harris, 2014
	Sock foot	Leong et al., 2016
Piezoelectric	Wearable power generating	Ahn, et al., 2015
	Body sensor network	Salibindla, et al., 2013
	Force sensor using PVDF fabric.	Y. R. Wang, et al., 2011
	Novel design	Y. Wang, et al., 2011
Capacitive	2D Touch pad	Gorgutsa, et al., 2011
	Robot tactile system	Maiolino, et al., 2013
	Stretchable strain sensor	Nakamoto et al., 2015
	Wet spinning	Park, et al., 2012
	Pressure sensitive fabric	Sergio, et al., 2001
	Capacitive pressure sensor	Sergio, et al., 2002
	Die coating waving technique.	Takamatsu, et al., 2012
	Keyboard	Takamatsu, et al., 2014
	Meter scale pressure sensor	Takamatsu, et al., 2014
Electrical Impedance Tomography (EIT)	Smooth surface humanoid	Alirezaei, et al., 2008
	Conductivity reconstruction	C.L. Yang et al., 2015
	Pressure mapping device	Soleimani, 2014
	EIT based pressure sensing.	Yao, & Soleimani, 2013

Table 2.2 showed that, the most popular technique in fabric sensor development is the piezoresistive mechanism . The piezoresistive mechanisms is more advantageous for the human surface pressure measurement due to its high adaptability to the curvature of the body surface , flexibility , stretchable and it minimally disturbs body motion (Ahn et al., 2015). The construction of piezoresistive pressure sensor is simple and more economical compare to another development technique. Apart from that, due to its flexibility, the sensor can measure external contact force on the human body in real time and transfer the data to the electronic device. This makes piezoresistive development technique more advantageous compared to capacitive, piezoelectric and EIT approaches (Büscher et al., 2015).

The problem with the capacitive approach is it's rigidity which restricts practical usage on curved body part (Gorgutsa et al., 2012) and insufficient textile pressure resolution(Maiolino et al., 2013) . Meanwhile , the piezoelectric approach is not very robust due to fragile external wiring (Wang et al., 2011). the EIT approach is advantageous in terms of accuracy (Yao et al, 2013) however, the sampling electronic is too complicated and requires complex algorithm (Büscher et al., 2015). There is also unwanted output from the EIT fabric pressure sensor due to mirroring and ghosting(C.L. Yang A. et al, 2015). Therefore, Piezoresistive technique are usually used in surface pressure measurement as compared to other useful technique and will be further discuss in this literature review.

2.3.2 Piezoresistive Fabric-Based Pressure Sensor

There are variations of piezoresistive fabric pressure sensor development approach that had been used and reported by researchers around the world. Different techniques give different results and functionalities. Thus, in this review, we would like to report few aspects in development approach that had been used by the past researcher. The most basic construction of the Piezoresistive FBPS is as shown in **Figure 2.7.**

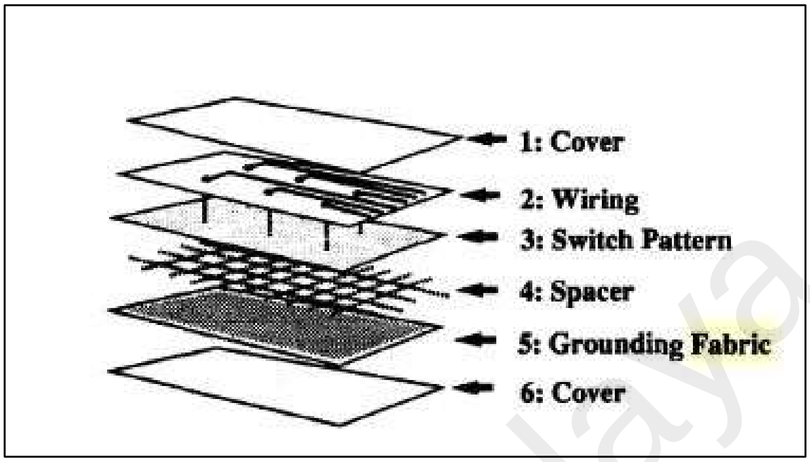


Figure 2.7 : Basic construction of piezoresistive FBPS (Castano & Flatau, 2014)

Piezoresistivity occurs once the surface of a material is pressed, i.e., mechanical stress applied, causing a change in the internal resistance . The effect is easily observed in semi-conductive polymeric materials due to an obvious change in resistance with very little mechanical stress applied. An ideal uniform material's electrical resistivity (ρ) can be described by the following formula(Kalantari, 2012):

$$\boldsymbol{\rho = R\frac{A}{L}} \qquad \textbf{Equation 1}$$

Where R is the electrical resistance of the materials, A is the cross-sectional area of specimen involved and L is the length of the material. The relationship gives a general overview on how a material's resistance can be modelled by:

- Changing the material's properties such as thickness, area and orientation (placed on a flat or curved surface)

- Changing the impurities concentration on the material
- Changing the temperature : The higher the temperature the lower the Piezoresistivity.

All the changes will affect the Piezoresistivity performance that will be useful for sensor development and real-time data collection. All factors such as temperature, material thickness, purity of materials, initial electrical resistance need to be considered during development and experimentation. Thus, selection of materials in FBPS is the most crucial step that will affect the performance of the sensor. Generally, from literature FBP sensor is developed by manipulating the material properties orientation layer by layer. From (Salibindla et al., 2013) the most simple layering technique is as in **Figure 2.8.**

Figure 2.8 : Flexible sensor assembly from left to right showing the electrode layers, conductive plastic layer and the final packaging. (Salibindla et al., 2013)

The sensor was designed using three basic materials as shown in **Figure 2.8** where the middle layer consists of a piezoresistive plastic sheet (Velostat) sandwiched between two conducting layers. Velostat is a carbon thin (4mm) infused plastic (polyolefin) that has a high resistivity (< 500ohm per cm). The resistance of Velostat changes when pressure is applied. The conducting layers act as electrodes and consist of either conducting fabric or conducting thread. The sensor package is then completed with insulating tape i.e., duct tape to avoid short circuits between the two conducting layers. In this design, the change in resistance of the piezoresistive Velostat is investigated with respect to applied force and deformation.

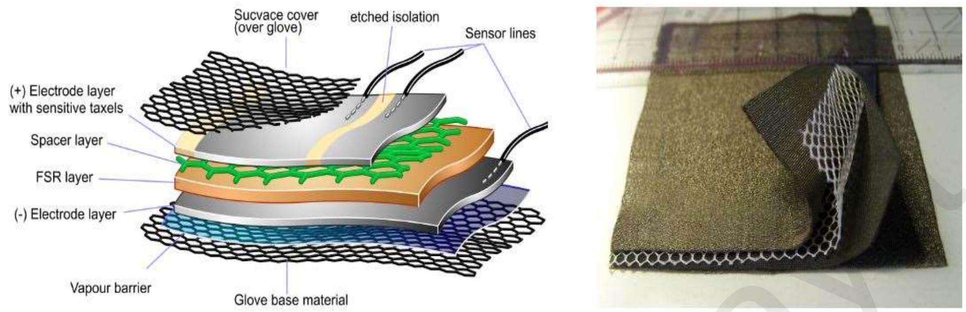


Figure 2.9: Additional of mesh fabric in piezoresistive FBPS (Bianchi et al., 2016)

Another approach in constructing piezoresistive FBPS is by adding mesh fabric in the middle of conductive fabric developed by (Bianchi et al., 2016). Bianchi designed the sensor by using piezoresistive materials that are highly stretchable knitted fabric (72 % nylon, 28% spandex) manufactured by Eeonyx named as Eeonyx piezoresistive fabric. This fabric is coated on a nanoscale with inherently conductive polymers. The materials are available at different resistance, determined by the thickness of the applied coating. Change of resistance can be measured when piezoresistive fabric were placed between two highly conductive materials (78% polyamide, 22% elastomers) with pure silver particles. An additional mesh layer is integrated between piezoresistive layer and an electrode layer, which keeps them insulated as long as minimal forces are applied. The thickness of the mesh layer and the size of the mesh opening affect the sensor performance. Smaller openings and thicker layers result in higher threshold, because more force is required to establish contact between conductive layers. The more contact between the conductive layers the more decrease in resistivity.

2.4 Summary

Tetraplegia is the spinal cord injury that occurs around neck which in turn affects the whole-body system. Nurse call bell system is the most important tools for tetraplegic patient for assistance and needs. Fabric-based pressure sensor, might be the solution for better call bell system to be used for tetraplegic patients.

CHAPTER 3: METHODOLOGY

This chapter describes the development of how Multi-Array Sensorised Pillowcase **(MASP)** is constructed, evaluated, and adapted into a call detection alarm system that is subsequently used in ward tetraplegic patients.

Pertaining to the first objective of the study, the effect of various methods of construction of a fabric-based sensor array will be investigated. Then the best array design was selected and further investigated as a mapping system and further evolved into call detection alarm systems. Therefore, there are 3 sub-section for each section in this chapter: Fabric sensor array construction, pressure mapping recognition system and case study on able-bodied and tetraplegic patients. The first sub-section reflects the first objective of the study, while the second and third both reflect the second and third objectives of the study.

3.1 System Description

In this project, a fabric sensor system was developed to be used in hospital settings and it is also extended for home users. Therefore, the essential problem is how to make the system straightforward to be deployed, convenient to access, and simple to be used and more importantly, it should be flexible and comfortable to the users. In addition, the system should also be affordable and compatible with existing call bell systems. **Figure 3.1** shows the architecture of the proposed **MASP** Pillowcase system. Basically, the system is 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 when he/she is laying down on the **MASP** Pillowcase. Then, the data sampling unit acquires the sensor values and transmits the data wirelessly to the processor unit.

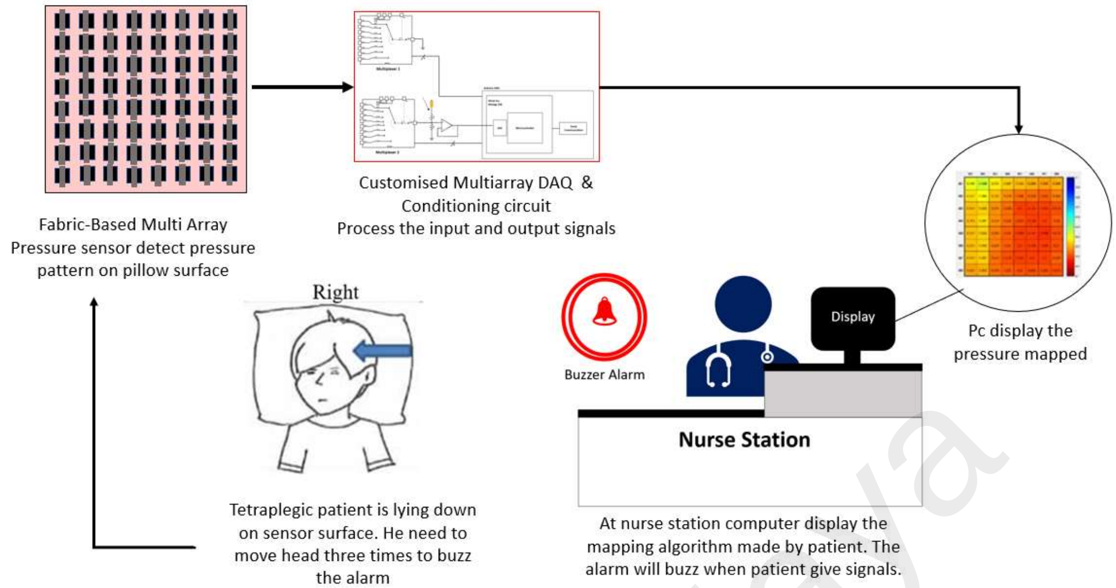


Figure 3.1: Multi-Array Sensorised Pillowcase as Call Detection Alarm System Architecture

The processor unit analyzes the sensed data and maps according to the patient's intention which then triggers a notification at the nurse's table. **Figure 3.2 (a)** shows the implementation of the proposed fabric-based sensor array in **MASP** Pillowcase. The total sensor surface is 0.3x0.3m^2, where the area of each square sensing area is 0.02x0.02m^2 as each row and column bus is 0.02m wide and the space between the sensors is 0.01m.

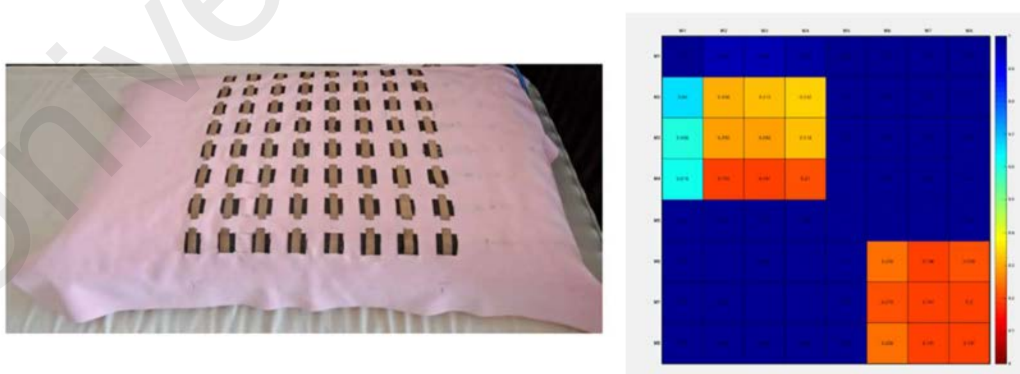


Figure 3.2: The prototype of MASP Pillowcase (a) Fabric sensor array (b) Mapping system on a computer screen

The construction and the design structure of the sensor array are presented in **Section 3.3.** The data sampling and conditioning circuit were designed based on AVR development board 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 activation of the alarm. Considering highly potential use in the hospital and for further data analytic studies, a user-friendly mapping application as shown in **Figure 3.2 (b)** was also developed for computer or laptop, which conveniently displayed real-time feedback of laying down head pressure distribution and facilitated continuous visualisation of the head position.

3.2 Fabric Sensor Array Design

This section deals with fabric sensor array design, where material selection, sewing technique and layering technique affecting the whole sensor properties will be further discussed in detail.

3.2.1 The basic design of a piezoresistive fabric-based pressure sensor

The construction of piezoresistive fabric-based pressure sensor is the simplest architecture as compared to the other related fabric-based sensors (Flagg & MacLean, 2013; Fu et al., 2018; L. Wang et al., 2016). The proposed sensor can be constructed by sandwiching three basic materials as illustrated in **Figure 3.3.**

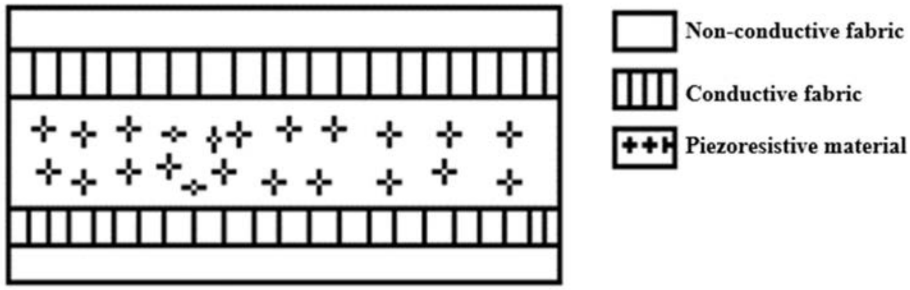
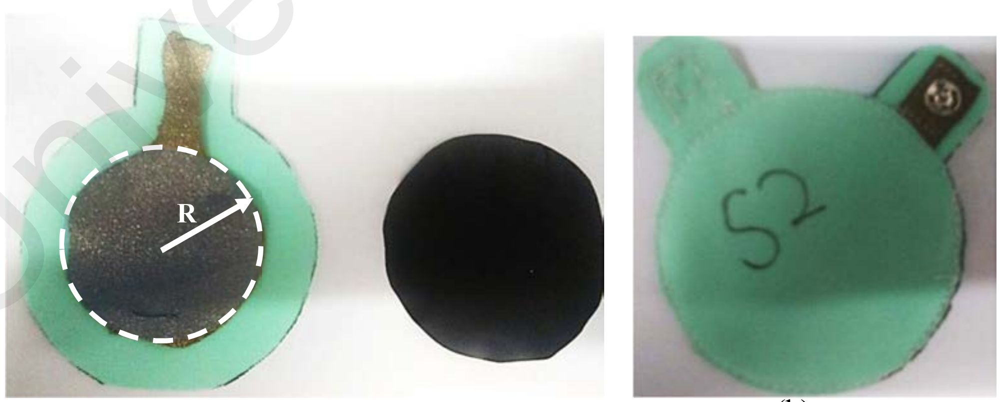


Figure 3.3: Basic construction of Fabric-based pressure sensor

To protect the circuit from a short circuit, a nonconductive fabric was used as a protection layer. In this case, a conductive fabric (MedTex130, Shieldex Trading, USA) was chosen. The conductive knit fabric was made up of 78% Nylon, 22% elastomer and 99% pure silver with surface resistivity less than 5Ω/m^2. The conductive fabric was constructed with 0.45mm thickness and 140g/m^2 density. The conductive fabric was used as electrodes to transport current in and out from the sensor and was sandwiched on the top and bottom of the piezoresistive material. A non-conductive fabric was used as a protective layer. The sensor construction is shown in **Figure 3.4.**



(a) (b)

Figure 3.4: (a) Internal design of the sensor, R= 5cm. (b) "Mickey Mouse" shape fabric-based pressure sensor with a sensing area of 12.6cm^2

3.2.2 Multi-unit of fabric-based pressure sensor design and investigations

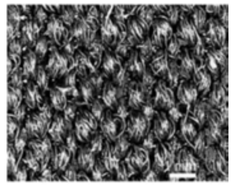
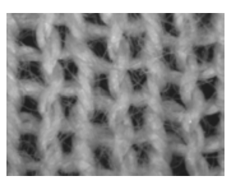
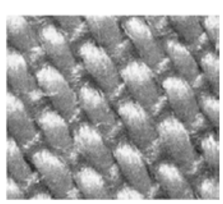
The real challenge in this investigation is constructing multi-units of the fabric-based pressure sensor. This is due to the need to ensure all constructed units are on their own while current and data transfer are connected to each other. To ensure this, a lot of trials, design and construction methods have been investigated. The investigation done are as follows:

1. Type of non-conductive materials. The investigation is done on various type of fabric materials which are: Felt, Sports Knit, Lycra, Neoprene, Cotton and Rubber
2. Sewing technique,
3. Type of piezoresistive materials
4. Layering technique.

3.2.2.1 Investigation on the effect of non-conductive materials toward sensor performance

Using basic design as mentioned in **Figure 3.3,** five units of the sensor were constructed using Lycra, Felt, Cotton, Jersey and Neoprene. The material properties were listed in **Table 3.1**. The fabrics were used as protective materials as shown in **Figure 3.5**. The investigation was done to find which is the most stable but flexible fabric that is suitable to be used as **MASP**. The use of stretchy conductive knit fabric, MedTex130 was maintained throughout the whole construction. For piezoresistive materials, Velostat and Eeontex were randomly used as the focus of this study is the multi-array design. An industrial sewing machine (Jack Model JK 9100 BS) and standard cotton thread were used to sew the materials together. A Multimeter was used to indicate the connectivity of the circuit. Throughout the sensor development, it was found that the area of piezoresistive material should cover the surface entirely, i.e., bigger in size, as compared to the conductive material for it to work as a sensor and should be in a constant position.

Table 3.1: Type of Material used for non-conductive fabric selection.

No.	Fabric Name	Microscope View	Properties
1	Lycra	 (Chen, Li, Qiao, & Lu, 2019)	• Also known as Spandex • Made of polyurethane synthetic fiber. • Can be stretched to four to seven times its initial length. • Strong • Flexible • Not lose its shape or stretch. • When pulled has excellent recovery
2	Felt	 (Castano & Flatau, 2014)	• Made of natural fibers such as wool or animal fur. • Is produced by matting, condensing, and pressing the fibers together. • Fire retardant • Self -extinguishing • Damped vibration • Absorb sound. • Can hold a large amount of fluid without feeling wet. • Rough texture
3	Cotton	 (Sirghie, Kozłowski, & Roskwitalski, 2012)	• A natural fiber made from the seedpod of the cotton plant. • Knitted or woven into cloth. • Rigid • Light • Smooth • Breathable nature
4	Jersey	 (Li, Frey, & Browning, 2010)	• Made of wool, cotton & synthetic fibers. • Have different two sides, one has a flat side and one piled side. • Stretchy 25% along its grains • Flexible • Lightweight • Breathable
5	Neoprene	 (Khattab, Rehan, & Hamouda, 2018)	• Synthetic Rubber • Produce from a combination of carbon, hydrogen & chlorine polymer. • Resistance to all sorts of environmental conditions • Insulation capability • Heat resistance • Non-wrinkled • Slightly stretchable

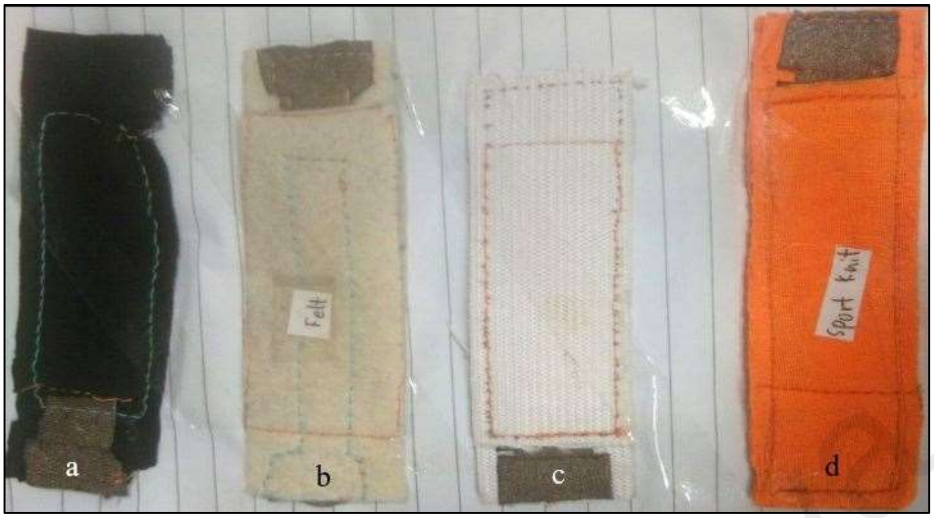


Figure 3.5: Single-array fabric-based pressure sensor using various types of non-conductive materials. (a) Lycra (b) Felt (c) Cotton (d) Sports Knit (e) Neoprene not in the picture

This test is important to ensure the sensor does not crumple and maintain its position on the 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. All findings are discussed in Chapter 4. From this experiment comfortability was defined as in **Table 3.2**.

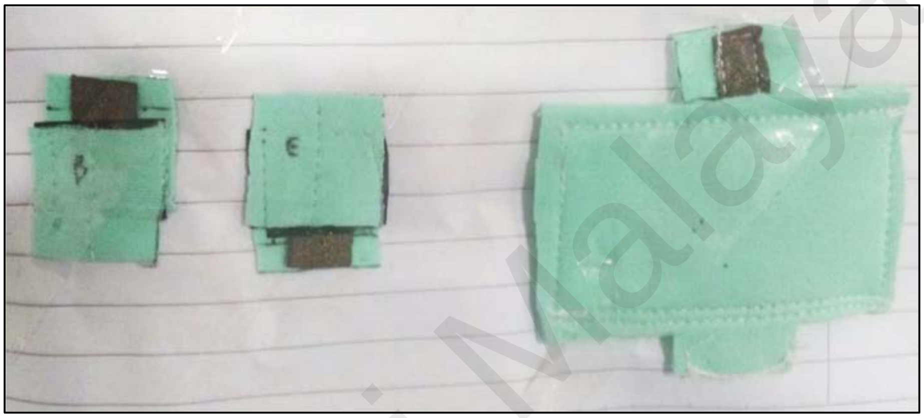
Table 3.2: The definition of comfort for MASP

No.	Comfort Parameter	Definition
1	Soft next to skin	The fabric should be soft to the skin , not causing irritation to the skin such as rashes or redness when in contact
2	Moisture Permeability	When perspiration, the fabric allows moisture vapour to pass through its structure
3	Thermal conductivity	From the body heat , the fabric able to conduct heat on the area
4	Stretch recovery	The fabric is able to stretch under deformation and recover to its original position after removal of deformation
5	Dimensional stability	The fabric is able to remain stable without change in its dimension after being crumpled or washed

3.2.2.2 Investigation on the effect of sewing technique toward sensor performance.

The investigation aimed to produce the most stable, individual unit, and easy to construct a multi-array sensor. For each design, the sensor is tested using a multimeter, that is set to a connectivity setting. Each unit is pressed using bare hand once and the production of ‘Beeb’ sound indicates that the design worked.

(a) ***Design 1: Single unit combined into multi-unit***



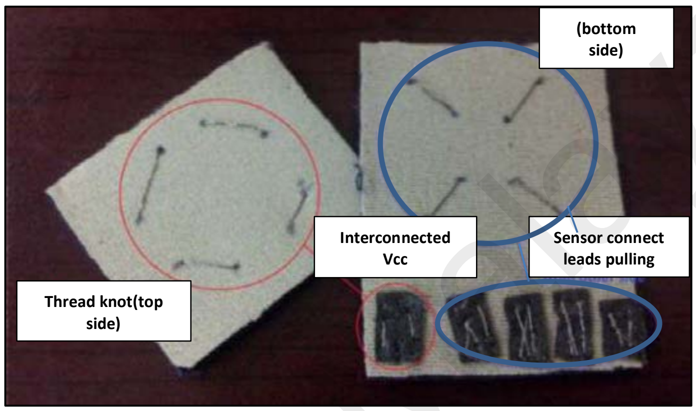
(a)

(b)

Figure 3.6 : Multi-unit fabric-based sensor (Design 1)

8-unit sensors with size 2x2m^2 **Figure 3.6 (a)** were made using sandwiching technique and were sewn together using conductive thread as illustrated in **Figure 3.6 (b)** forming Design 1 sensor. This sensor was then tested using a multimeter. The result was recorded and tabulated in Chapter 4.

(b) ***Design 2: Thread technique***



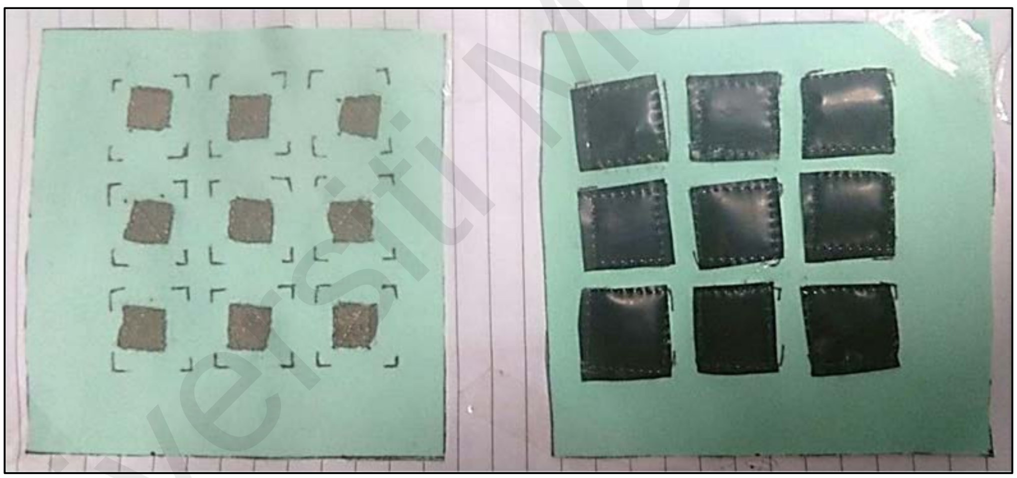
(a)

(b)

Figure 3.7: Multi-unit fabric-based sensor (Design 2). a) internal view, b) Complete Unit

Design 2 was adapted from (Harris, 2014). Two pieces of neoprene were cut – one 2x5cm and the other 4x3.5cm. The shorter piece was laid over the top of the longer ones, with a 1.5cm overlap for installation of leads with an average sensor size of 90mm^2 with a +/- 1mm^2 variation. The smaller top layer was designated as the power layer, the larger lower layer is assigned to pick up the change in resistance through the Velostat™. The conductive thread was stitched into the power layer in the pattern shown in **Figure 3.7 (b)**. The thread forms a complete “X”, half of which is exposed on top of the neoprene, and a half on the bottom. The exposed thread is the conduit between the top layer and the bottom layer (right). The bottom layer has four individual threading sections, each representing one output. Each thread from the bottom layer is exposed to its respective thread from the top layer, creating a bridge between the layers. Each thread was isolated to avoid crosstalk between sensor outputs.

(c) ***Design 3: Square of Velostat and conductive fabric***



(a) (b)

Figure 3.8: Multi-unit fabric-based sensor (Design 3)

Design 3 was developed using the patching technique, where non-conductive material (neoprene) was cut into two pieces with the size of 10x10cm$^{2.}$ Then, nine pieces of conductive material were cut into 1x1cm^2 then sewn on a neoprene surface as shown in **Figure 3.8 (a)**. Each conductive material was sewn three by three in row and column with a distance of 1cm from each other and 1.5cm space on the left and bottom side of the neoprene area. Then on another neoprene piece, 2.0x2.0cm^2 Velostat were sewn three by three in row and column with space of 0.5cm to each other as shown in **Figure 3.8 (b).**

2cm space was left on the right and bottom of the neoprene. Both two neoprene pieces were patched facing each other and sewn at each side. The functionality of the sensor was then tested using a multimeter.

(d) ***Design 4: Velostat Array design - circle shaped***

Figure 3.9: Multi-unit fabric-based sensor (Design 4)

Design 4 was adapted from the array design technique. Four arrays of $0.5x5cm^2$ conductive fabric were sewn vertically on non-conductive fabric (lycra) with 2cm space to each other. Then 24 piece of velostat was cut into a circle with 1.5cm diameter. Each circle was sandwiched into three layers and arrange into four sets horizontally and two set vertically with a distance of 2cm each as shown in **Figure 3.9**. Then two arrays of $0.5x5cm^2$ conductive fabric were sewn horizontally on lycra. Finally using a multimeter, the sensor was tested.

(e) ***Design 5: Eeontex array design – square shaped***

Using the array design technique, design 5 was developed. Eight arrays of conductive fabric were cut into $0.5x10cm^2$ then were vertically sewn into $10x10cm^2$ non-conductive fabric surface with 1cm distance to each other **(Figure 3.10).** Then 32 units of Eeontex sample with 1x1cm^2 were cut into a square shape and arranged on sewn vertical conductive fabric array horizontally and vertically with a gap of 1cm each. Then an array of 0.5x10cm^2 conductive fabric was sewn on the Eeontex horizontal surface. The sensor is then being tested using a multimeter.

Figure 3.10: Multi-unit fabric-based sensor (Design 5)

(f) Design 6: Weft and Warp technique non-sewn

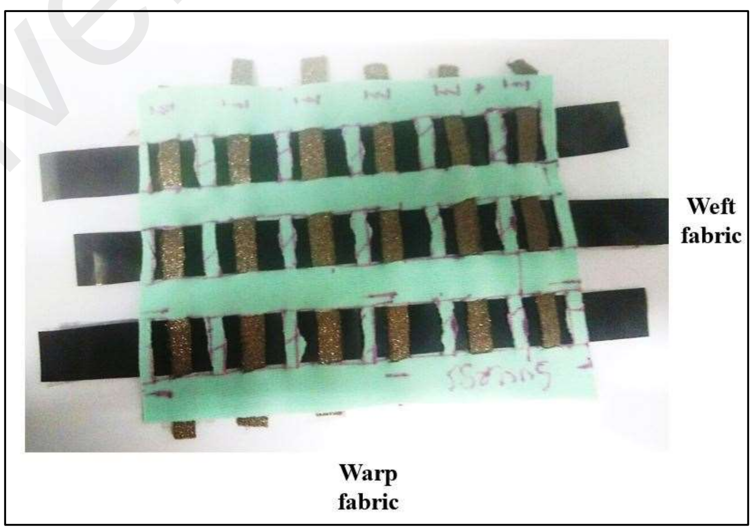
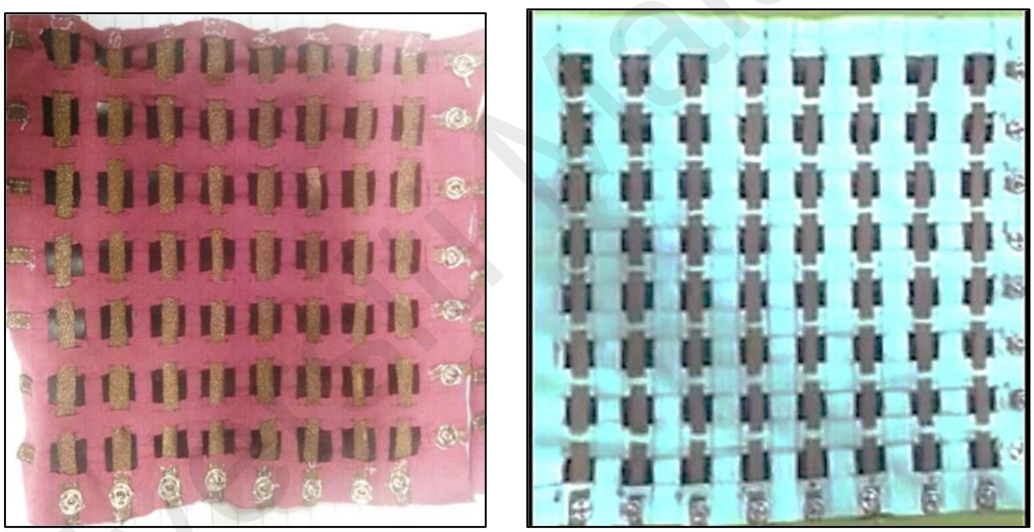


Figure 3.11: Multi-unit fabric-based sensor (Design 6)

Illustration in **Figure 3.11** described design 6 of multi-array fabric-based pressure sensor using weft and warp technique. Weft fabric is made of Velostat with the size of 1x8cm. The warp fabric is made of conductive fabric with a size of 0.5x5cm. Initially, square shape holes with the size of 1x1cm (some were randomly measured) were cut on a non-conductive fabric surfaces. Then, each warp fabric was crossed over and under the weft fabric. Then the warp fabric went under and over the weft fabric. The third warp fabric repeats the action of the first, going over and under, and so forth until completed 3x6 array units.

(g) ***Design 7: Weft and Warp technique were sewn on Lycra and Neoprene.***



(a) **(b)**

Figure 3.12: Multi-unit fabric-based sensor (Design 7 a & b)

Design 7 as shown in **Figure 3.12** is the upgraded version of design 6 where there are more consistent sizes of the square hole, Velostat and conductive fabric. This 8x8 array was sewn on the surface of Lycra. Metal buttons were sewn on the left and bottom sides of the fabric sensor.

3.2.2.3 Piezoresistive material test

For the sensor construction, there are two piezoresistive materials available in the lab which are Velostat and Eeontex. To understand the properties of piezoresistive material, a simple test was done on both materials as shown in **Figure 3.13.**

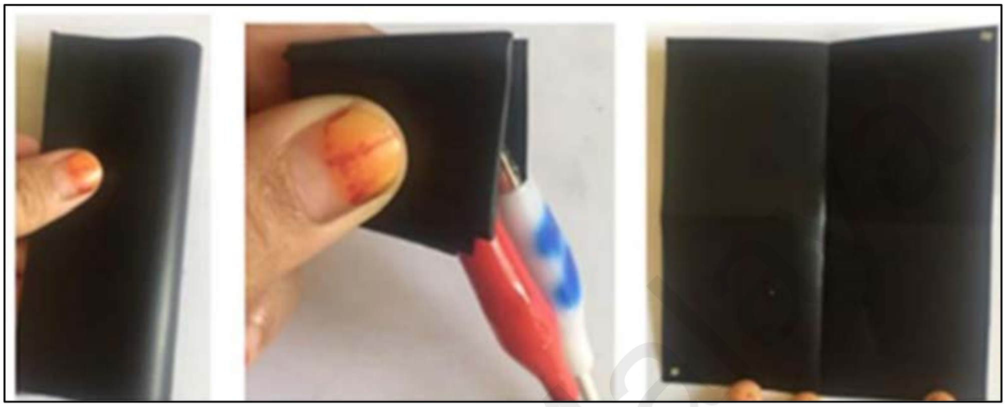


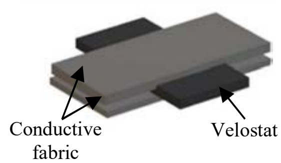
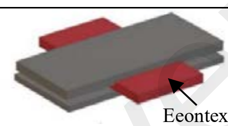
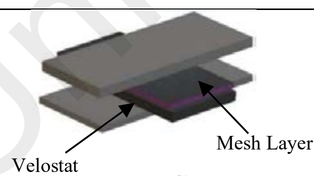
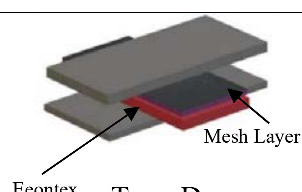
Figure 3.13: Experiment on piezoresistive materials Velostat and Eeontex using the folding technique.

Samples from each Velostat and Eeontex were prepared into $5x5cm^2$ square-shaped pieces. The resistance between the 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.

3.2.2.4 Investigation on an internal layer of the fabric-based pressure sensor

As mentioned earlier, these investigations were made to construct a multi-unit fabric-based pressure sensor. Thus, this section explained the innovative technique was improving the basic layering method mentioned in **Figure 3.3**. The innovation was constructing the sensor using two techniques, 1) sewing in multi-array and 2) add a mesh layer between the conductive fabric. This technique is the application of Bianchi et. Al. Bianchi, had applied multiple layering techniques using mesh fabric, multi-layer of piezoresistive fabric, and spacer layer (Bianchi et al., 2016). Any changes in 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 (Büscher et al., 2015). Thus, another experiment was conducted to investigate which layering technique is most suitable for the **MASP** system. Four sets of sensors designed as in **Table 3.3** were constructed and investigated.

Table 3.3: Construction of four types of the internal layer of MASP sensor

Type sensor internal layer of the fabric-based pressure sensor	Type of Piezoresistive Material	Mesh Layer
 Type A	Velostat	No Mesh Layer
 Type B	Eeontex	No Mesh Layer
 Type C	Velostat	With Mesh Layer
 Type D	Eeontex	With Mesh Layer

Throughout the experiment MedTex 130 (the grey color) was maintained to be used as the conductive fabric. Meanwhile, the piezoresistive fabric was alternately changed, Velostat was applied to **Type A** and **Type C** and Eeontex NW170SLPA2K was applied to **Type B** and **Type D.** For **Type C** and **D,** a Nylon mesh fabric with 0.3mm openings were added as an additional layer.

Advance Force Gauge (AFG 500,850-419) was used to measure force onto each set from 0N until a maximum of 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 tabulated as shown in Chapter 4.

3.2.3 Summary of Multi-unit fabric-based design investigation

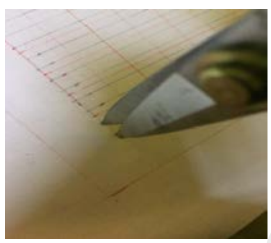
From the investigated trials, design and construction method mentioned experiment in **section 3.2.2**, it is concluded that the experiment had shown types of nonconductive material, sewing technique, type of piezoresistive materials and an internal layer of the sensor affect the performance of the sensor. Each category showed a different effect on the sensor performance. This effect was tabulated in **Table 3.4.** The experiment results will further be reported in chapter **4.**

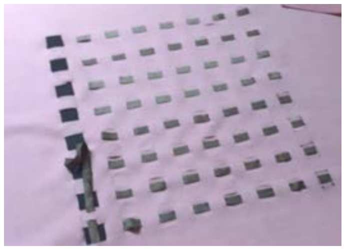
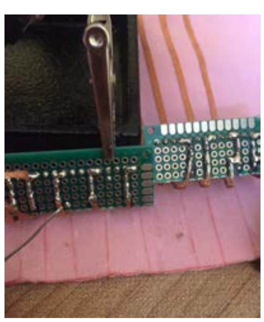
Table 3.4: A selected design for multi-unit fabric-based pressure sensor.

Investigation done	Experiment Result	Best Performance
Type of non-conductive materials	From the experiment the used fabric (Lycra, Felt, Cotton, sports knit and Neoprene) show different textures and responses to human skin. The most important feature for the sensor is, it does not crumple and maintain its position on the 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.	From this experiment, Neoprene shows the best performance as the desired characteristic
Sewing Technique	From the experiment , the sewing technique does affect the sensor performance , the technique was varied as the following list : 1) Single unit combined into multi-unit 2) Thread technique 3) Square of Velostat and conductive fabric 4) Velostat array design – circle shaped 5) Eeontex Array design – Square shaped 6) Weft and warp technique , non-sewn 7) Weft and warp technique is sewn on lycra & neoprene.	The weft and Warp technique sewn on Neoprene shows the most stable sewing technique.
Type of Piezoresistive materials	There are two types of piezoresistive material being tested which was Velostat and Eeontex	The best piezoresistive material that is suitable for pillow sensors is Eeontex.
Layering Technique	Throughout the experiment MedTex 130 (the grey color) was maintained to be used as the conductive fabric. Meanwhile, the piezoresistive fabric was alternately changed, Velostat was applied to the sensor and a Nylon mesh fabric with 0.3mm openings was added as an additional layer.	By not putting any layer underneath the conductive material is the best for pillow sensor application

Throughout the sensor development, 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 caused a short circuit. The wefts and warps technique as illustrated in **Table 3.5** 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 lay down on it.

Table 3.5: Steps of construction of the chosen technique for multi array fabric-based pressure sensor

Picture of weft and warps technique	Explanation
	**STEP 1:** Neoprene was horizontally and vertically cut to make the hole for 8 rows
	**STEP 2:** the conductive fabric was wafted vertically into the hole of Neoprene.
	**STEP 3:** Continue wafted next conductive fabric vertically into the hole of Neoprene.

	**STEP 4:** The conductive fabric was inserted into Neoprene's hole. Then Insert the conductive fabric for another 7 rows.
	**STEP 5:** Wrapped piezoresistive materials on top of wafted conductive materials
	**STEP 6:** wraps horizontally conductive materials on top of piezoresistive material until complete 64 cells
	**STEP 7:** The Circuit board was placed at the edges of the sensor and rows are linked in an array manner.

3.3 Sensor Array Architecture

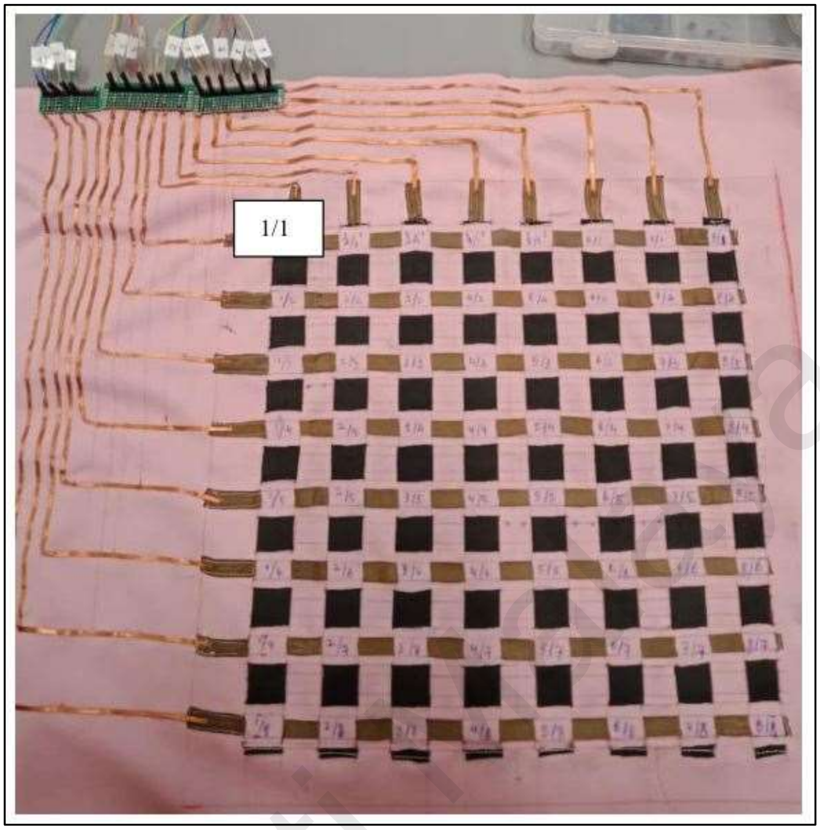


Figure 3.14 : Final design of fabric-based multi-array pressure sensor

The final construction of this Fabric-based multi-array pressure sensor is shown in **Figure 3.14**. The arrangement was made up of an array of a force sensor in a parallel-series configuration forming 8×8 matrices with 1.6mm thickness. Each sensor was placed between the overlapping surfaces of interlacing microfilament and interconnection with respect to other sensor placement in their respective rows and columns forming 64 force sensing elements. Using row and column numbering system, each force sensing element was labelled from (1,1), (1,2) …. (8,8). Ideally, each sensor should be equipped with an independent analogue to a digital channel (ADC) to sample the pressure. To build an *N*-by-N sensor array, *N*×*M I/O* pins were required. For this case, the *N*×*M* structure only requires *2N I/O* pins. Thus, this system is equipped with a two-unit multiplexer that acted as *I/O* pins.

3.4 IV. Data Acquisition System

Three important elements are involved in this **MASP** system: 1) Hardware system, 2) software system and 3) Buzzer alarm system.

3.4.1 Hardware System

This system was built using commercially available electronics tools which are: AVR based as a processing unit, two units of CD4051B Analog Multiplexor, a unit of LM324 op-amp and 10KΩ resistor as in **Figure 3.15**.

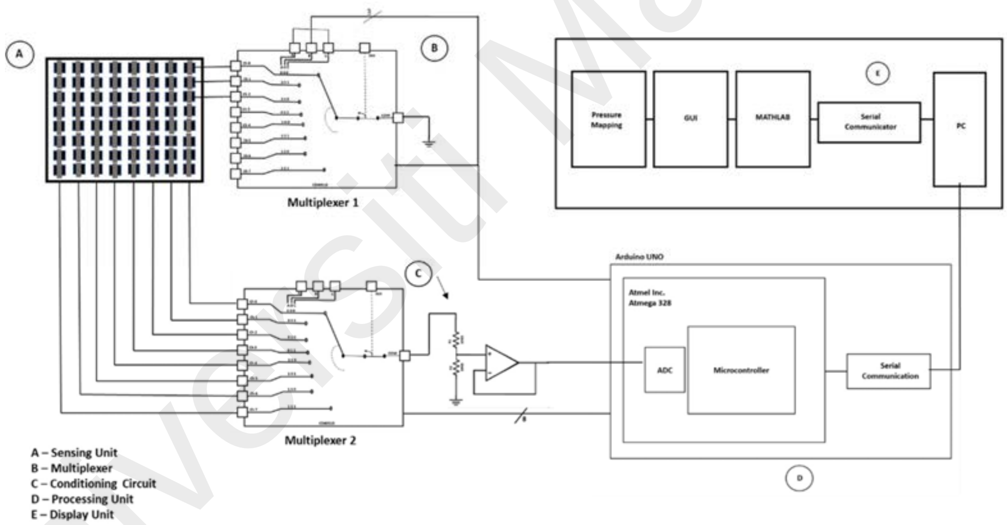


Figure 3.15: Fabric-based multi-array flexible pressure sensor acquisition system

The build-in ADC within the microcontroller can read analogue 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 was configured to be connected to a fixed 10kΩ resistor with a multiplexing technique. The output voltage terminal was connected to the analogue input pin of the microcontroller as shown in **Figure 3.15**. The equation of voltage output is as follows:

$$V_{out} = V_{in}\frac{\mathbf{R2}}{\mathbf{R1+R2}} \qquad \textbf{Equation 2}$$

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 in the R2 sensing element. For the 8×8 array sensor, IC CD2051B was chosen as the multiplexor unit which acted as a solid-state switch with rapid switching frequency. This property enabled the microcontroller to read the signal from all the sensing elements. A voltage follower constructed using LM324 op-amp was used to ensure stable voltage at the ADC input terminal.

3.4.2 Software System for Pressure Mapping Recognition

The microcontroller was programmed using standard AVR IDE software. The serial monitor displayed the analogue 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 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 as shown in **Figure 3.16**.

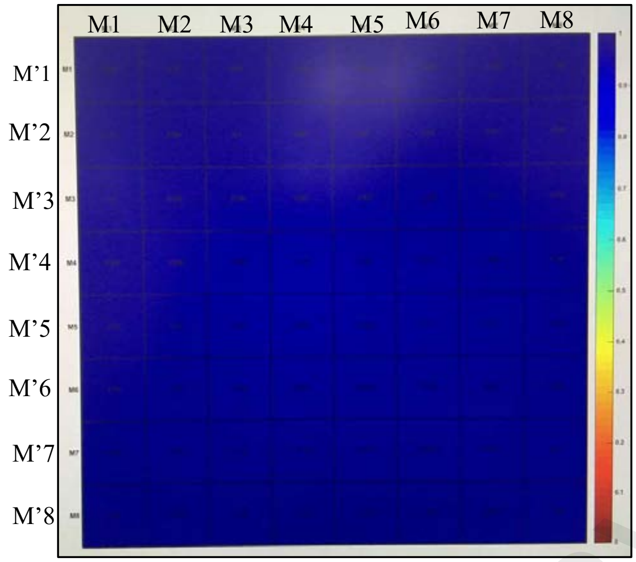


Figure 3.16: MATLAB color-coded mesh plot

The colourmap 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 the applied force would change in color according to the magnitude of force applied to the sensor cell. At freeloading conditions, the sensor value displayed on pressure mapping was dark blue. When slight force was applied, the pressure mapping cell changed colour to light blue, green, yellow, orange and red corresponding to the increased force application the response will be discussed in Chapter 4.

3.4.3 Buzzer Alarm System

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 LEDs as shown in **Figure 3.17**.

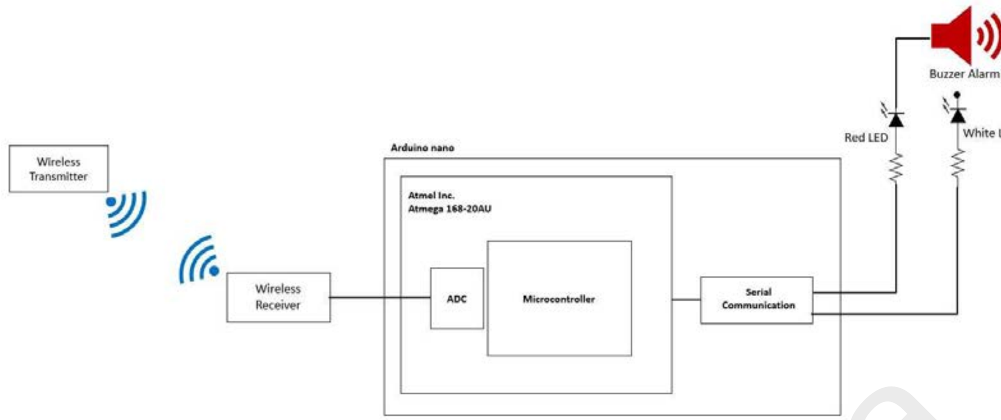


Figure 3.17: Receiver circuit design

For the receiver circuit board, NRF24L0 was used to capture the transmitted wireless signal containing sensor data. An AVR based microcontroller was employed as the processing unit along with a buzzer to alert the caregiver shown in **Figure 3.18**. The receiver is located at the hospital's counter or near the caregiver. A coding algorithm was formulated in Arduino as shown in **appendix A** to classify between the three tapping head movements to initiate the buzzer alarm or a false alarm. The flow chart in **Figure 3.19** shows how the receiver circuit works.

(a) **(b)**

Figure 3.18: The integration of (a) transmitter circuit and (b) receiver circuit

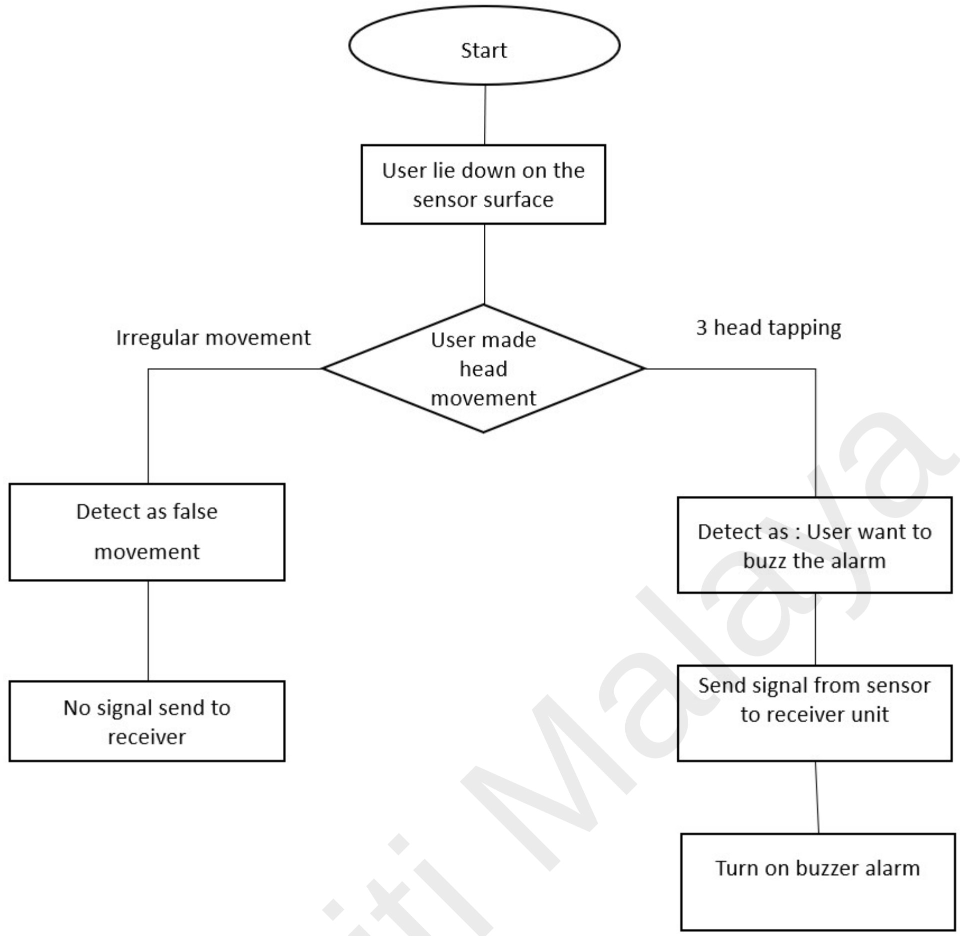


Figure 3.19 : Flow chart to classify the head tapping or irregular movement in Arduino programming.

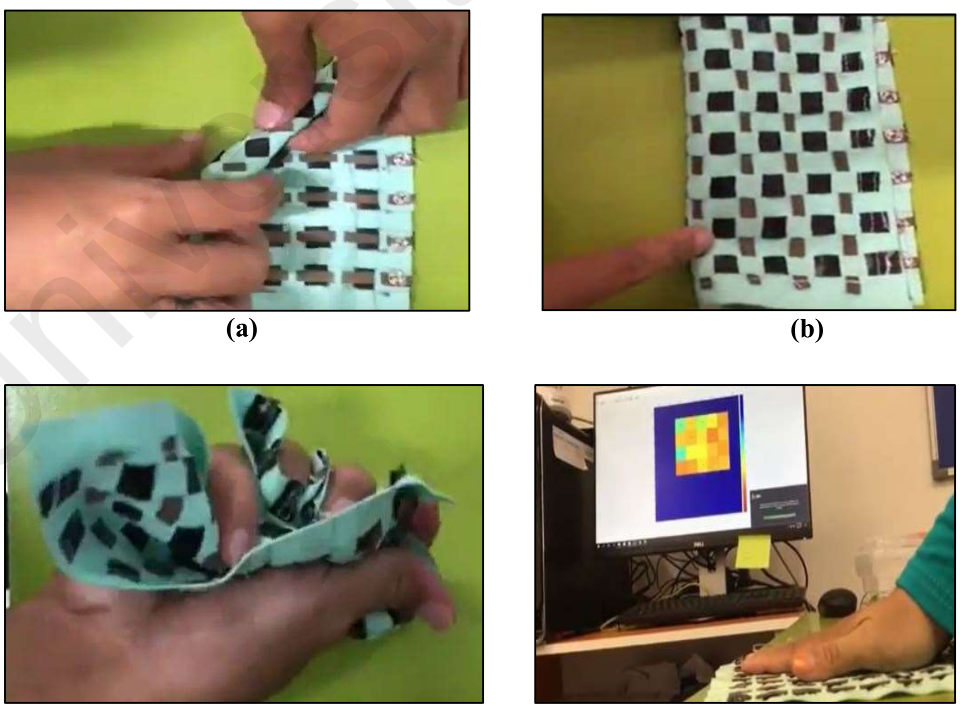
In arduino proggramming , the total voltage inside the circuit is only 5V. When the input pin reaches 5V the system was proggrammed as HIGH. In **Figure 3.19**, as shown in box lable 1, Pin 0 until Pin 7 was programmed as the analog input pin and all the voltage values were read from the pot . In box 2 When Pin 1 is being selected (means there is force is being applied to the array in Pin 1) the system was proggramed as HIGH. This programmed was being repeted the same as to all pins from Pin 0- Pin 7 (please refer to Appendix A). The buzzer alarm was proggramed to buzz when all the Pins were read as HIGH and the buzzer will stop buzzing when one or all the input pin signal as LOW.

3.5 Case Study

To ensure its functionality, the multi-array fabric-based pressure sensor was tested non-clinically and clinically. This is to ensure that the device was proven to be working before being tested on a person.

3.5.1 Non-clinical test

The developed mapping system was first tested randomly by folding, crumpling, rolling and tipping fingers on its surface **Figure 3.20**. This test was done to see the response of the mapping software toward the random condition of the fabric sensor. Then a specific test was done 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 as shown in **Figure 3.21** all the results were analysed and tabulated in chapter 4.



(a) (b) (c) (d)

Figure 3.20 : Fabric-Pressure random test by rolling(a), folding(b), crumpling(c), and tipping fingers(d) on the sensor surface.

Figure 3.21: The manual usage of Advanced Force Gauge (AFG 500, 850-419)

The customised 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 with colour-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. Another simple test to indicate force localization capability was performed by placing round-shaped metals on the sensor array.

3.5.2 Clinical Trial

3.5.2.1 Clinical Protocol

(a) ***Settings***

Rehabilitation Medicine Ward (9SA) UMMC (monitored by Prof Julia & Medical officers) *(b)* ***Patient Recruitment***

The patients who are referred to spinal cord injury rehabilitation will be screened for eligibility. Criteria: traumatic and non-traumatic SCI, aged more than 18 years old, limited hand function causing the inability to use the current call bell, good cognitive functions. Exclusion: patients with contact precaution pillow.

(c) ***Procedures***

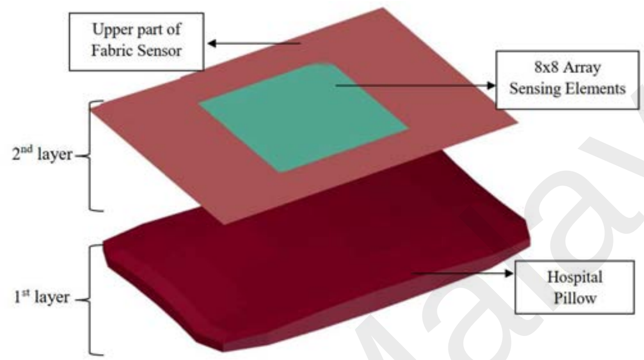
In the first phase, the patients were asked to try different head positioning in attempting to activate an alarm from the nurse call system. From here, the head placement and movement were determined in handling the bell pillow. The pressure needed was measured and the positioning and movement needed to activate the bell. Technical issues that cause problems with bell activation were addressed in this stage.

Subsequently, in the second phase was the observation phase where the bell pillow was left on the same patient for 12 hours (9am-9pm). The data of the experiment should cover two major pieces of information, which are the number of successful and unsuccessful alarm activation, and the number of false alarm activation. The data were collected and evaluated the accuracy of the device quantitatively.

The third phase, was to explore the acceptability of the device in terms of the patient's comfort and practicability. A questionnaire was distributed to patients, family members and nurses who have participated in the experiment. The reliability of the device in terms of comfortability, preferences and practicality were analyzed. From the questionnaire, the opinion of the user on the usefulness of the bell pillow, its weakness and their suggestion for improvement were inquired.

(d) ***Sensor placement***

The sensor was placed on the surface of the hospital pillow as shown in **Figure 3.22 (a)** The pillow was made using standard measurement and material. This pillow is being used throughout the experiment. The size of the pillow is 74cm x 52cm x 11cm shown in **Figure 3.22 (b).**



(a)

(b)

Figure 3.22: (a) Sensor Placement on the Pillow Surface (b) Dimension of standard hospital pillow used in the experiment

3.5.2.2 Device validation on real user

A clinical trial was performed on the fabric-based pressure sensor as an ePillow system. The fabric-based multi-array sensor was placed on the surface of a pillow. To ensure the device really work for the tetraplegic patient, the first attempt was made to test the system on real tetraplegic patient as shown in **Figure 3.23**. After the test, we found out that the sensor system needed to be upgraded to avoid false alarms.

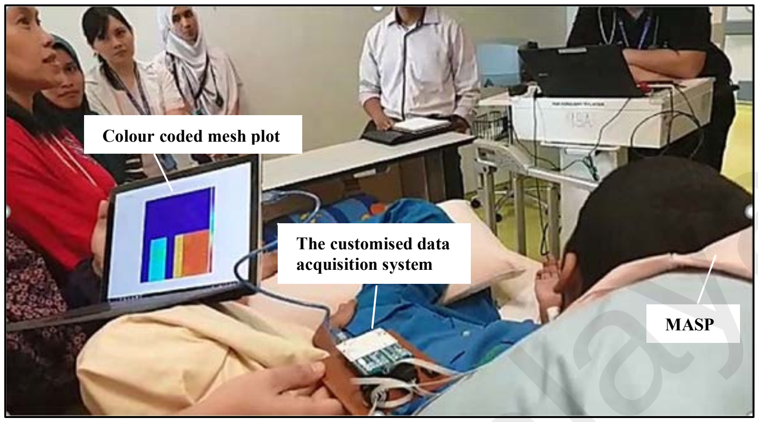


Figure 3.23: First test on real tetraplegic patient in hospital tetraplegic ward under the supervision of medical doctors

3.5.2.3 Feasibility testing of the sensor with able-bodied individuals

After the upgrade, we first tested the device on a healthy individual. They were asked to place his or her head in the middle of the sensing area of the sensor. The subject was instructed to move the head to a different position, upward, downward, left and right as shown in **Figure 3.24**. The data were recorded and analysed whereby the mapping system successfully differentiated the pressure given with the head movement.

Figure 3.24: Testing of the sensor with able-bodied individuals

This action was important for calibration and as a method to differentiate between real intended calls and false alarm.

3.5.2.4 Clinical testing of the sensor with tetraplegic user

Multi-array sensorised pillowcase was implemented with the fabric pressure sensor when the sensor was evaluated to be reliable to be used as the input sensor of the system. The clinical testing was conducted after ensuring the tetraplegic pillow has been well developed in terms of the stability of the transmitter and receiver circuit to exchange signals.

The test was performed on one tetraplegic patient aged 32 (male) with having limited hand function but could move around using a motorised wheelchair and a normal subject aged 23 (female) as control. This test was important because tetraplegia patient can only lift their head to a lesser degree and their energy is lower compared to a normal user. This experiment focused on the reliability of the nurse call system interface with the patient. Its main purpose was to evaluate the accuracy, sensitivity and reliability of the device when in use with tetraplegic patients.

(a) ***Accuracy and sensitivity test***

To determine the accuracy of the multi-array sensorised pillowcase quantitatively, the frequency of three different types of alarms (successful, false, unsuccessful) were recorded. The basic procedures to determine these types of alarms are as follows. The frequency of successful alarm activation is recorded through validation with the patient every time a call is activated:

1. If it is intentionally activated, then the alarm is counted as successful alarm.
2. If it is not, it is counted as an unsuccessful alarm.
3. If it is unintentionally activated, the alarm is counted as a false alarm.

The investigation was done during two conditions, awake and sleeping. While awake, the investigator gave instruction to patients to activate the call bell system and when the device failed to do so, it will then be counted as an unsuccessful alarm. Any buzzer that was activated outside the activation attempts was counted as a false alarm. Then, during sleeping, the patient was required to sleep on the pillow as their normal routine. A video camera was filming during the experiment. The activation of alarm was recorded from the captured video.

(b) ***Reliability Assessment***

A reliability assessment was done by distributing a questionnaire to caretakers and nurses to obtain their individual experience and thought as well as suggestion on improving the nurse call system. An interview was conducted with tetraplegic patients to consider their experience and how helpful the system has been doing during the whole testing as well as challenges encountered during the whole period of using the pillowcase. Through the questionnaire distribution, the reliability of the device was analysed in terms of comfortability, preference and practicality.

3.6 Summary

Multi-array sensorised pillowcase was developed, tested and analysed based on its sensitivity, reliability and practicality as call detection alarm system for in ward tetraplegic patients.

CHAPTER 4: RESULT AND DISCUSSION

This chapter presents all the findings of the study. The results are presented in graphs and tables. This chapter is divided into 7 main sections associated with the non-conductive materials performance, sewing technique and their effect on sensor performance, performance of two types of piezoresistive materials, the effect of different layer on multi-array fabric- based pressure sensor, MATLAB colour code mesh plot, non-clinical and clinical test results.

4.1 Performance of non-conductive materials

Non-conductive materials are the main protective fabric that will highly influence the sensor performance. This fabric needs to adapt the sensor with the force applied during lying down on pillow surface and to sew on all the components for multi-array sensor. The fabric should be stable, non-wrinkle, slightly flexible, easy to sew and comfortable to be wear. Comfort parameter was well explain in **Table 3.2**. In **Table 4.1** described the performance of single array fabric-based pressure sensor mentioned in Chapter 3.

Table 4.1: Performance of non-conductive materials

Type of Fabric	Non-wrinkle	Slightly flexible	Easy to sew	Comfortable	Stable
Lycra	✗	✓	✗	✓	✗
Felt	✓	✗	✓	✗	✓
Rubber	✗	✓	✗	✗	✗
Sports Knit	✗	✓	✗	✓	✗
Neoprene	✓	✓	✓	✓	✓

In this investigation, it was found that Lycra, Sports knit, and rubber were very flexible and stretchy fabric, this makes them become very difficult to sew. As time goes by, the materials become easily wrinkled and not stable when we put on the surface of the pillow. Meanwhile, for Felt and Neoprene, both are easy to sew and non-wrinkle. When being squeezed and being put on the pillow surface both fabric surfaces were still stable, and the sensor were still intact its internal materials. However, in between Felt and Neoprene in terms of comfortability, Neoprene is more comfortable to skin. In conclusion, utilisation of Lycra, Sports knit, and Rubber are not the best choices, as it is relatively more difficult to sew and put all the sandwich materials together due to its highly stretchable properties. The best non-conductive fabric among these materials is the 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 sensor.

4.2 Performance of different design and sewing technique.

Sewing was done mainly to ensure the electrical connectivity of the sensor as alignment of the sensing elements and all the sandwiched layers are in place for effective multi-array design. **Table 4.2** shows the performance of all the developed design as mentioned in Chapter 3.

Table 4.2: Performance of various multi-array design

Design	1	2	3	4	5	6	7
Sewing Technique	Combine single	Thread	Patching	Circle array	Square array	Weft & wasp (unstitched)	Weft & wasp (stitched)
Is it easy to sew?	✗	✓	✗	✗	✗	✓	✓
Connectivity	✗	✓	✗	✗	✗	✓	✓

Throughout the sensor development, it was found that the sewing technique affects the performance of the sensors. Conductive fabric cannot be directly sewn on the surface of piezoresistive material as it causes micro contact between two conductive fabrics on the top and bottom layers. Thus design 1-5 cannot be adapted for MASP. Wefts and warps technique showed positive results, whereby all units were able to detect individual pressure as well as multiple applied force. The technique was simple to be sewn, stable on any surface and comfortable when one lay down on it.

4.3 Performance of piezoresistive materials

The core structure of the piezoresistive fabric-based sensor is the piezoresistive materials that influence the resistance properties of the sensor. It was reported that Velostat and Eeontex (Giovanelli & Farella, 2016) are the most popular piezoresistive materials used in fabric-based pressure sensor construction. Velostat is made from carbon that is fused into a plastic sheet, while Eeontex is made from carbon fused into a fabric sheet. The structure between plastic and fabric had significant differences in terms of flexibility. The plastic, will wrinkle easily and not restore to its original shape once it is crumpled but the fabric will not wrinkle easily and easily restore to its original shape. The properties of the materials are shown in **Table 4.3.** From the table, it is reported that Velostat has higher resistivity compared to Eeontex but has lower flexibility because Velostat is made from PLA plastic while Eeontex is made from Nylon fabric.

Table 4.3: The Properties of Piezoresistive Material

Material Properties	Velostat	Eeontex
Part Number	Velostat	EeontexNW170SLPA 2K
Surface resistivity	<31,000Ω/sq.cm	2000Ω/sq.cm
Density	17g/m^2	18.66g/ m^2
Thickness	0.2mm	0.8mm
Material	PLA Plastic	Nylon Fabric

An experiment was conducted to compare the properties between Velostat and Eeontex. In other words, the experiment sought to determine how the structure of the material affects the resistivity of materials. **Figure 4.1** reports the result of the experiment conducted on both piezoresistive materials.

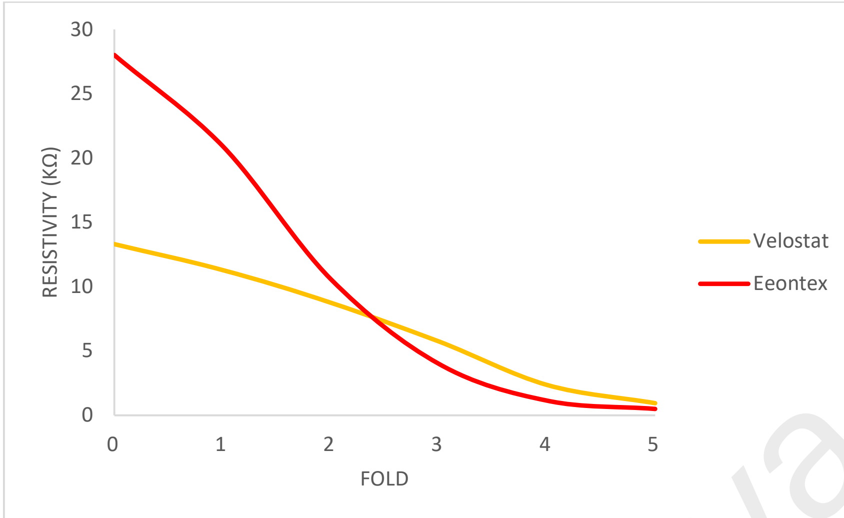


Figure 4.1: Resistivity change of Velostat and Eeontex when Folded.

Figure 4.1 shows that, the results of resistivity change between Velostat and Eeontex when folded. Before the experiment started at zero fold, there are clear differences in initial resistivity values between Velostat and Eeontex. Eeontex has 30 KΩ resistivities while Velostat has 15 KΩ initial resistivities. From here, it is shown that Eeontex has higher initial resistivity values compare to Velostat. The obtained values are comparable as reported from the published datasheet (Adafruits, n.d.; Hitek, 2018). 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 in 0KΩ resistivity. From this experiment, Eeontex is better to be used in the MASP system based on its' response and resistivity change when in pressed or folded condition.

4.4 The internal layer of the multi-array fabric-based pressure sensor

According to section 3.2.3.4 in Chapter 3, 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 that will be discussed in this chapter. In this experiment, using the same multi-array design, four types of fabric-based sensor were constructed, and a steady force were applied on the sensor array units using AFG to collect pressure data reading. All the data were collected and analysed as shown below.

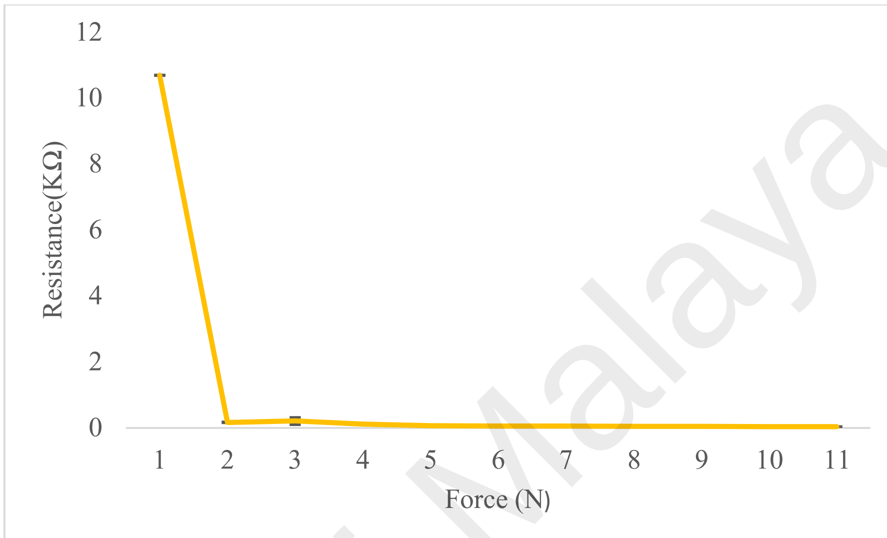


Figure 4.2 : The graph is the result of the average and standard deviation of multi-array sensor performance with internal layer of Velostat only.

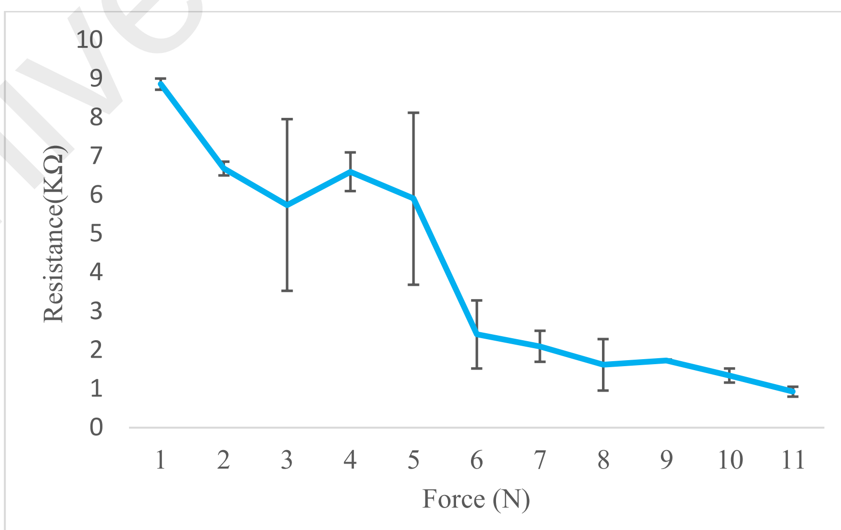


Figure 4.3 : The graph is the result of the average and standard deviation of multi-array sensor performance with internal layer of Velostat & Mesh.

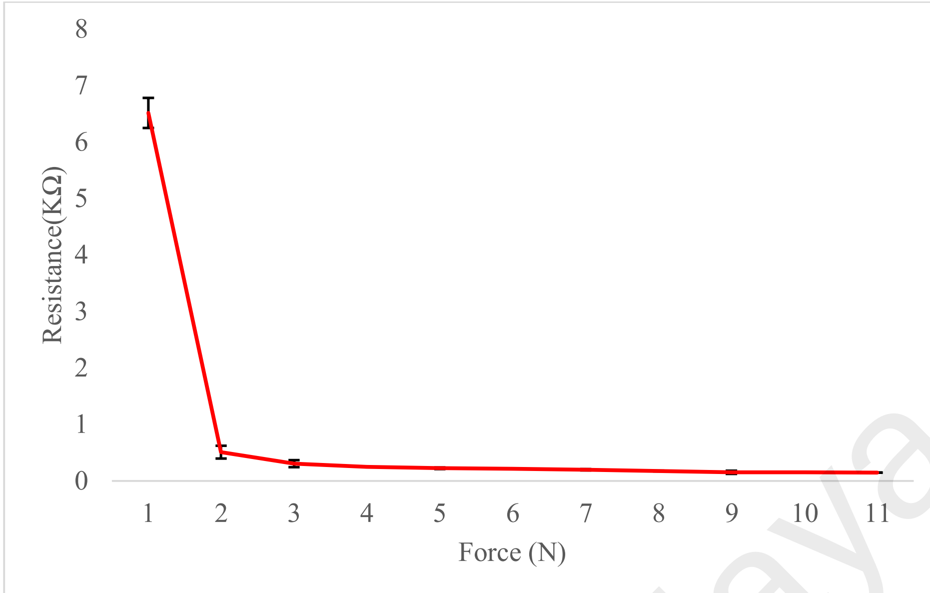


Figure 4.4 : The graph is the average and standard deviation result of the multi-array sensor performance with internal layer of Eeontex only.

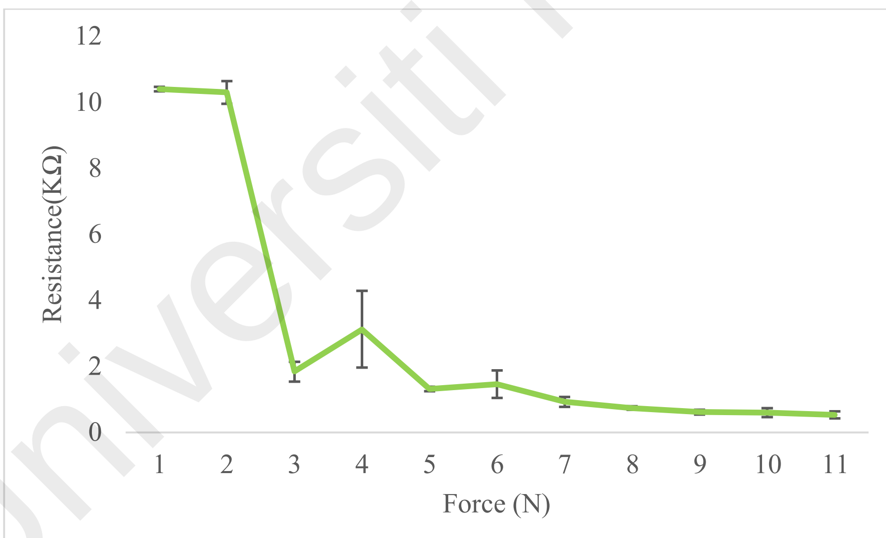


Figure 4.5 : The graph is the result of average and standard deviation of the multi-array sensor performance with internal layer of Eeontex & Mesh.

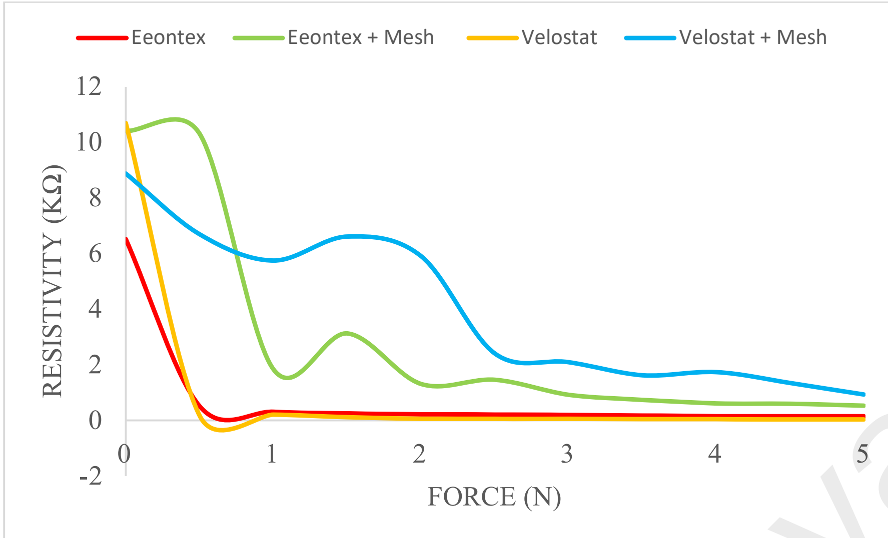


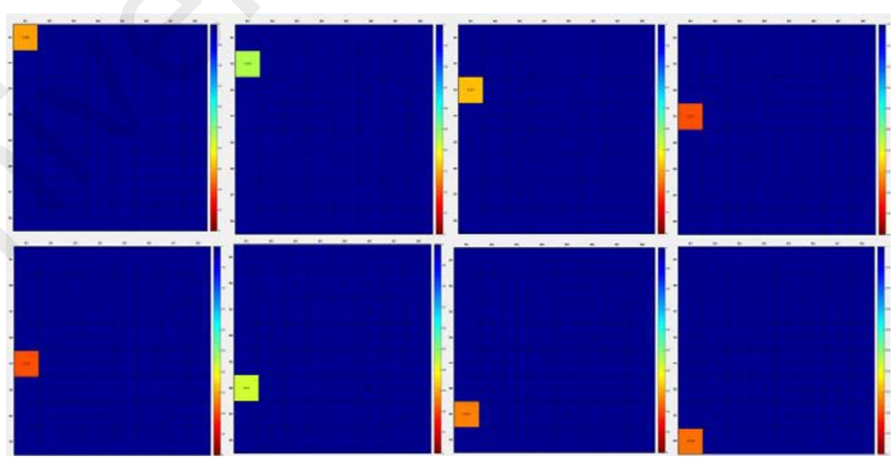
Figure 4.6 : The graph is the overall result of the constructed multi-array sensor.

The graphs in **Figure 4.2 until Figure 4.6** proved that changes in materials inside the fabric sensor resulted in significant differences in term of sensitivity, consistency, and resistivity. When the sensor was made of Velostat alone, the reading was relatively consistent as shown in **Figure 4.2** The reading decreased gradually with increasing force with very low readings due to its lower resistance. With the presence of a mesh layer, the ability of the sensor to detect higher force was increased, however, the captured data showed relatively higher inconsistency as shown in **Figure 4.3 & Figure 4.5.** For Eeontex alone according to **Figure 4.4**, the reading was consistent but too sensitive. Plots in **Figure 4.6** concluded all the properties for each set of the sensors. In essence, adding a mesh layer with Velostat and Eeontex increased the ability of the sensor to detect higher force.

4.5 MATLAB colour-coded mesh plot

A MATLAB program was used to interface with Atmega 328 by visualisation of sensor data using a colour-coded mesh plot. This plot is collated with the amount of force applied to each individual sensor. The scale of colour ranged from dark blue, light blue, green, yellow, orange and red. The colourmap change would respond in accordance with the amount of force applied to each sensor.

When a greater amount of force was applied, the acquisition system would detect the decrease in voltage that occurred at the sensor cell. The cell on the pressure mapping screen that represented the location of applied force in turn displayed changes in colour according to the magnitude of force applied on the sensor cell. At the free loading conditions, the sensor value displayed on pressure mapping was dark blue. When a slight force was applied, the pressure mapping cell changed colour to light blue, green, yellow, orange and red in order of increasing force application. **Figure 4.7** illustrates the colour changes of the system according to the amount of force design. Here we can see the pressure mapped based on the force applied on its surface.



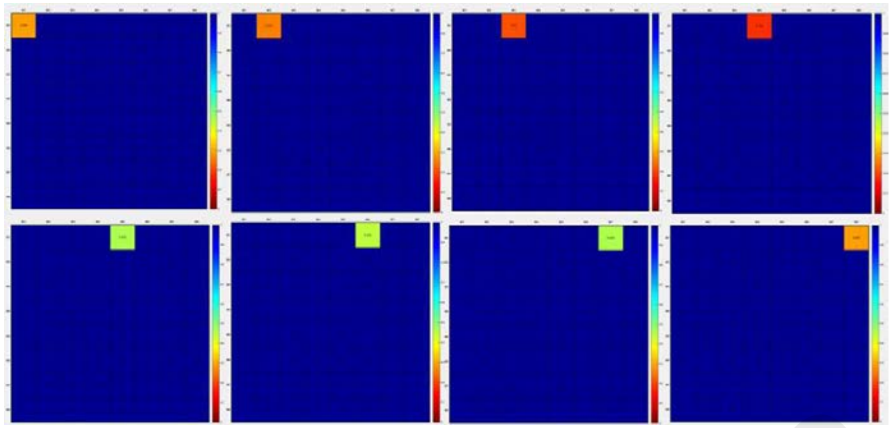


Figure 4.7 : Visualisation of colour-coded mapping system under MATLAB program

4.6 Result on the non-clinical test

A non-clinical test was mainly done only in lab using specific tools that do not involve volunteer to test the device. The test was mainly aimed to investigate the functionality of the sensor, whether it can map the position, respond to the pressure given, or be affected when the surface change Thus, to answer the stated questions, two non-clinical tests whereas done which are: random test and load test.

4.6.1 Random mapping test

This test was done randomly on the surface of table, then the sensor was pointed with one finger, pressed with five fingers, folded and crumpled" as shown in **Figure 4.8.** As illustrated from the figure, it is shown that no matter how bad the fabric sensor was being treated, the sensor was still able to sense the pressure given and give real time data on the mapping screen. This shows that, the sensor can be used on any surface and still detect the force given.

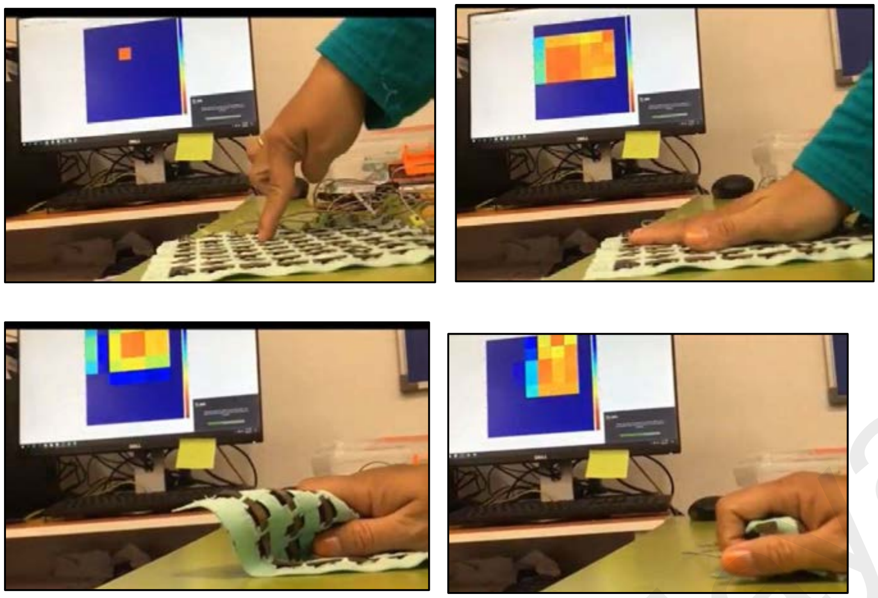


Figure 4.8: Random mapping test

4.6.2 Load mapping test

Another simple test to indicate force localisation capability is performed by placing round shape metal on the sensor array. In **Figure 4.9,** 1N circular block (smaller in size) and 5N circular block (bigger in size) were used. These circular blocks were placed into wo, three, distributed circular block, and large area load application.

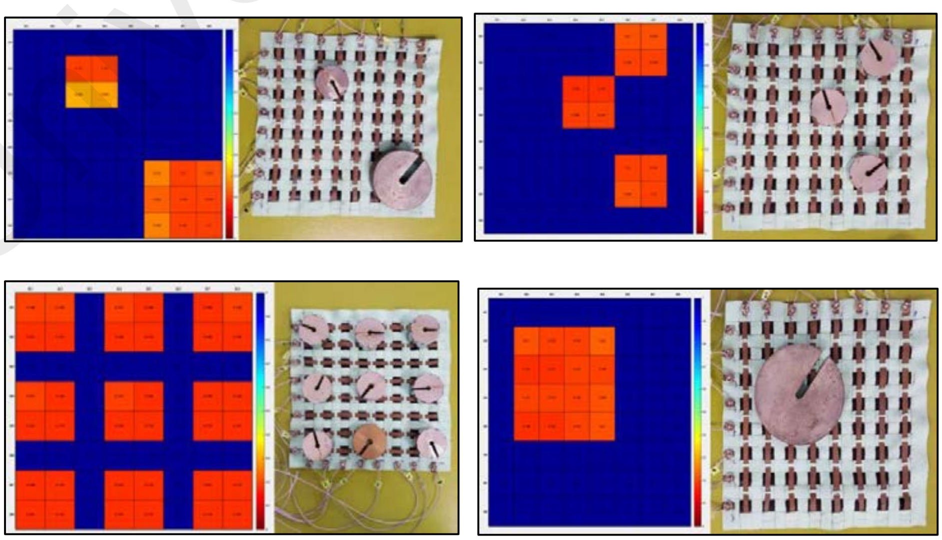


Figure 4.9 : The mapping result on MATLAB display when a metal circular block was applied to the multi-array fabric-based pressure sensor surface.

During free loading, the initial value of the sensor cell was in the range of 3V to 4V indicating the blue colour in the pressure map. At minimal load the highest voltage display was 1V. Hence, the colour bar scale setting was adjusted at a range from 0 to 1 without altering the value of data acquisition at each load, and to ensure the display mapping could differentiate between free-loading and applied load.

From these two-simple experiments, the system has proven successfully that the mapping algorithm could detect force and location of the applied force in any surface and sensor conditions.

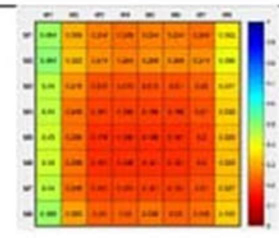
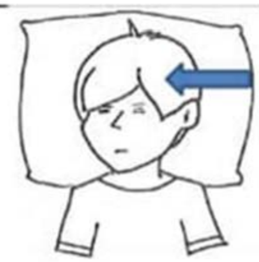
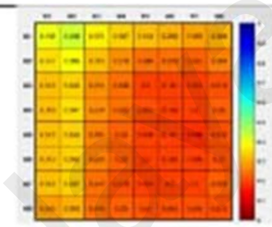
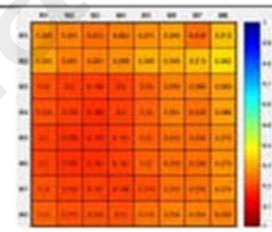
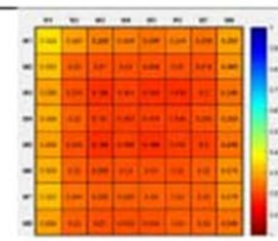
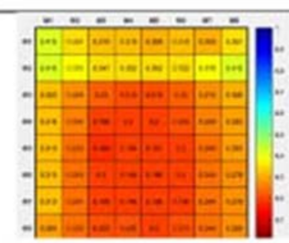
4.7 Result on the clinical test

These clinical trials ware done to investigate whether the system can successfully be used as call bell system for in ward tetraplegic user. The sensor was covered by waterproof fabric to avoid any unintended direct contact with liquid or perspiration. The multi-array fabric-based sensor was placed on the surface of a pillow. The experiment was done on able-bodied subject and tetraplegic subject.

4.7.1 Result of feasibility testing of the sensor with able-bodied individuals

This section illustrates the coloured mesh plots obtained from able-bodied individuals. Each movement was obtained when individuals moved their head to their left and right, and upward and downward orientation.

Table 4.4 : Volunteer’s head orientation and its respective pressure map

Orientation	Illustration	Pressure Mapping
Normal		
Right		
Left		
Upward		
Downward		

The colour mesh plots obtained were directly influenced by the pressure applied onto the fabric pressure sensor cell. A dark orange to red colour represents large pressure applied with value close to zero while a light yellow to green color represents small pressure with value close to one. The pressure mapping that was displayed through

MATLAB formed mirrored image of volunteer's head orientation. This is presented in **Table 4.4** where volunteer's right-hand side was displayed as viewers right-hand side and vice versa. However, the pressure mapping displayed for upward and downward movements was not affected by the mirror effect.

From these findings, an algorithm was improved, by setting the alarm to the only buzz when the head was lifted upward and downward for three times. This technique was found to be an effective method to eliminate false alarm. 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 **MASP** system.

4.7.2 Result of clinical testing of the sensor with tetraplegic users

This clinical testing was done to tetraplegic patients to determine the accuracy and sensitivity of MASP system when the call bell is activated. The tetraplegic patients were required to do head tapping for three times to activate the alarm. Ten trials ware done for system activation, the frequency of successfully and unsuccessfully activated alarm was recorded as successful alarm and unsuccessful alarm respectively. Any alarms activated out of ten trials was considered as a false alarm and was also recorded. The experiment was conducted with guidance from the investigator, in which all attempts were made through instructions. The purpose of making it done through instructions is to see how effective the activation methods are when attempt under full intention to activate a call. **Table 4.5** illustrates the results of the experiment.

Table 4.5: Total Frequency of the head tap during awake

Types of alarm	Total Frequency
Successful alarm	53/60
Unsuccessful alarm	7/60
False alarm	7

Based on observation, the head tapping mechanism successfully activates a call when it detects the head being lifted off the pillow three times. The head movement was more towards a chin downward movement orientation and was easily done by the subjects compared to other head movements. Factors from patients include the limited range of motion that was inhibited by the subjects' neck". However, head tapping mechanism is the most effective method for tetraplegic patients to activate the alarm. Then accuracy of the sensor was measure by using the indications stated in **Table 4.6.**

Table 4.6: Indication used in the accuracy test.

Terms	Description	Definition
True Positive (w)	When the call is intentional, and the alarm turns on.	Successful alarm
False Positive (x)	When the call is non-intentional, and the alarm turns on.	False alarm
False Negative (y)	When the call is intentional, but no alarm is activated.	Unsuccessful alarm
True Negative (z)	When the call is non-intentional, and no alarm is activated.	No activation

The duration of each type of alarm activated during treatment or consultation with doctors was assumed according to the observation that took place during sleeping that was recorded in a video. From the video, it was observed that an average duration taken for a successful and unsuccessful alarm take place was around six seconds, while ten seconds for false alarm activation. The total duration of observation during treatment or consultation with doctors was 30 minutes. Meanwhile, the total duration of observation during sleeping is two hours and 20 minutes. The value of z was calculated by subtracting the total duration of each observation, w, x and y respectively. z values represent the duration of the MASP when remained unactivated where there were no types of alarms present as shown in **Table 4.7** and **Table 4.8.** From this table, the accuracy and sensitivity values were calculated according to the (Šimundić, 2009). The formula is as follows:

$$\boldsymbol{Accuracy} = \frac{w+z}{w+z+x+y} \qquad \textbf{Equation 3}$$

$$\boldsymbol{Sensitivity} = \frac{w}{w+y} \qquad \textbf{Equation 4}$$

Table 4.7 : The respective sum of duration per each term for observations during sleeping

Outcome of buzzer	Condition of alarm		Total
	Intentional	Non-intentional	
Turn on.	21	7777	7798
Turn off.	19	8983	9002
Total	40	16760	16800

Table 4.8: The respective sum of duration per each term for observations during treatment

Outcome of buzzer	Condition of alarm		Total
	Intentional	Non-intentional	
Turn on.	204	190	392
Turn off.	24	1382	1406
Total	228	1572	1800

Table 4.9: Accuracy and sensitivity of Multi-Array Sensorised Pillowcase system in percentages

Observations	Accuracy	Sensitivity
During treatment with doctors	88%	89%
During sleeping	54%	52%
Average	71%	70%

From these tables, the average values of multi-array sensorised pillowcase system is 71% accurate and 70% sensitive and is suitable to be used as tetraplegic in ward call bell system.

4.8 Summary

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.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

Finally, this chapter presents the major conclusions based on the contributions that have been made in this thesis. The chapter begins with an overall conclusion then highlights the major contributions. The chapter ends by declaring the limitations of this study with suggestions and recommendations for future works.

5.2 Conclusions

In this thesis, a new technique of fabricating a fabric-based sensor array was developed and clinically investigated. A multi-array fabric-based sensor was designed, fabricated and tested based on the new technique. The pressure sensor array was entirely customised from off-the-shelf conductive and piezoresistive fabric and designed with weft and warped woven form.

To understand the sensitivity of the sensor, different layers, materials and construction methods was developed and tested. It was found that carbon-infused fabric (Eeontex) is more sensitive and flexible compared to carbon-infused plastic (Velostat). Apart from that, by increasing the number of the piezoresistive layer the resistivity increased causing higher pressure measurement to be measured. In addition, adding mesh fabric in between the layer will affect the sensitivity of the sensor. With the presence of mesh fabric more heavyweight can be measured. We also found that warp and weft are the best designs for the multi-array fabric-based pressure sensor.

A data acquisition system was specially designed to read and visualize real-time pressure data from an array of piezoresistive fabric-based pressure sensors. In addition, a pressure mapping algorithm which runs on an AVR based platform and MATLAB was developed to continuously read and visualize the pressure profile from the fabric pressure sensor. To ensure low component count and simple hardware, the concept of multiplexing has been employed in the hardware architecture and the firmware was written to support this architecture. This approached allows the system to perform even with a single processor and single ADC.

Finally, a multi-array fabric-based pressure mapping sensor was constructed in the form of a pillow and used as an alarm system for tetraplegic users which is known as a Multi-array sensorised pillowcase call detection alarm system. The alarm system has not only successfully measured pressure given by tetraplegic patients, but also acted as an alarm system for the user. The system has successfully differentiated between a false alarm and a true alarm when the user lies down on the system. The alarm system was very helpful in many other biomedical applications specially to disabled users. In conclusion, the piezoresistive fabric-based pressure sensor has shown simple fabrication and high potential in a wide variation of biomedical device applications. All the set objectives have been successfully addressed.

5.3 Summary of major contributions

The following are the list of major contributions made by this thesis:

i Development of Multi-Array Sensorised Pillowcase as call detection alarm system for in ward tetraplegic patients

A fabric-based pillow system was developed to detect pressure imposed by tetraplegic patients to activate the alarm at the nurse counter. The system consists of a fabric-based pressure sensor array, conditioning circuit, processing unit, display unit and wireless alarm system.

ii A new design of Multi-Array Fabric-Based Pressure sensor

Various methods of constructing a fabric-based sensor array were evaluated. The effect of utilisation of mesh layers and type of piezoresistive material were analysed in terms of its multi-array sensor performance.

iii Pressure mapping recognition

An algorithm for position pressure mapping recognition was presented in order to differentiate the head movement pattern. The system performance was then evaluated with three subjects, one normal subject and two tetraplegic subjects. The experimental results showed that the system was able to differentiate between the pressure pattern produced by the patient's head for buzzer activation in lying down conditions with 71% accuracy and 70% sensitivity. This method is also applicable to other applications that demand a flexible pressure sensing platform.

5.4 Limitation of the Study

This thesis mainly focused on the design and development of a multi-array sensorised pillowcase as a call detection alarm system. However, there are a few obvious limitations during the process. The first limitation is the small range of noise of the mapping system that makes the detection of mapping alarm slightly delayed. Then the second limitation is the lack of subjects that participated in the study. During the feasibility testing, a total of two subjects participated while during clinical testing and available to participate in the study. We need more real patients to validate the results. Also, the mapping system on a computer screen at the nurse counter is not practical to be used, as the nurse does not understand what the mapping language means. Further improvement needs to be made to improve the system.

5.5 Recommendations for Future Works

The research work reported in this thesis can be further extended as listed below:

i Hardware system Improvement

The performance of the system can be further improved by utilising sub-components with higher specifications incorporating noise filters and auto-calibration. The circuitry of the multi-array fabric-based pressure sensing system should be simplified and miniaturised so that it is more accurate, portable and user-friendly.

ii False alarm detector

An algorithm needs to be upgraded so that a false alarm can be avoided and only the intended alarm that will trigger the buzzer.

iii Meaningful mapping system

The mapping system needs to be upgraded so that it gives more meaning to the users. For example, if they tap on the left means they want to eat and on the right means they are in danger.

iv Phone apps

In addition, the system will need to have an algorithm to produce notifications to the users' families using phone applications. With all integrations, a multi-array sensorised pillowcase system can be used in a wide variation of biomedical engineering applications.

LIST OF PUBLICATIONS, PAPERS PRESENTED, AND AWARDS

List of Publication

1. Alias N., Razak ZA., Janjori M., Ahmad MY., Engkasan JP.,& Hamzaid NA. (2020). ePillow: A Fabric-Based Pressure Sensor Array for Tetraplegic Patient Call Detection System. Jurnal Teknologi (Sciences & Engineering)

List of Papers Presented

1. Alias N., Ahmad MY., & Hamzaid NA. (2016). Fabric-Based Sensor for applications in Biomedical Pressure Measurement. *MoHE 2016 3rd International Conference on Movement , Health and Exercise* (28-28 September 2016).

2. Alias N., Razak ZA., Ahmad MY., & Hamzaid NA. (2017) Multi-channel Fabric Based Pressure Mapping Data Acquisition System. *International Federation for Medical & Biological Engineering and Malaysian Society of Medical and Biomedical Engineering ICEBEL 2017.* (10th -13th 2017)

List of Awards

1. Sports Innovation Award . *MoHE 2016 3rd International Conference on Movement, Health and Exercise* (28-28 September 2016)

2. Third Prize Award, IFMBE-Sponsored Young Investigator Award 2017. *International Federation for Medical & Biological Engineering and Malaysian Society of Medical and Biomedical Engineering ICEBEL 2017.* (10th -13th 2017)

List of Patent

1. Multi-Array Sensorised Pillowcase as Call Detection Alarm System for In Ward Tetraplegic Patients 2019-02-20

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