DESIGN AND DEVELOPMENT OF A POSTURE MONITORING SEAT BACKREST USING AN ELECTRO-TEXTILE SENSOR MATRIX

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**ABSTRACT**

Lower back pain is one of the most common prevalent spinal diseases, where up to 84 percent of adults are reported to experience pain within their lifetime (Ninds.nih.gov., 2016). As reported, bad or incorrect postures are one of the major contributing factors for this condition.

This MPhil report describes the design and development of the technology for a textile-based posture monitoring system by using a sensor matrix combined with accelerometers. The proposed system references the pressure distribution resulting from a human back when leaning against a soft backrest, on which a network of pressure sensors and accelerometers are placed. Therefore, the sensor system can evaluate the local curvature of the lumbar spine arch, allowing a clinician to advice on the posture. Posture feedback data from this system can benefit people who are suffering progressive degeneration of the spine disc.
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Chapter 1. Introduction

1.1 Textile-based sensors

As long as a physical change is observed against external stimulation, any material can be used as a sensor (Cho, 2009), including sensors based on electro-textiles. In the past two decades, textile-based sensor has been attracting more attention, mainly thanks to the advances in nanotechnology, which allows miniaturized sensors to be integrated onto fabrics.

An appropriate example for the above is a recent research in mounting miniaturized electronic chips on the flexible printed circuit board (FPCB) to be applied to a garment. In this case, what stands out is that the FPCB serves as a buffer between solid electronic chips and the fabric, where it remains stiff but keeps all the functions as well (Cho, 2009).

Textile is the interlacement of fibre, which can be classified into three main types: woven fabric, non-woven fabric and knitted fabric. After manufacturing, the textiles go through various processes like dying, softening and antistatic finishing. Based on their mechanical and electronic properties, many kinds of finished fabrics, therefore, can be used as an electro-textile sensor. In such a material, if a certain physical change occurs, for instance, a change in the pressure it experiences, that change could be observed in an analogue/digital processing device. For this purpose, the change has to be converted into an electric quantity. And then, to transmit the converted electric
signal, a conductive fabric is required (Cho, 2009). Combining electronic components with textile materials would not hinder the user’s activities or influence the signal’s capture. Then an ideal textile-based sensor ought to change its resistance to emit signals or change the flow of electric current in its reaction to external stimulation.

Pressure is a wildly used physical quantity in our daily life. When pressure is sensed by a pressure sensor, as shown in Figure 1.1, it can be monitored as the change in resistance in the sensor. Mechanical pressure sensors, strain gauges, and semiconductor piezoresistive or piezoelectric sensors are some of the ordinary pressure sensors. Various pressure sensors employ electro-textile structures (Sung et al., 2007), such as piezoresistive sensor, capacitive pressure sensor (Meyer et al., 2006; Sergio et al., 2004), and flexible plastic optical fibre (POF) based sensors (Rothmaier et al., 2008).

![Figure 1.1. Principles of piezoresistive sensor and capacity pressure sensor (Cho, 2009)](image)

1.2 Research problem

Postural control is expressed as the way our central nervous system regulates sensory
information from other systems in order to produce adequate motor output or muscle activity to maintain a controlled, upright posture (Therapies, 2012). When talking about a healthy body, posture is just as important as eating right and regular exercising, because correct posture means bones are properly aligned, so that our muscles, joints and ligaments can work as nature intended them to, which is a way of doing things with more energy, less stress and fatigue.

Nowadays, posture-related problems are on the increase, and bad postures are developing bad habits due to reasons such as incorrect posture while viewing the television, and also due to more work being done deskbound, such as people spending more time sitting in front of computer terminals. Long-term sitting without changing postures might result in tight, achy muscles in the neck, back, arms and legs or even nerve damage.

Looking at research done in creating posture monitoring systems. Most of the current and previous studies focus on the pressure on the seat pan. Meyer et al. (2010) have used a textile sensor with 240 elements for pressure patterns measurement. And Xu et al. (2013) also used a smart cushion placed on the seat pan for posture analysis. Furthermore, by sewing the silver-coated yarns directly on the cotton fabric with lockstitches, Saenz-Cogollo et al. (2016) proved that it is possible to measure the normal pressure experienced by the sole while a person is in an upright posture.

Although some commercial products are available for body pressure mapping, such as the BPMS (Body Pressure Measurement System) from the Tekscan® (Tekscan, 2014) and Model 5233 from the PPS (PPS, 2016), they are not capable of demonstrating the
curve shape of the human back while sitting. Additionally, their price also makes them prohibitive for regular use.

1.3 Main aim and objectives

Therefore, in order to help address the above need, the main aim of this research project is to ‘design and create a textile-based sensor system to obtain a person’s back posture while sitting’.

Additionally, the following objectives will need to be realised in order to support the achieving of the main aim. They are:

1. construction of a pressure sensor matrix to fit a backrest of a seat to measure contact between the back and the seat backrest.

2. integration of accelerometer systems on the pressure sensors to determine the back profile.

3. construction of an electro-textile pathway for data collection from the accelerometers.

4. use the data from the accelerometers/pressure sensors to give a profile that describes the back curve.

5. combine the data from the sensor matrix and accelerometers together, then analyse
the sitting postures.

The proposed technology is a timely research that can benefit wherever people remain seated for long durations, by reminding them to correct their posture or move around. Besides this, automotive vehicles that have poorly designed seats too could benefit from this technology and thereby contribute to reducing accidents and injuries, which may be caused indirectly due to posture related problems.

1.4 Thesis layout

The body of this thesis comprises mainly five chapters as explained below.

Chapter 1 introduces the general research area and summarizes the research problems and objectives.

Chapter 2 provides a detailed literature review, describing the previous work in the field and presenting alternative posture monitoring backrest designs at the same time, including the description of electronic textiles, the materials and other methods used for creating textile-based sensors.

Chapter 3 focus on sourcing of different engineering materials and investigates the electro-mechanical properties of materials, especially the ability to sense pressure signals. The compared results help to make a decision on the optimum piezoresistive materials for sensors. Additionally, this chapter shows the construction of sensor matrix and integration of accelerometers to the posture monitoring system. And the
software used for data collection and other involved equipment are explained with their specifications.

Chapter 4 is about the results and discussion of the experimental work.

Chapter 5 summarises and concludes the major findings and limitations in this project. It also suggests further areas of research which can be beneficial for posture monitoring.

1.5 Summary

This chapter briefly introduces the background to the research problem. The chapter presents the main aim and the objectives that need to be met in order to address the research gap. Since creating such a sensor system for monitoring the profile of a person’s back involves many challenges, the research work is conducted to prove the concept rather than provide a fully functional posture monitoring system.
Chapter 2. Literature review

In this chapter, a survey regarding the theoretical and empirical literature will be provided as a support and guide for this project. For a certain application, seat backrest, in this case, an overview of the principle of electro-textiles and textile sensors will be highlighted.

2.1 Introduction to electronic textiles

Electronic textiles are utilised in almost everywhere in our daily lives, such as medical rehabilitation, athletes training, personal security, communication and monitoring of health signals including pressure, temperature, displacement and humidity. Textiles provide an appropriate approach for wearable platforms due to its low mass per unit area, flexibility and portability in diverse form. Smart textiles are becoming more and more practicable thanks to the booming development of new types of fibres and structures such as conductive material and the miniaturisation of electronics, which makes it possible to consolidate electronics into textile constructions.

Locher (2006) has also claimed that acceptance of electronic textiles requires a smooth and unobtrusive integration of textiles and electronics, maintaining the comfortable properties for the users. The difference in physical properties between textiles and electronics, and combining these into one structure is a challenge.

For unobtrusive integration of microelectronics into clothing, textile-based wiring
structures, which is also called data ribbons, transmission lines and electro-conductive pathways, are required (Locher, 2006). They are able to provide the communication pathways of electrical or optical signals between electrical components, such as sensors mounted on a piece of fabric. Therefore, the electronic textiles provide us with a new lifestyle.

### 2.2 Textile pressure sensor

When an external force is applied to a pressure sensor, the output signal of pressure indicates the numerical amount of pressure itself (Cho, 2009). The strain responsive pressure sensors mainly include piezoelectric sensors, piezoresistive sensors and capacitive sensors. The characteristics, such as stiffness, hardness, size or shape, are the parameters which decide whether a sensor is suitable for the wearable applications. The subsequent sections of this thesis will give a detailed survey regarding the different types of textile pressure sensors.

#### 2.2.1 Piezoelectric sensors

Piezoelectric techniques can be used to create textile-sensing structures. While mounting on the object and the object is stretched, the piezoelectric sensor generates the current itself, which can be directly used as analogue input. The piezo film is similar to a fabric due to its lightweight and flexibility. But the piezoelectric film does have limitations for certain applications. Compared to ceramics, it makes a relatively weak electromechanical transmitter, particularly at resonance and in low frequency applications (Fraden, 2015). Also, if the electrodes on the film are exposed, the sensor
can be sensitive to electromagnetic radiation, which results in decreasing signals, good insulation is therefore required.

PVDF (polyvinylidene difluoride) polymer is normally used to give piezoelectric properties, but one of the drawbacks of PVDF is the strong temperature depending performance (temperature drift) due to the pyroelectric properties and low thermal stability. The temperature also influences on the electromechanical properties of PVDF (Janocha, 2007). And piezoelectric sensors cannot be used for accurate static measurements, because a static force will result in a fixed amount of charge on the piezoelectric material (Ghosh, 2012). They are better at detecting high frequency signals.

2.2.2 Piezoresistive sensors

Piezoresistive sensing technique is the most common strain measurement method. The principle can be explained as follow: when a piezoresistive material is compressed, it achieves a thinner thickness and larger surface area due to a Positive Poisson ratio, leading to a resistance change. Kon et al. (2007) concluded that piezoresistive sensor was capable of detecting both dynamic and static load, but it can only detect strain effectively in the direction parallel to the strain sensor.

And piezoresistive property can be introduced into the textiles by knitting, weaving, embroidering and through nonwoven fabric manufacturing processes. Capineri (2015) used piezoresistive sensors with sandwiched structures for monitoring the step rate, by recording dynamically the spatial distribution of foot pressure. Chung et al. (2013)
created a pressure sensor array for decubitus ulcer monitoring. Pacelli et al. (2006) also used same technology for biomechanical variables monitoring. And Huang et al. (2008) produced a yarn-based sensor by wrapping the piezoresistive fibres and claimed it was more comfortable for wearable applications. Roh et al. (2015) used a sandwich-like stacked piezoresistive nanohybrid film to detect small strains on human skin. Hamdani and Fernando (2015) also placed piezoresistive sensors in a vehicle safety belt and seat backrest to monitor heart rate.

### 2.2.3 Capacitive sensors

A capacitive pressure sensor utilizes the principle of a capacitor of electronics (Cho, 2009). Capacitance is proportional to permittivity and the area of each metal electrode, and inversely proportional to the distance between them. A capacitive sensor can be sensitive enough, but it is weak to electric and mechanical noises.

Yilmaz et al. (2010) used capacitive electrodes for vital signs detecting. Merritt et al. (2009) also used textile-based capacitive sensors for respiration monitoring, and claimed that it was as an inexpensive method for long-term sensing. Chang et al. (2014) used a capacitive-sensing mattress to classify the sleeping postures. Sergio et al. (2004) introduced an approach to show the pressure from a palm of the hand using a textile-based capacitive sensor.

### 2.2.4 The sensor structures

The size, resolution and measurement range of a sensor largely depends on how the
sensor is designed (Meyer et al., 2010). There are mainly three sensor structures: knitted (Figure 2.1), woven (Figure 2.2), nonwoven (Figure 2.3) and embroidered (Figure 2.4).

**Figure 2.1. Kitted structure** (Preece et al., 2011)

**Figure 2.2. Woven structure** (Ahn et al., 2015)
As an example for woven textile sensors, Sergio et al. (2004) designed a woven circuit for the pressure sensor. This approach enables the sensors and the electrodes on a single piece of fabric. However, the size of the routing channel, which is used to connect the electrodes to the printed circuit board (PCB) is assignable. Li and Ding (2009) also used woven structure to make strain sensors. Di Rienzo et al. (2013) have introduced a woven ECG electrodes for the electrocardiogram monitoring.

Mergl (2006) used embroidered structure to complete a pressure sensor. For this kind structure, the mechanical flexibility is better than woven structure due to the zig-zag
pattern used while drawing the electrodes. The cost of the end product is higher than weaving. Shimojo et al. (2004) also developed an embroidered structure, they stitched wires into the conductive rubber, to create a single layer structure instead of the traditional double layer structure.

Atalay and Kennon (2014) have proved the possibility to manipulate the sensing properties of knitted sensors. And Paradiso et al. (2005) developed a health care system based on knitted integrated sensors.

### 2.3 Electrical resistance

Electrical resistance indicates the difficulty to pass an electric current through a conductor. The international unit of resistance is Ohm (Ω) while the conductance is Siemens (S). The resistance is defined as the ratio of voltage (V) applied on an object, and current running thought it (I), and the conductance (G) is the reverse. In other words, high resistivity is the same in low conductivity and low resistivity is the same in high conductivity. And it should be highlighted that electrical resistance is not the same concept as resistivity. While resistivity is a material property, and resistance is the property of an object.

#### 2.3.1 Volume resistance

Volume resistance, also known as bulk resistance, measures the resistance across a defined thickness, as shown in Figure 2.5 (left).
It can be expressed as: \( R = \frac{\rho}{A} \)

where:

- \( l \) is the length of the conductor measured in metres,
- \( A \) is the cross-section area of the conductor measured in square metres,
- \( \rho \) is the electrical resistivity of the conductor measured in ohm-metres.

### 2.3.2 Sheet resistance

Sheet resistance, also called surface resistance, is a measure of resistance of thin films with a uniform thickness. As shown in Figure 2.5 (right), it is applicable to approximate two-dimensional materials due to the current is along the plane of the sheet, rather than perpendicular to it.

It can be express as: \( R = \frac{\rho}{t w} = \frac{1}{R_s} = \frac{l}{w} \)

where:
\( \rho \) is the resistivity measured in ohm-metres,

\( l \) is the length measured in metres,

\( w \) is the width measured in metres,

\( t \) is the thickness measured in metres,

\( R_s \) is the sheet resistance.

Sheet resistance is a special case, from its unit it can be seen that the term "(m/m)" cancels, and what remains is a special "square". The unit is thus expressed as \( \Omega / \square \) (ohms per square), for instance, a square sheet with sheet resistance 10 ohm/square has a resistance of 10 ohm, regardless of its size (1cm or 1m side length).

The resistance of a conductor differs based on its contents and structure and it is reciprocal proportion to the cross sectional area. In this project, the volume resistance was measured for piezoresistive sensors.

### 2.4 Conductor materials

An electrical conductor is an object or a type a material which enables the current flow to one or diverse directions. Conductors demonstrates linear Ohmic current density corresponding to electric current density (Harlin and Ferenets, 2006).

There are various types of conductors including metals, electrolytes, superconductors, semiconductors, plasmas and some non-metallic conductors like conductive polymers. And Table 2.1 shows the resistance among different yarns.
### Table 2.1. Characteristics of yarns (Kursun-Bahadir et al., 2011)

<table>
<thead>
<tr>
<th>Sample no</th>
<th>Role of yarn in fabric</th>
<th>Material type</th>
<th>Yarn count, dtex</th>
<th>Linear resistance, ohm/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Non-conductive Yarn</td>
<td>Polyester Microfibre</td>
<td>330</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Conductive Yarn</td>
<td>100% Stainless Steel</td>
<td>2600 2-ply</td>
<td>&lt; 15</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Silver Plated Nylon 66-4 ply</td>
<td>312/34f 4-ply</td>
<td>&lt; 50</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Silver Plated Nylon 66-2 ply</td>
<td>140/17f 2-ply</td>
<td>&lt; 230</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>Insulated Copper Yarn</td>
<td>1440</td>
<td>&lt; 10</td>
</tr>
</tbody>
</table>

Copper is normally used due to its availability and annealed copper is also used as an international standard in comparison to other conductors. The copper is universally utilised in electrical apparatus such as wires, cables and busbars. Besides, copper is simple and convenient for soldering and fixation. But its physical properties, such as less soft than silver coated yarn, make it difficult to process in textile machinery.

Kursun-Bahadir et al. (2011) tested the signal quality of an ultrasonic sensor using the five different conductive yarns. He concluded that silver plated nylon 66-4 ply yarn achieved the best compromise between signal quality and preserving textile properties.

#### 2.5 Formation of electric circuits

The integration of textile and electronics must be stable enough for information collection. There are many approaches and materials employed to produce the circuit substrate in the sensor. The traditional printed circuit boards (PCB) consist multi-layer structure of the organic material, they are commonly sturdy and heavy (Parkova et al., 2011). Smart textile integrates into fabric, but still requires linking to the fabric. A
high amount of conductive fabrics using conductive fibres or yarns are used in the production of electroconductive data ribbon cable (Tao, 2005). Fabric based circuits provide advantages of higher flexibility in bending, being tear resistance and fatigue resistance while exposed in continuous deformation (Harlin and Ferenets, 2006). Therefore, such data ribbons are required to integrate electronics with fabric to promote user’s utilisation (Parkova et al., 2011). The following section will present different manufacturing technology of constructing the electronic control circuit on textiles.

2.5.1 Conductive ink printing

Smart textiles can be manufactured using specialised conductive inks, to generate electric circuits as shown in Figure 2.6. This method is quite similar to plastic printed circuit manufacturing procedure. The specialised conductive inks should contain a large amount of conductive metal precursor, including Ag, Cu and Au nanoparticles (NPs) and a carrier vehicle (Stoppa and Chiolerio, 2014). When the substrate or base fabric has a stretchable nature, printed transmission lines are susceptible to cracking, resulting in shorting/discontinuity in the electrical circuits. Conductive ink printing is suggested as an appropriate method for low volume production. Stoppa and Chiolerio (2014) also indicated that the ink jet print has low handling capacity and produces lower resolution, if a high viscose materials were used as base fabric, then there would be trouble in the application of this method, especially on account of outbreak of clogging on nozzle. Moreover, conductive ink printing is not suggested to be employed on elastic fabric, because it will cause collapsing of printed conductive path (Parkova et al., 2011).
2.5.2 Embroidery

Conductive threads are utilised in the embroidery of circuit path (Cho, 2009). By using this technique to create circuits, conductive threads can be embroidered in any configuration on the base fabric (no consideration about the yarn path). For example, the embroidery approach can be used for wearable keypad manufacturing. And the circuit layout can be accurately embroidered to provide a wide range of stitch patterns. The conductive yarns used in embroidery method are under various levels of stresses and friction during the embroidering process. Thus, the threads must possess relatively high strength and flexibility, to prevent from yarn breaking.

Kallmayer et al. (2003) regarded sewing with conductive yarns as key methods to attach electronics to conductive pathways. And Fraunhofer (2005) also created a method to interconnect flexible substrate on fabric by using conductive yarn, as shown in Figure 2.7.
Figure 2.7. Flexible electronic module connected with conductive yarn by embroidery (Fraunhofer, 2005)

2.6 Scanning electron microscope (SEM)

Scanning electron microscope (SEM) determines the morphology of the surface of solid materials, and it is suitable for conductive surface (Patel and Vashi, 2015). While capturing the images, areas ranging from 1cm to 5nm in width are generated by using a conventional equipment, whose magnification can range from 20x to 30,000x, whereas more advanced ones enable to obtain better than 1nm resolutions.

There are many parts inside a SEM equipment, but mainly including lens system, electro gun, electron collector, visual and recording cathode ray tube and the control electronics (Goldstein et al., 2012). Such a circuit can be sketched as shown in Figure 2.8. The scanning process involves with a high-energy beam of electrons in a raster scan pattern, and these electrons will interact with the atoms making up the sample and then produce various signals containing information about the surface topography.
of the sample. And these signals are further collected by detectors, and then the screen of a monitor will form an image by using the output of these detectors modulates. In this project, the SEM test is conducted under a voltage of 20 kV and magnification is approximately 90 for characterization.

![Figure 2.8. Schematic of an SEM](image)

### 2.7 Energy-dispersive X-ray spectrometry (EDX)

Energy-dispersive X-ray spectrometry (EDX) is an analytical technique which identifies the elemental components of an object and the proportions of each one. More, EDS can perform analyses of selected point locations on the sample, which is especially useful in qualitatively or semi-quantitatively determining chemical compositions, crystalline structure, and crystal orientations by using Electron Back Scatter Diffraction (EBSD) (Patel and Vashi, 2015). EDS analysis involves X-ray spectrum due to that each element has a unique atomic structure allowing a unique set of peaks on its electromagnetic emission spectrum (Joseph et al., 2003).
Similar with the SEM techniques, a high-energy beam of charged particles such as electrons is used to stimulate the emission of characteristic X-rays from the sample. An atom from the sample contains ground state at rest, and the electrons are in discrete energy levels. The high-energy beam may excite an electron in an inner shell, and then this electron will eject from the shell and meanwhile create an electron hole, as shown in Figure 2.9. To fill the hole, an electron from the outer shell will involve, and the difference between the higher-energy and lower energy shell leads to an energy form as an X-ray. The X-ray indicates the atomic structure of the element, which further shows the elemental composition of the sample.

![Figure 2.9. Principle of EDX](image)

### 2.8 Accelerometer

Accelerometer sensors measure acceleration of the body the sensor is attached, which is the acceleration it experiences rather than the same concept as coordinate acceleration (rate of change of velocity). For steady state performance, an accelerometer sensor will indicate an acceleration due to Earth's gravity, upwards (by
definition) of \( g \approx 9.81 \text{ m/s}^2 \). For dynamic performance, an accelerometer sensor in free fall will measure zero.

Einstein's equivalence principle (Einstein, 1920) states that the effects of gravity on an object are indistinguishable from acceleration. Therefore, in order to obtain the acceleration with respect to the Earth, the gravity offset must be subtracted. Otherwise, an accelerometer cannot distinguish the situations that a person is standing on the surface of the Earth, and being inside a rocket which is in deep space and being accelerated at 1 g by the engine.

### 2.8.1 Physical principles

The principle can be explained as the following schematic: the mass, also called proof mass or seismic mass, is suspended by a spring, which is in parallel with a dashpot. When the system is subjected to linear acceleration, the deflection on the mass will be sensed and converted to electric signal.

![Figure 2.10. Principle of an accelerometer (Kraft, 1997)](image)
To derive the motion equation of the system, Newton’s second law and D’Alembert’s principle are used. From the stationary observer’s point of view, the sum of all forces in the y direction is:

\[ m \frac{d^2 y}{dt^2} = m \frac{d^2 x}{dt^2} + b \frac{dx}{dt} + kx \]

where:

- \( m \): mass of the proof mass,
- \( y \): displacement of the body of interest,
- \( x \): displacement of the proof mass,
- \( b \): damping factor,
- \( k \): spring constant,
- \( t \): time.

In a steady state, the sensitivity of the accelerometer is defined by \( S = \frac{x}{a} = \frac{m}{k} \), where \( a \) is the acceleration.

In a dynamic state, Laplace transform is used,

\[ \frac{X(s)}{a(s)} = \frac{1}{s^2 + \frac{b}{m}s + \frac{k}{m}} \]

2.8.2 Applications

There are many different types of accelerometers, such as piezoelectric, piezoresistive and capacitive accelerometers (two extra fixed electrodes are added in Figure 2.10), but they share the same principle—to convert the mechanical motion into an electrical signal. Modern accelerometers are commonly micro electro-mechanical systems (MEMS), which enable a smaller volume and feasibility for integrated circuit.
Single-axis and multi-axis models of accelerometers are capable of detecting magnitude and direction of the proper acceleration. Also, acceleration is a vector quantity, then the accelerometers can be used to sense orientation and vibration.

For various applications, accelerometer sensors are increasingly being used in the biological sciences. High frequency recordings of bi-axial (Yoda et al., 2001) or tri-axial acceleration (Shepard et al., 2008) can be used to distinguish the behavioural patterns of animals while they are in the wild. And these data also allow researchers to quantify the energy consumption rate, by determining the frequency of limb-stroke (Kawabe et al., 2003) or measuring the acceleration of the whole body in a dynamic state (Wilson et al., 2006) Similarly, accelerometer sensors can be used to monitor people’s gait parameters, such as stance and swing phase (López-Nava and Muñoz-Meléndez, 2010). Wong and Wong (2008) proved the ability of using tri-axial accelerometers to detect the posture change in sitting positions. A similar system for meditation monitoring has also been made by Chang et al. (2012).

2.8.3 Angle measurement

In order to define the angles in three dimensions, all three outputs of the accelerometer are used (Manjiyani et al., 2014).

\[
\rho = \arctan\left(\frac{A_{x,\text{out}}}{\sqrt{A_{y,\text{out}}^{2}+A_{z,\text{out}}^{2}}}\right) \quad (2.1)
\]

\[
\phi = \arctan\left(\frac{A_{y,\text{out}}}{\sqrt{A_{x,\text{out}}^{2}+A_{z,\text{out}}^{2}}}\right) \quad (2.2)
\]

\[
\Theta = \arctan\left(\frac{\sqrt{A_{x,\text{out}}^{2}+A_{y,\text{out}}^{2}}}{A_{z,\text{out}}}\right) \quad (2.3)
\]
where:

ρ in (2.1) is defined as the angle of the X-axis relative to ground,
φ in (2.2) is defined as the angle of the Y-axis relative to ground,
Θ in (2.3) is defined as the angle of the Z-axis relative to gravity,

$A_{x,\text{out}}, A_{y,\text{out}}$ and $A_{z,\text{out}}$ are readings from the X-axis, Y-axis and Z-axis respectively.

By combining the accelerations due to gravity on the X-axis, Y-axis and Z-axis, the resultant is equal to 1g when the accelerometer is static, and it can be expressed as below.

$$\sqrt{A_{x,\text{out}}^2 + A_{y,\text{out}}^2 + A_{z,\text{out}}^2} = 1g$$
Chapter 3. Experimental work

3.1 Materials selection

In integrating solid state electronic devices on to textile material or in connecting electro-textile material with solid state electronic devices is not a straight forward process. Due to the higher degrees of freedom the fabric/yarn materials would have, interconnections need to be well planned. Therefore in order to achieve a good electrical connection, the researcher needs to think outside of the box (Cho, 2009). Thus, the first step was about the materials selection. In order to satisfy this requirement, numerous options for material were investigated. In selecting the backrest material, users prefer comfortable materials rather than tough and rigid one. Therefore the sensor system that would pick up the back profile needs to have pressure sensors to confirm contact and accelerometer sensors in order to determine the surface angle at the contact point. Therefore, one of the option is to create a matrix using pressure sensitive ink, but previous experience (Stoppa and Chiolerio, 2014) has indicated that printed circuits are easily broken and not appropriate for mass production. Therefore, fabric-based pressure sensors were selected as the sensor that gives feedback on the contact. Since capacitive sensors pose problems related to mechanical noise, and piezoelectric sensors are not suitable for static measurement and they are sensitive to the temperature change, then piezoresistive pressure sensors were selected for this project.

Therefore as piezoresistive textile materials, three different types of commercially
available piezoresistive fabrics, were sourced from a company called HITEK. Various experiments were carried out to identify the optimum materials. Due to the results from Kursun-Bahadir et al. (2011), silver plated thread was used in embroidering, to create an electric circuit for data collection from the accelerometers.

3.2 Introduction to materials

The three types of piezoresistive fabrics sourced from HITEK respectively are EeonTex™ NW170-PI (sample 1), EeonTex™ T-PI (sample 2) and Eeontex™ NW170-SLPA (sample 3).

A sensor system that is integrated to determine the back profile of the user could experience both tensile and compressive stresses. Therefore, the standard test (BS EN ISO 142:1998) was carried out to characterise the textile materials used for their tensile behaviour. For this, two sets of test pieces (longitudinal and transverse directions) were tested, where each test piece had the dimensions of 50mm±0.5mm wide and 200mm±1mm length. Each sample was tested for five times in order to calculate the mean value. The three samples sourced from HITEK were all only A4 size, there were not sufficient materials for tensile test. Hence tensile tests were not carried out in this project and the decision of the final material was mainly based on the result from compression, cyclic and signal drift tests.

3.3 SEM and EDX tests

First of all, scanning electron microscope (SEM) test and Energy Dispersive
Spectrometry (EDX) were performed in order to characterize the fabric, where SEM test was for surface characterisation, such as fibre orientation while the EDX test was for material composition mapping. Because the piezoresistive fabrics are manufactured by coating plain nonwoven fabrics with piezoresistive materials and those materials remains unknown, the EDX test was carried out in order to identify the materials were hazardous (such as heavy metals) to human health or not.

These two tests were conducted by the same apparatus, which was HITACHI S-3000N. Before testing, the specimens were required to be in a clean state in order to obtain correct data. The reason for this requirement is that the electron probe can investigate the superficial part of material, and the results therefore are highly influenced by the surface condition (Ford et al., 2011). Then the specimens were placed upon a holder, which provided a circular area whose diameter is 10 millimeters. A layer of electrical conducting carbon tape was placed between the holder and the specimen. After the above processes were completed, the specimen was placed inside the chamber for testing. The clear images of magnified structure of the specimens were taken from 500um in this case.

### 3.4 Compression test

The compression test was conducted to characterise the electromechanical properties of the samples. When leaning against the backrest, different magnitudes of force are applied on it. In order to consider this, the samples were tested for the full pressure range (Zemp et al., 2016).
The piezoresistive sensor was constructed by sandwiching a piezoresistive layer in between two electro-conductive textile electrodes (Capineri, 2015). As shown in Figure 3.1, the top and bottom layer are knitted silver fabric acted as electrodes while the medium layer is a piece of piezoresistive fabric. The conductivity of these sensors is expected to change according to the applied mechanical pressure.

![Figure 3.1. Three different sensor samples](image)

The following Table 3.1 shows the initial (original) resistance for three sensors, and the size are all 2cm x 2cm.

<table>
<thead>
<tr>
<th>Sample</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average resistance(Ω)</td>
<td>38</td>
<td>65</td>
<td>160</td>
</tr>
</tbody>
</table>
The optimum sensor size is critical for capturing good signals since an optimum sensor size will reduce the chances of capturing unwanted noise. Though sensor size can be increased indeed, due to the function of calculating volume resistance of a piece of fabric it would reduce the overall resistance of the sensor as well. Thus in this particular case, referencing the previous work done by Mergl (2006) and considering the dimensional restriction of the backrest area, a sensor size of 20mm x 20mm was selected.

The samples were tested on Zwick Roell/Z050 tensile tester using 100N load cell at a rate of 1mm/min and each sample was tested for five times.

The tensile test and the resistance measurement were conducted simultaneously. For acquiring the data in resistance change, National Instrument card (NI 9219) was used by employing a half-bridge circuit. The half-bridge circuit was completed according the circuit connection as shown in Figure 3.2.

Figure 3.2. Half-bridge circuit connection
The $R_{samp}$ means the resistance of sample and the $R_{ref}$ means a balanced resistor selected according to the $R_{samp}$ while the dotted lines represent circuitry connected inside the NI 9219 module. And the output voltage of the bridge $V_0$ (the two points between ADC) can be shown as the following formula where $V_{EX}$ means the supply voltage.

$$V_0 = \left(\frac{R_{ref}}{R_{samp} + R_{ref}} - \frac{1}{2}\right) \times V_{EX}$$

From this equation, it is apparent that when $R_{samp} = R_{ref}$, the voltage output is zero. LabVIEW SignalExpress was used as an interface to acquire the resistance data. The output from the NI 9219 was in a unit of mV/V and resistance was further calculated by applying the following formula, where $x$ was the reading from the NI 9219.

$$R_{samp} = R_{ref} \times \frac{1 - 2x}{1 + 2x}$$

The NI 9219 obtains data per 0.5 second and the tensile tester obtains data per 0.1 second, then the interpolation function was required to be performed by MATLAB to correspond the resistance value accurately to the applied pressure.

To minimize the error, the samples were placed on the top of a wooden cube which had the same area size and shape as the samples, and the wooden cube was placed between the two electrodes. In the half-bridge circuit connection, a pair of crocodile clips was used, and 0.1N pre-load was thus applied to the samples to prevent the crocodile clips pulling the sample out of the wooden cube.
3.5 Cyclic test

Hysteresis phenomena occurs in every material when it is bended or compressed (Meyer, 2008). Since the piezoresistive sensor uses compressible materials, hysteresis has to be taken into consideration. Cyclic tests were conducted for each sample (100 times) to characterise their hysteresis behaviours. Similar to the compression test, a 0.1N pre-load was applied to the samples and the force limit was set at 3N.

The following papers have investigated the pressure variables, for example, the mean and peak pressure (Hostens et al., 2001; Moes, 2007), contact area (Paul et al., 2012; Kyung and Nussbaum, 2008; Vos et al., 2006). Aissaoui et al. (2001) indicated the mean pressure on the backrest is around 14.7mmHg with a standard deviation of 1.9mmHg. And Mergl (2006) demonstrated a peak pressure of 2-7 kPa on the backrest (1 kPa is equal to approximately 7.5mmHg). And Reed et al. (1994) also concluded that backrest pressure distributions should show peaks in the lumbar area, and found lumbar pressure peaks of about 2.5 kPa in seats judged to be comfortable compared with lower values in uncomfortable seats. And large variance in peak pressure across sitters can be expected since peak pressure is strongly dependent on body weight. For instance, a heavier person will generally exhibit higher pressure peaks, but with substantial fat tissue in the buttock area, the heavier person may experience lower pressure peaks. And due to this variability, it is probably unreasonable to specify a target value for peak pressure (Reed et al., 1994).

Therefore, 3N was selected as the limit force applying on the area of 4cm^2 (around 56.25mmHg), to see the behaviours of three samples.
3.6 Signal drift test

Drift problem has been widely reported in textile-based sensors (Atalay et al., 2013). And Meyer (2008) indicated that drift is an additional error source in sensors under constant compression. Then the three samples were compressed from 0.1N to 3N, while at 1N and 2N, the pressure was kept static for 60 seconds in order to observe and investigate the signal drift phenomenon.

3.7 Design and construction of sensor matrix for the seat backrest

Figure 3.3. Model 2006-BM036, 2006 high back operator chair, adjustable arms, back rake action, black moulded base (Chair, 2016)
The design and construction of the sensor matrix was based on the chair shown above. For the part that provides support for the lumbar area of the human body, by manual measuring, it is approximately a rectangle which is 24cm width by 32cm length.

There are several guidelines to the design and construction:

1. In this project, knitted silver fabric (0.45mm thickness) was used for terminal lines, which is medical grade, and made of by 99.9% of pure silver. The knitted structure allows elastic bidirectional movement in both course and wales directions, therefore it shows desirable performance while experiencing the deformation in practical use. And the silver fabric reduces the weak signal loss in the terminal lines.

2. In the form of a matrix rather than a single one, sensor provides more feasibility for larger area of application, as a sensor matrix is capable of improving the signal to noise ratio (SNR) while capturing the pressure signals. And when human body is leaning against the seat backrest, the sensor matrix enhances the possibility of obtaining valuable signals from almost all the lumbar area, and reduces the chance of missing ones.

3. During the period of initial research, air pockets were generated by layering the sensor materials together, which resulted in noises while capturing the signals. Then the breathable and waterproof fabric is chosen for the cover fabric, in order to prevent air pockets and impurities like dust and water drops.

According to these guidelines, the main construction steps of the prototype sensor
matrix are stated below by AutoCAD, and all given dimensions are in millimetres.

![Sensor Matrix Diagram]

**Figure 3.4. The sensor matrix**

The sensor matrix is composed of five layers (two cover layers are not shown in the figures): the top and bottom layers are silver knitted fabric (grey strips) as shown in Figure 3.4, acting as electrodes and one piece of nonwoven piezoresistive fabric is in the middle (white rectangle). And there are totally 35 sensors (yellow squares).

### 3.8 Manufacturing processes

Due to the structure features, knitted silver fabric is highly stretchy and it is not easy to be tailored in certain dimensions. Therefore, the stabilizer material is required for relatively precise cutting. As shown in Figure 3.5, the stabilizer (white rectangle) is
attached to the silver fabric by 505 spray, which is a temporary adhesive that can combine two layers together and can be removed easily after the cutting process.

Figure 3.5. The stabilizer (white rectangle)

When the designed terminal lines were ready to use as shown in Figure 3.6, the hot melt adhesive was used for assembling the three fabric layers together, where the middle layer was a nonwoven fabric. And a thermometer was used to detect the temperature, it showed around 45°C and there was no resistance change due to the heat.
Figure 3.6. The tailored piezoresistive fabric (black rectangle) and knitted silver fabrics (grey strips)

In this case, the terminal lines were all selected at 20mm width due to the limitation in the manual manufacturing process. And to ensure isolation, 20mm width of gap between terminal lines was maintained as well. The final prototype of sensor matrix is shown below (Figure 3.7).
3.9 Resistance data acquisition

In this project, due to the limitation of equipment (lack of device that can capture multi-signals simultaneously), the data from all 35 sensors were collected individually. It required the person seated to keep still for a long duration for carrying out the individual measurement.

Figure 3.7. The sensor matrix
As shown in Figure 3.8(a) and 3.8(b), a National Instrument data acquisition card (NI 9219) is used to collect data from 4 sensors simultaneously.

Figure 3.9. Data collection
3.10 Accelerometer

During the practical use, the chair user’s back curve also relates to different postures. Accelerometers hereby are introduced to monitor this parameter.

In the literature review, a certain number of previous papers in this area of the use of accelerometers were studied. There are mainly 3 types of accelerometers commonly used for movement monitoring, respectively LSM303D (Felisberto et al., 2014), ADXL335 (Manjiyani et al., 2014) and LSM9DS0 (Abhayasinghe and Murray, 2014). LSM303D was manufactured by STMicroelectronics, ADXL335 was manufactured by Analog Device and LSM9DS0 was manufactured by Adafruit.

<table>
<thead>
<tr>
<th>Type</th>
<th>Size</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSM303D</td>
<td>3.15mm x 3.15mm x 1mm</td>
<td>0.061mg/LSB (digital)</td>
</tr>
<tr>
<td>ADXL335</td>
<td>4mm x 4mm x 1.45mm</td>
<td>330mV/g (analogue)</td>
</tr>
<tr>
<td>LSM9DS0</td>
<td>Diameter 16mm Thickness 0.8mm</td>
<td>0.061mg/LSB (digital)</td>
</tr>
</tbody>
</table>

Through the comparison of these devices, LSM9DS0 was selected for this project due to its smaller size, and suitable orientation display. Digital output can be noise-immune compared to analogue output, and the data transmission experiences no deterioration during test. Moreover, a wearable LSM9DS0 in a round shape has been recently designed by Adafruit. And it can be sewn upon the fabric, as shown in Figure 3.10.
3.10.1 Pathway construction

As described in the literature survey, embroidery is selected for the pathway construction to obtain signals from the accelerometer.
The embroidery process requires two set of yarns: the upper thread which will show on the face of fabric, and the underneath yarn which will show on the back. While embroidering, the needle penetrates through and out of the fabric rapidly, bringing much friction to the upper thread. If the silver yarn was mounted as upper thread, the fibres would scatter everywhere and the whole fabric would be conductive. Therefore, in this case, the silver yarn purchased from Shieldex® under the trade name of 235/34 dtex HCB (polyamide 6.6 filament yarn around, 99% pure silver plated), was used as under yarn and the upper thread was polyester yarn purchased from AMANN group under the trade name of ISACORD 40.

The design geometry was completed by PE Design, which is a commercial software.
suite, as shown in Figure 3.11. And due to the small distance between terminals (holes) on the accelerometer board, the Zigzag width was selected as 1mm and under yarn sewing was used to provide the electro-conductive yarn. And in order to decrease the layer number, the accelerometers were sewn on the cover fabric. Since rather than a fully completed prototype, the research was carried out to prove the concept of the research, only three accelerometers were used to demonstrate the determination of the back profile. The three accelerometers were placed on different positions to obtain information from different area of the back. When the three accelerometers were mounted on the backrest (vertical state), the one in upper left corner (A1) and right corner (A2) aligned their x-axis with the absolute vertical, while the bottom one (A3) aligned its y-axis with the absolute vertical, as shown in Figure 3.12.

![Figure 3.12. The three accelerometers](image)

While embroidering onto fabric, extra weight and tension caused by thread and stitches were added. If the base fabric was not stabilized properly, then puckering and
dimpling would be found. And a layer of stabilizer was thus used to support the base fabric, as shown in Figure 3.13. And this stabilizer can be easily torn away after the embroidering process was done.

Figure 3.13. The stabilizer

And the holes on the accelerometer board were almost the same size as the needle’s diameter. In order to prevent from damaging the board, manual control was required to sew the accelerometers on the back of fabric.

A multimeter was used to test the connection between the accelerometer and silver yarn as shown in Figure 3.14 and it showed a good conductivity.
Final prototype contains 5 layers, and from the bottom to top: cover layer with accelerometers, sensor matrix, cover layer.

3.10.2 Data acquisition

Since the accelerometer is not strain-based sensor, and it thus cannot be connected to the NI 9219, which was previously used for resistance measurement. Coyle et al. (2009) proved the use of an Arduino platform called Lilypad to obtain accelerometer signals. A similar board developed by Adafruit was used in this case, as shown in Figure 3.15.
Due to the limitation of this board, only two accelerometers can be measured simultaneously. And by running the program (the code is given in Appendices), the orientation data was represented as shown in Figure 3.16. Here the three numbers indicated the rotation in Euler angles around x-axis (roll), y-axis (pitch) and z-axis (yaw or heading) respectively, as shown in Figure 3.17.
With no pressure on the accelerometer, there was a static reading, and when the chair user started to change postures, the accelerometer would rotate around one of its axis. According to the reading change, angles can be calculated to represented the user’s back curve.
Chapter 4. Results and discussion

4.1 Scanning electron microscope (SEM)

In this experiment, two screens were connected to the HITACHI S-3000N showing the results of SEM and EDX separately, and due to the deficiency of one of the screens the images obtained for two tests were put in one picture for analysis. Figure 4.1 shows the results for three kinds of piezoresistive fabrics respectively. According to the structure images, it can be seen that conductive materials cover the surface uniformly for sample 1 and sample 3, except for sample 2 which shows several white areas on the microscopic images, because regions of high average atomic number will appear bright relative to regions of low atomic number (Joseph et al., 2003). Also, it demonstrates that sample 1 and sample 2 are nonwoven fabric, having a large volume of fibres bonded together in random directions. There are no weft or warp yarns existing in non-woven fabric, it is thus easy for cutting, tailoring and finalizing the design. Compared to woven or knitted fabric, non-woven fabric enables more flexibility and it is more soft and light-weight meanwhile. On the contrary, sample 2 is 1-up-1-down plain woven fabric, of which the yarns are interlaced with each other tightly leading to a strong structure with relatively high strength.

4.2 Energy-dispersive X-ray spectrometry (EDX)

From the same pictures, characteristic spectrum of the three samples can be seen. The X-axis indicated the energy level of X-ray counts while the Y-axis shows the proportion of the component. For instance, in sample 1 carbon has the highest peak
and oxygen comes the second. Due to resolution deficiency, some contents cannot be identified precisely in this experiment. By taking the weight percentage of carbon into consideration, which are 76.5%, 75.17% and 80.62% respectively, it can be concluded that there is a high amount of carbon among all samples. Especially for the sample 3, carbon almost takes up to $\frac{4}{5}$ of its weight, therefore it shows an advantage in low weight.

![Figure 4.1(a). EDX result of sample 1](image)
Figure 4.1(b). EDX result of sample 2

Figure 4.1(c). EDX result of sample 3
4.3 Compression tests

As mentioned in the previous chapter, compression tests were carried out on all three samples, each for 5 times. By calculating the mean values and standard deviations, Figure 4.2 shows the outcome of resistance change against pressure from 5mmHg to 50 mmHg for three samples.

![Resistance versus applied pressure](image)

**Figure 4.2. Resistance change along the pressure**

It can be observed that each sandwiched sensor demonstrates different initial resistance which is attributed to different manufacture processes. And for all three samples, the resistance decreases due to the increased pressure.
According to the circuit connection shown in Figure 3.6, the voltage change of $V_0$ can be expressed as the following formula:

$$
\Delta V = 0 - \left( \frac{R_{\text{ref}}}{2R_{\text{ref}} + \Delta R} - \frac{1}{2} \right) \times V_{EX}
$$

And by applying $K = \frac{\Delta R}{\Delta P}$ into the above formula, then:

$$
\Delta V = \left( \frac{1}{2} - \frac{1}{2 + \frac{K}{R_{\text{ref}}} \times \Delta P} \right) \times V_{EX}
$$

where $K$ is the gradient of the curve at 15mmHg,

$\Delta P$ is the change in pressure,

$\Delta R$ is the resistance change of the sample,

$V_{EX}$ is the supply voltage.

Based on the study of Aissaoui et al. (2001), the biasing pressure is selected as 15mmHg. And according to the formula above, it can be found that $\Delta V$ will increase with an increasing $K$, in other words, the higher value of $K$ the more sensitive the sensor is. Comparing the gradient of the curve at 15mmHg, sample 3 shows the steepest slope among three samples, which means sample 3 is more sensitive than other two samples.
4.4 Cyclic tests

Figure 4.3(a). Cyclic test result of sample 1

Figure 4.3(b). Cyclic test result of sample 2
It can be found that for all samples, the peak value decreases as cycle time increases. By calculating the relative resistance change between the start and end point after 100 cycles, sample 1 shows a change of 28.3%, sample 2 shows a change of 33.9% and sample 3 shows a change of 32.7%. For sample 2, there may be a contact problem between 2000 to 2500s, which caused a rapid drop and rise of the peak value.

And considering the long-term stability, for all three samples, the curve formed by peak values has a trend of being unchanged and it is the same for the curve formed by bottom values. In other words, sensor has a trend of being stable when subjected to repeated testing. In order to identify the long-term performance, more cycles are required (or increasing the frequency of pressure change), and those proposed tests were not carried out due to the limitation of the machine. Comparing the change from
the original state, sample 1 is expected to perform more reliably, and sample 3 is better than sample 2.

4.5 Signal drift analysis

![Signal drift test curve of sample 1](image)

**Figure 4.4(a) The signal drift test curve of sample 1**
Figure 4.4(b) The signal drift test curve of sample 2

Figure 4.4(c) The signal drift test curve of sample 3
Signal drift (reduction in resistance) was observed within the load holding time as shown in Figure 4.4. And signal drift decreases with the increasing pressure. This could due to the sensor sample becoming less variable after being more compressed. During the holding time of 1N per 4cm^2 (around 18.75mmHg), sample 1 shows a resistance drift of 1.42 Ω, sample 2 shows a resistance drift of 5.25 Ω and sample 3 shows a resistance drift of 5.09 Ω. Sample 1 demonstrates the best stability among three samples, and sample 3 is better than sample 2.

Although the results of cyclic tests and signal drift tests show that sample 1 is the most stable one among three samples, sample 1 still has a flaw in sensitivity, which is the most important property when using a sensor to indicate if it is pressed or not. Besides, sample 1 has the lowest resistance, which gives it a narrow range of change in resistance. Therefore, considering the sensitivity of three samples, sample 3 was selected for this application, though it is not that perfect in all aspects.

4.6 “On” and “Off”

Each sensor serves as a switch. If not pressed, it is called “Off” state, otherwise it is called “On” state, which indicates that the human back is in contact with the seat backrest. Firstly, the initial resistance (at rest state) of 35 sensors was collected and put in an array as shown in Table 4.1.
Then a person (height:181cm, weight:68kg) kept seated in an upright posture (in contact with the sensor matrix), and the resistance data was collected as shown in Table 4.2.

The comparison of resistance between “On” and “Off” state is shown in Figure 4.5.
From Table 4.1 and Table 4.2, it can be seen that when the sensor is “Off”, the range of resistance is from 132 Ω to 180 Ω, and when the sensor is “On”, the range of resistance is from 50 Ω to 90 Ω. And Figure 4.5 shows a significant decrease in resistance when pressure is applied upon a sensor. It can be seen that there is a distinct boundary between “On” and “Off” conditions. Therefore, a sensor can be regarded as “On” when its resistance is lower than 100 Ω.

Five postures were studied by the sensor matrix: seated upright, leaning left, leaning right, leaning backward and bending forward. And Figure 4.6 represents the pressure distribution data under different postures. In Figure 4.6, a red sensor means it is pressed by human body with a resistance lower than 100 Ω, while a yellow sensor means that it is not pressed or its resistance is higher than the threshold.
Figure 4.6. Pressure distribution data in different seated posture types:
(1)bending forward, (2)leaning left, (3)upright, (4)leaning right, (5)leaning backward

4.7 Accelerometer

The sensor matrix is used to detect whether the human body is in contact with the backrest, while the accelerometers are used to give the curve shape of the human
back. And due to the limited number of accelerometers, three postures were studied. In the following tables, “before” means the accelerometer is in a static state and “after” means there is pressure applied upon the accelerometer. And all curve shapes are lateral views of the chair.

### 4.7.1 Seated upright

#### Table 4.3. Reading from A1

<table>
<thead>
<tr>
<th>Axis</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>before</td>
<td>-31.97°</td>
<td>-79.11°</td>
<td>-128.48°</td>
</tr>
<tr>
<td>after</td>
<td>-18.40°</td>
<td>-61.77°</td>
<td>-146.42°</td>
</tr>
</tbody>
</table>

#### Table 4.4. Reading from A3

<table>
<thead>
<tr>
<th>Axis</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>before</td>
<td>96.93°</td>
<td>11.00°</td>
<td>43.83°</td>
</tr>
<tr>
<td>after</td>
<td>86.60°</td>
<td>13.87°</td>
<td>44.43°</td>
</tr>
</tbody>
</table>

For A1 (position: right shoulder), the angle between x-axis and the –g was 79.11°-61.77°=17.34° while for A3 (position: L5), the angle between y-axis and the –g was 96.93°-86.60°=10.37°. And the curve was sketched as shown in Figure 4.7.
4.7.2 Bending forward

<table>
<thead>
<tr>
<th>Axis</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>before</td>
<td>98.78°</td>
<td>9.31°</td>
<td>57.84°</td>
</tr>
<tr>
<td>after</td>
<td>116.61°</td>
<td>7.56°</td>
<td>47.05°</td>
</tr>
</tbody>
</table>

Then the curve can be sketched as shown in Figure 4.8, the angle between x-axis and the -g was 116.61°-98.78°=17.83°
4.7.3 Leaning backward

Table 4.6. Reading from A1

<table>
<thead>
<tr>
<th>State</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>before</td>
<td>8.62°</td>
<td>-81.69°</td>
<td>-111.36°</td>
</tr>
<tr>
<td>after</td>
<td>19.46°</td>
<td>-47.25°</td>
<td>-159.66°</td>
</tr>
</tbody>
</table>

Table 4.7. Reading from A3

<table>
<thead>
<tr>
<th>State</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>before</td>
<td>92.49°</td>
<td>4.00°</td>
<td>10.15°</td>
</tr>
<tr>
<td>after</td>
<td>74.96°</td>
<td>-0.42°</td>
<td>35.78°</td>
</tr>
</tbody>
</table>
For A1, the angle between x-axis and the –g was $81.69^\circ - 47.25^\circ = 34.44^\circ$ while for A3, the angle between y-axis and the –g was $92.49^\circ - 74.96^\circ = 17.53^\circ$. And the curve was sketched as shown in Figure 4.9.

![Figure 4.9 Curve shape when leaning backward](image)

**4.8 Mathematic modelling and calculation**

Referencing the works by Meng and Bao (2013), a mathematic model was built to analyse the sitting posture, as shown in Figure 4.10.
While sitting, the angle between trunk and vertical line is $30^\circ(\alpha)$, and the upper arm shows a degree of $60(\beta)$ with trunk and $120(\Theta)$ with lower arm respectively (Meng...
and Bao, 2013). Assuming the barycentre (O) of upper body lies in the thoracic vertebra, then a gravitational moment is built as shown in Figure 4.11.

\[
M_1 = G_1 L_{o1} \sin \alpha \quad \ldots \ldots \quad (4.1)
\]
\[
M_2 = G_2 L_{o2} \sin \alpha \quad \ldots \ldots \quad (4.2)
\]
\[
M_3 = G_3 L_{o1} \sin \alpha \quad \ldots \ldots \quad (4.3)
\]
\[
M_4 = G_4 L_{o4} \sin \alpha \quad \ldots \ldots \quad (4.4)
\]
\[
M_5 = G_5 L_{o5} \sin \alpha \quad \ldots \ldots \quad (4.5)
\]
\[
M_G = \sum M_i \quad \ldots \ldots \quad (4.6)
\]

where:

\( M_i \) (i=1,2,3,4,5) represents the gravitational moment on each lumbar vertebra (L1,L2,L3,L4,L5), 
\( G_i \) means the weight above each vertebra, 
\( L_i \) means the horizontal distance between the barycentre and each vertebra, 
\( M_G \) indicates the resultant moment on the lumbar area.

<table>
<thead>
<tr>
<th></th>
<th>L1-2</th>
<th>L2-3</th>
<th>L3-4</th>
<th>L4-5</th>
<th>L5-S1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ant.</td>
<td>6.73</td>
<td>8.29</td>
<td>9.88</td>
<td>10.74</td>
<td>10.19</td>
</tr>
<tr>
<td>Mid.</td>
<td>7.80</td>
<td>8.39</td>
<td>9.57</td>
<td>9.73</td>
<td>8.97</td>
</tr>
<tr>
<td>Post.</td>
<td>5.01</td>
<td>5.96</td>
<td>6.63</td>
<td>7.12</td>
<td>5.92</td>
</tr>
<tr>
<td>Width</td>
<td>30.86</td>
<td>32.34</td>
<td>34.00</td>
<td>34.22</td>
<td>33.41</td>
</tr>
</tbody>
</table>

Table 4.8. The distance of intervertebral space of male (unit: mm) Ant: Anterior disk space, Mid: Middle disk space, Post: Posterior disk space (Hong et al., 2010)
From Table 4.8, it can be found that the distance between vertebrae increases from L1 to L5. And according to the formula, it can be evaluated that the moment decreases from L5 to L1 due to the decreased weight and distance between barycentre and each vertebra.

The angle $\alpha$ increases as chair users bending forwards, which results in the increasing of gravitational moment on each vertebra, and the component of the weight of upper body decreases along the vertical direction and increases along the horizontal direction, and this will lead to a heavy load on soft tissues around lumbar vertebrae. That is the cause of back pain.
Chapter 5. Conclusions and further research

This chapter summarises and concludes the major findings in this project. It also suggests further areas of research which can be beneficial for posture monitoring.

5.1 Conclusions

The textile-based sensor matrix operates well like a switch, and by showing an “On” or “Off” condition, it is able to detect which part of the human back is in contact with the seat backrest. Although the initial resistance of each sensor differs from each other, this might be caused by the manual cutting of electrodes.

Three accelerometers supplement the function of pressure sensors, and they can roughly show the curvature of the spine. Compared to an upright posture, when a person is bending forward or leaning backward, there is an angle of 17° to 35° between the spine and the absolute vertical.

This investigation shows a desirable result regarding to the posture changes. However, the evaluation of the posture data collected is not within the scope of this research. Again incorrect postures are such a subject feeling, it differs from person to person. According to the result, the lumbar vertebrae always bear the highest load and act as a role of transferring loads. While sitting, the stress concentrates on the lower location of vertebra body and in order to reduce the stress on the intervertebral disk and
decrease the risk of hurting lumbar vertebrae, the spine forward or backward angle should be controlled within a reasonable range.

5.2 Further research

Due to the limitation of measurement equipment, the pressure data was obtained in several times, in other words, it was not a demonstration of a real-time pressure distribution map. Further work should focus on the construction of a real-time system, by creating a data acquisition platform such as a mobile phone app. This system can be used to monitor posture changes and provide useful feedback to users.

Under the premise of maintaining comfort and increasing the accuracy, the number of accelerometers should be increased, which will provide a more precise profile about the human back.

The data from sensor matrix and three accelerometers was collected separately, and this can be solved by employing a MUX (multiplexer), but meanwhile it will bring challenges regarding the formation of electric circuits. However, future research is necessary in order to provide a fully functional posture monitoring system.
APPENDICES

1. MATLAB code for linear interpolation

clear all
a1=xlsread('file name.xls','sheet name');
inta=interp1(a1(1:x,a), a1(1:x,b), a1(:,c));
%x is the total number of ‘Time’ data obtained by LabVIEW
%a is the column number of ‘Time’ obtained by LabVIEW
%b is the column number of ‘Resistance’
%c is the column number of ‘Time’ obtain by tensile tester
figure
plot(a1(:,y),inta);
%y is the column number of ‘pressure’
grid on;
xlabel('Pressure (mmHg)'); ylabel('Resistance (\Omega)')

2. Arduino code for angle measurement

#include "Adafruit_Simple_AHRS.h"

// Create a simple AHRS from an explicit accelerometer and magnetometer sensor.
Adafruit_Simple_AHRS::Adafruit_Simple_AHRS(Adafruit_Sensor* accelerometer,
Adafruit_Sensor* magnetometer):
_accel(accelerometer),
_mag(magnetometer)

// Create a simple AHRS from a device with multiple sensors.
Adafruit_Simple_AHRS::Adafruit_Simple_AHRS(Adafruit_Sensor_Set& sensors):
// Compute orientation based on accelerometer and magnetometer data.
bool Adafruit_Simple_AHRS::getOrientation(sensors_vec_t* orientation)

// Validate input and available sensors.
if (orientation == NULL || _accel == NULL || _mag == NULL) return false;

// Grab an accelerometer and magnetometer reading.
sensors_event_t accel_event;
_accel->getEvent(&accel_event);
sensors_event_t mag_event;
_mag->getEvent(&mag_event);

float const PI_F = 3.14159265F;

// roll: Rotation around the X-axis. -180 <= roll <= 180
// a positive roll angle is defined to be a clockwise rotation about the positive X-axis
//
//      y
// roll = atan2(---)
//      z
//
// where: y, z are returned value from accelerometer sensor
orientation->roll=(float)atan2(accel_event.acceleration.y, accel_event.acceleration.z);

// pitch: Rotation around the Y-axis. -180 <= roll <= 180
// a positive pitch angle is defined to be a clockwise rotation about the positive Y-axis
//
//      -x
// pitch = atan(--------------------------)
// y * sin(roll) + z * cos(roll)

// where: x, y, z are returned value from accelerometer sensor
if (accel_event.acceleration.y * sin(orientation->roll) + accel_event.acceleration.z * 
cos(orientation->roll) == 0)
    orientation->pitch = accel_event.acceleration.x > 0 ? (PI_F / 2) : (-PI_F / 2);
else
    orientation->pitch = (float)atan((-accel_event.acceleration.x)/
    (accel_event.acceleration.y * sin(orientation->roll) +
    accel_event.acceleration.z * cos(orientation->roll)));

// heading: Rotation around the Z-axis. -180 <= roll <= 180
// a positive heading angle is defined to be a clockwise rotation about the positive Z-axis
//
// z * sin(roll) - y * cos(roll)
// heading = atan2(-----------------------------------------------)
// x * cos(pitch) + y * sin(pitch) * sin(roll) + z * sin(pitch) * cos(roll))
//
// where: x, y, z are returned value from magnetometer sensor
orientation->heading = (float)atan2(mag_event.magnetic.z * sin(orientation->roll) -
mag_event.magnetic.y * cos(orientation->roll), \ 
    mag_event.magnetic.x * cos(orientation->pitch) + \ 
    mag_event.magnetic.y * sin(orientation->pitch) * sin(orientation->roll) + \ 
    mag_event.magnetic.z * sin(orientation->pitch) * cos(orientation->roll));

// Convert angular data to degree
orientation->roll = orientation->roll * 180 / PI_F;
orientation->pitch = orientation->pitch * 180 / PI_F;
orientation->heading = orientation->heading * 180 / PI_F;

return true;
REFERENCES


