University Of Nottingham
DEPARTMENT OF ELECTRICAL AND
ELECTRONIC ENGINEERING

Connection of wearable electronics to photonic textiles

Final Year Project Final Report

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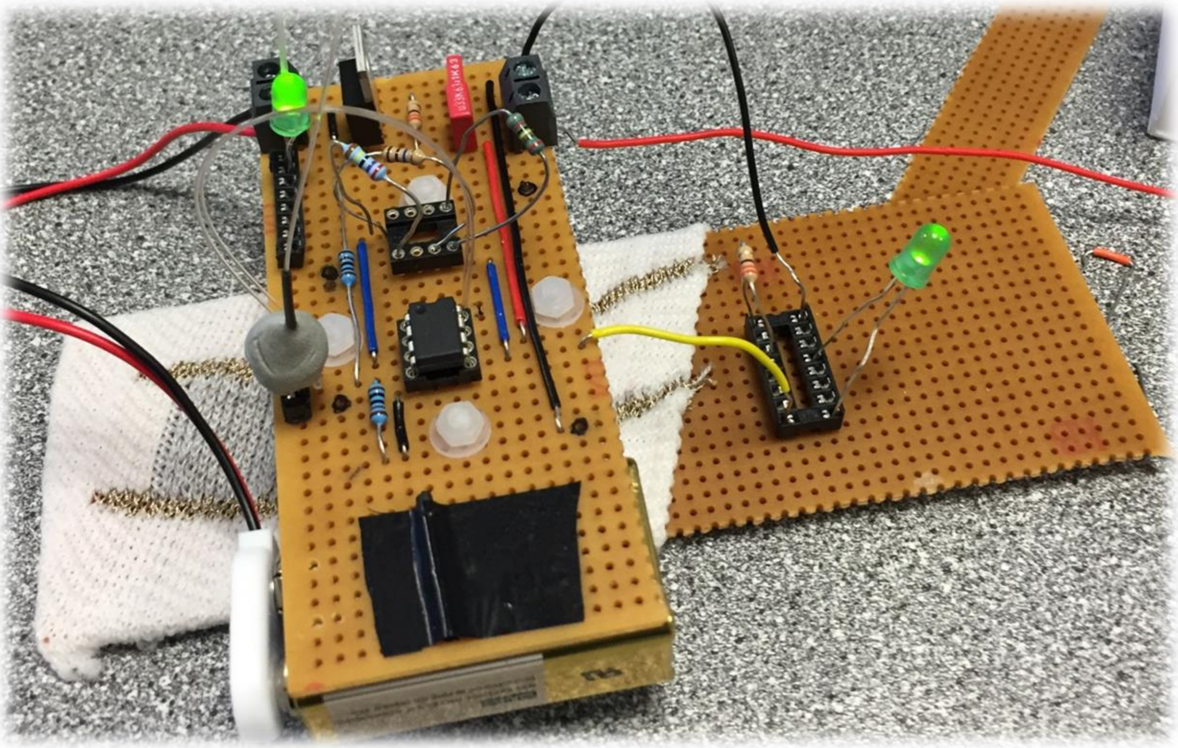
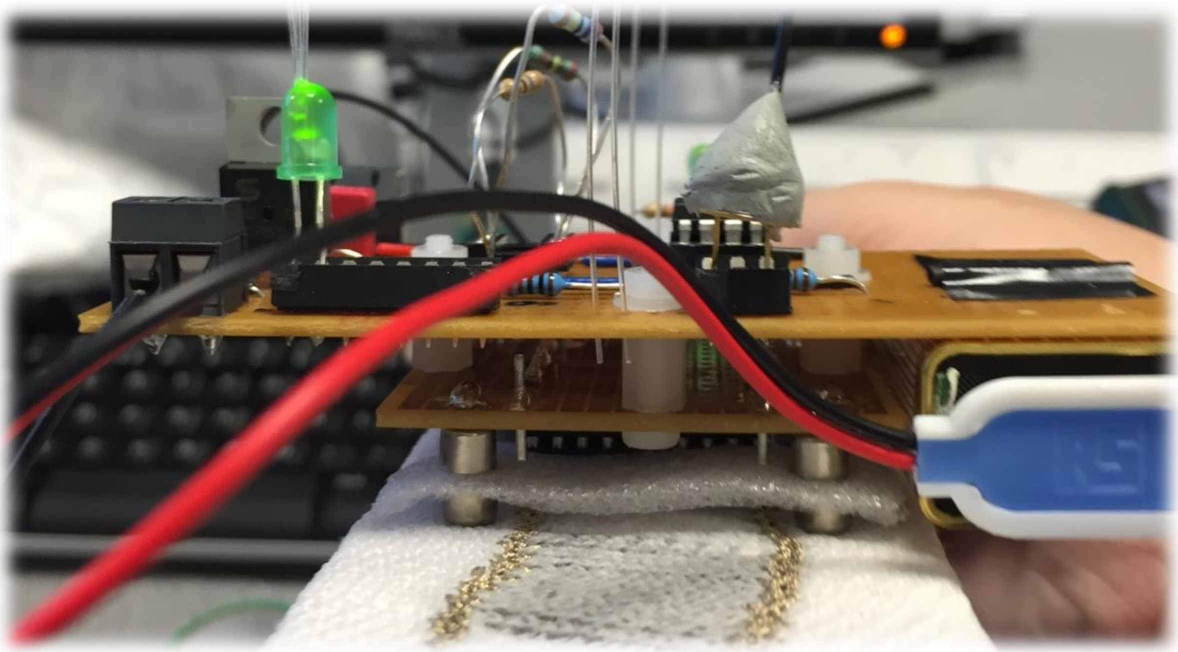
This project the collaboration with Footfalls and Heartbeats (Simon Mc Master)
---Simon McMaster is the Founding Scientist of Footfalls & Heartbeats Limited and has many years' experience in researching smart textile structures and the nanoscale interactions that govern the movement of these micromechanical structures. During the last ten years Simon has conducted on-going academic research in the fields of chemistry, nanotechnology and textile technology while developing a network of research and professional relationships with world leading research groups and institutions within these disciplines. Available from: http://www.footfallsandheartbeats.com/

Abstract:

The thesis was written to design a connector product which could link the wearable electronics to the photonic textiles. One of the main applications of the designed product was in developing socks for those with diabetes to monitor blood flow and pressure under the foot. Noiseless and robustness were main features for an expected design especially for movement artefacts. Two connection methods had be achieved in this designed connector with a function of transmitting electrical and optical signals from both direction from the textiles to the electronic circuits vice versa. Eight individual experiments had been implemented successfully to testify the functions of the designed product, including the pressure responses and heart rate measurements. So far the outer packing of the product was rough but more humanization design would be improved in the future.





1. Introduction:

---*This chapter contained a brief overview of the whole project, including brief introduction, project aims and structure of the thesis.*

1.1 Brief introduction:

The combination of enhanced comfort while wearing the textiles makes intelligent textiles practical for long-term monitoring systems of human health. Long term monitoring systems with enhanced haptic is very significant in monitoring patients since any type of rigid sensors is a danger of skin damage. If this early signs of tissue breakdown could be predicted then which could lead to a reduction on diabetic foot ulcers and amputations. [1][2] So far the study of monitoring using optical fibers in textiles as a monitoring device was in its infancy. There were some attempts such as using an optical fibre-based sensor for respiratory monitoring, optical fibre pressure sensor in medical applications and fibre optic micro-bend sensor for heartbeat monitoring. [3][4][5] However, less study was researched about using the optical fibres and textile electronic yarns as a combination to achieve the purpose of monitoring pressures and heartbeat together. One of main problems was that not easy to find an effective connector linking the textiles and electronic parts. The challenges of developing an effective connector including: reduce motion artefacts, disassemble easily and flexibly, improving higher transmission efficiency etc. In this thesis, the more effective connector to combine using optical fibers and electrical yarns would be investigated and designed as a new project.

1.2 Project aims:

The main aim of this project was designing a connector to link the textile sample and the electrical circuits to transmit optical and electrical signals. The whole product would contain electronic circuits (un-washable), the designed connector and the given textile sample (washable). One of the main methods to help complete this design was optimising the electrical and optical connection in movement artefacts with easily detachable so that the textile part could be taken down and washed (see **Figure 1.2a**).

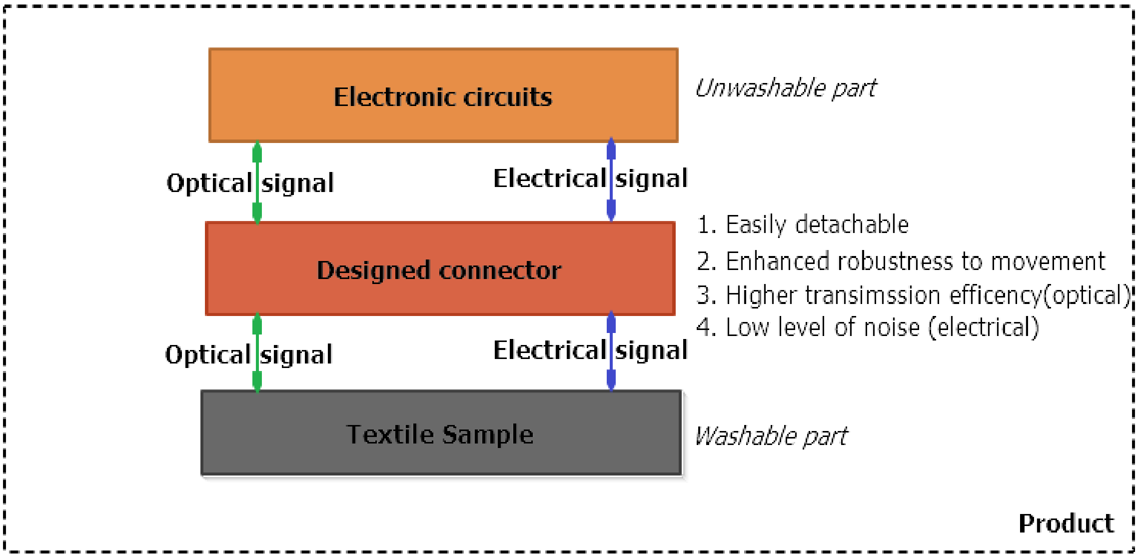


Figure 1.2a: Graphical representation of project aims

The designed connector aims to achieve a higher transmission efficiency to transmit optical signals, and get transmitted electrical signals with low level of noises. The final function of this product would be measuring the pressure and heart rate from the human finger. The pressure signal was transferred from the electrical signal, and the heart rate signal was transferred from the optical signal. The required data would be collected on the **textile sensing window*** from a tested human finger. The

Notes***:** the 'textile sensing window' would be introduced in the background section designed connector would as a 'bridge' to transmit electrical and optical signals between the electronic circuit and the textile sample. The feedback signal would be affected by the quantity of the applied pressures and the heart beats. By analysing the changed feedback signal in the final circuits, the detected signal would become a measurable voltage signal from the output which could be visible on the oscilloscope (see **Figure 1.2b**).

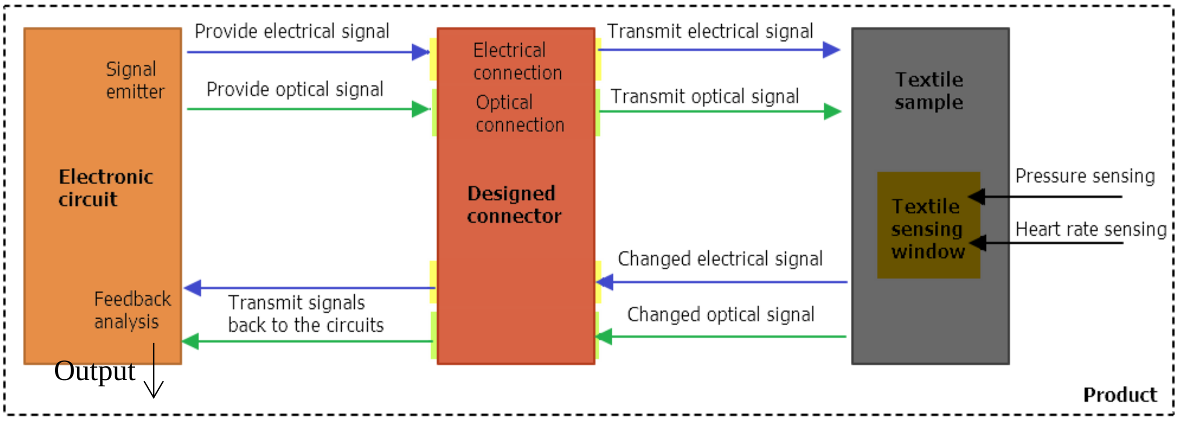


Figure 1.2b: Schematic of transmitting electrical and optical signals in the product

1.3 Structure of the thesis:

There were 6 sections in this thesis, the main achievement would be written in 'section 3: Product design' and 'section 4: experiments and results', including discussion and errors analysing. The background would work for the base knowledge about electrical and optical connections to the textile, and the definition of 'textile sensing window' would be mentioned in this particular part. The introduction and conclusion would be an overall review of the whole project. The conclusion would contain future works and improvements for the project. Finally, adding the declaration of the reflection on the original time plan (shown as **Table 1.3**).

Sections	Main contents
Section 1(Introduction):	A brief overview of the whole project, including project aims and structure of the thesis.
Section 2 (Background):	To introduce the modern development of the intelligent textile and give detail acknowledgments about the mechanism in a conductive textile fibre. Give a basic knowledge about optical fibres and introduce the function of detecting the pressures by using a textile sensing window.
Section 3 (Product design):	Details and schematics to design and build the product. Electrical connection, optical connection and combine both works together to get an integrity system to measure the pressures and heart rate from a human finger.
Section 4 (Experiments and results):	Contains eight separately designed experiments (Experiment1-8) to analyse the built product. Discuss the errors and give the detailed solution to overcome the challenges met in this project.
Section 5 (Conclusion):	Give a final summary of the whole thesis, analysis the merits and shortages, with possible development and the future work of the product with reflection of the time plan.

Table 1.3: structure of the thesis

2. Background:

--- *This chapter was written to introduce the modern development of the intelligent textile, and give a detail acknowledgment about the mechanism in a conductive textile fibre. Give a basic knowledge about optical fibres and introduce the function of detecting the pressures by using a textile sensing window.*

2.1 Photonic textiles:

Textiles are common materials for many medical and sports applications. They are used, for example, as bandages, medical stockings, sports suits, or socks. In 21st century world, textiles not only do all the traditional textile things but discreetly and unobtrusively include a host of additional attributes, which called **smart/intelligent textile**. And with the special integration of common electronic components (e.g. sensors, amplifiers), intelligent textiles are developed rapidly in recent years. [6]

Photonic textiles as one of the most original intelligent textile for monitoring peoples' health not only contain the electrical material, but also use the optical fibres together. On the other hand, the use of textile integrated optical fibres in biomedical applications is a relatively new subject. This project would mainly focus on the connection of optical fibres together with the electrical intelligent textile sensing and providing a combination function. [7]

2.2 Wearable electronics

Developments during the last 10 years in the area of wearable electronics, intelligent textiles and material research offer new possibilities to create textiles with higher level of functionality and allow the development of completely new active textiles. This trend was made possible by the interdisciplinary cooperation of electrical engineering, textiles and information science, together with sports and medical experts. [8]

The integration of electronic devices into textile base materials enables new possibilities for personal monitoring and therapeutically systems for sports and medical applications. And such monitoring devices are not restricted to electronic-based intelligent textiles; more interesting functions have been discovered in many other areas as a futuristic novelty. [9]

However, there is less study about combining the optical fibres together with the electrical wearable electronics on the modern researching area. In this project, a totally new method would be investigated to using optical fibres with electrically conductive yarns to provide a path-breaking way to the photonic-wearable electronics.

2.3 Electrically conductive yarn:

Three types of fibres are contained in the photonic textile, including electrical fabric, optical fabric and classical fabric. Most of the textile is made of classical fibres such as the ones used for commercial textiles (e.g. cotton, polyamide or elastane).

Electrically conductive threads were manufactured in antiquity before electricity was discovered. In modern times, metal wires, metal-wrapped yarns, metal-coated yarns, inherently conductive polymers and other technologies have been employed to confer electrically conductive pathways to textiles. Originally, conventional electrical wires were used, but then more sophisticated approaches were adopted. With the high growth in wearable devices and electronic textiles in particular, there will be an added impetus for the development of electrically conductive pathways with properties more in line with conventional fibres and yarns. [10]

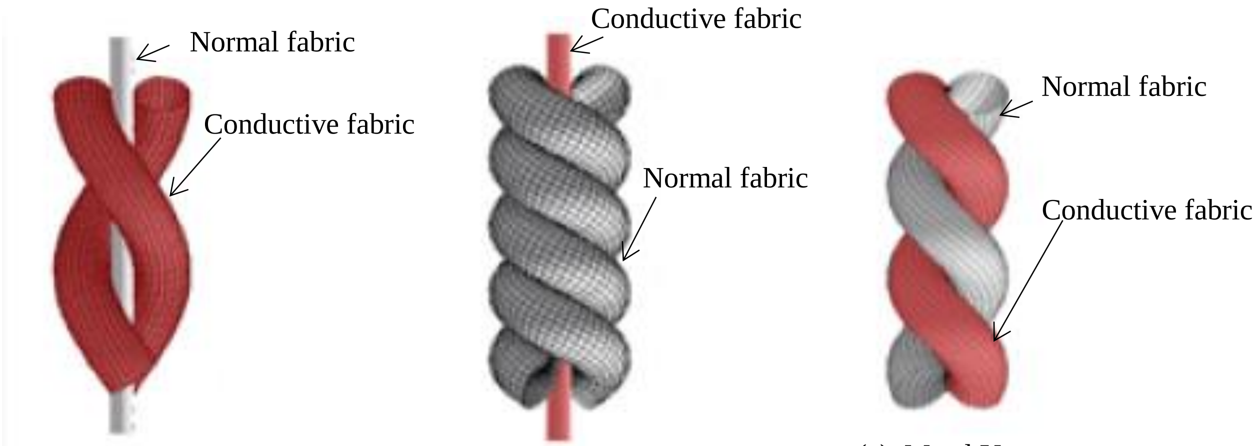
Metallised fabric:

The **electrically conductive yarns** (electrical fibres) are coated with conductive material which could therefore conduct current. Some of them have a pressure sensing effect, which means any normal forces exerted on to these fibres change the electrical resistance of the material. Two conducting electrical fibres connected to a pressure sensing fibre can thus transmit and collected a signal which intensity is a function of the pressure. Smart textile for wearables is in its infancy, current technologies used for conductive textiles include:

• Weaving of separate metal threads into the textile. ----- **2.3.1**
• Printing metallic inks on to the surface. ------**2.3.2**
• Electroless plating. ------**2.3.3**

2.3.1 Weaving of separate metal threads into the textile:

There are three method of processing



(a) Metal-wrapped Yarn (b) Metal-filled Yarn (c) Metal Yarn

Figure 2.3.1: three method of weaving conductive fabric with the normal fabric *[1]

These weaving methods perform poorly when the underlying fabric is stretched, bent or twisted, and easily be damaged. [11]

2.3.2 Printing metallic inks on to the surface:

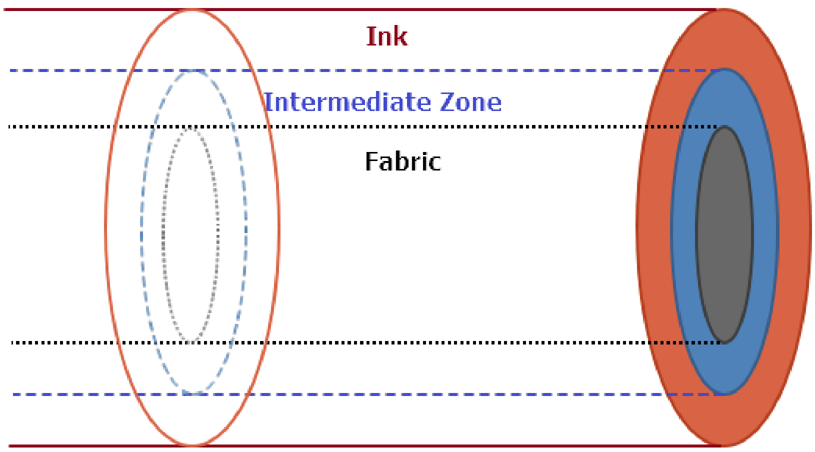


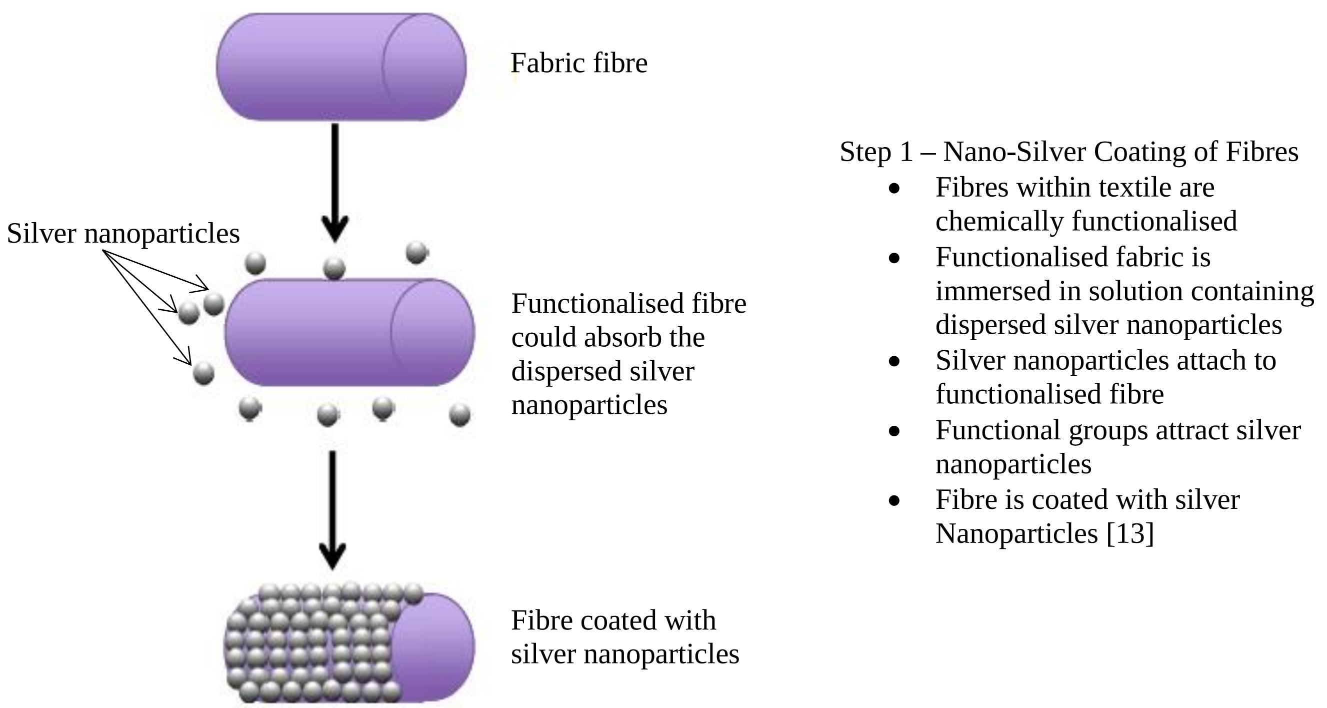
Figure 2.3.2: Schematic of printing metallic inks on to the surface of normal fabric

This printing method required a conductive medium that can follow the fibres, ideally without affecting their ability to deform, while this method not performs well in wash cycles. [12]

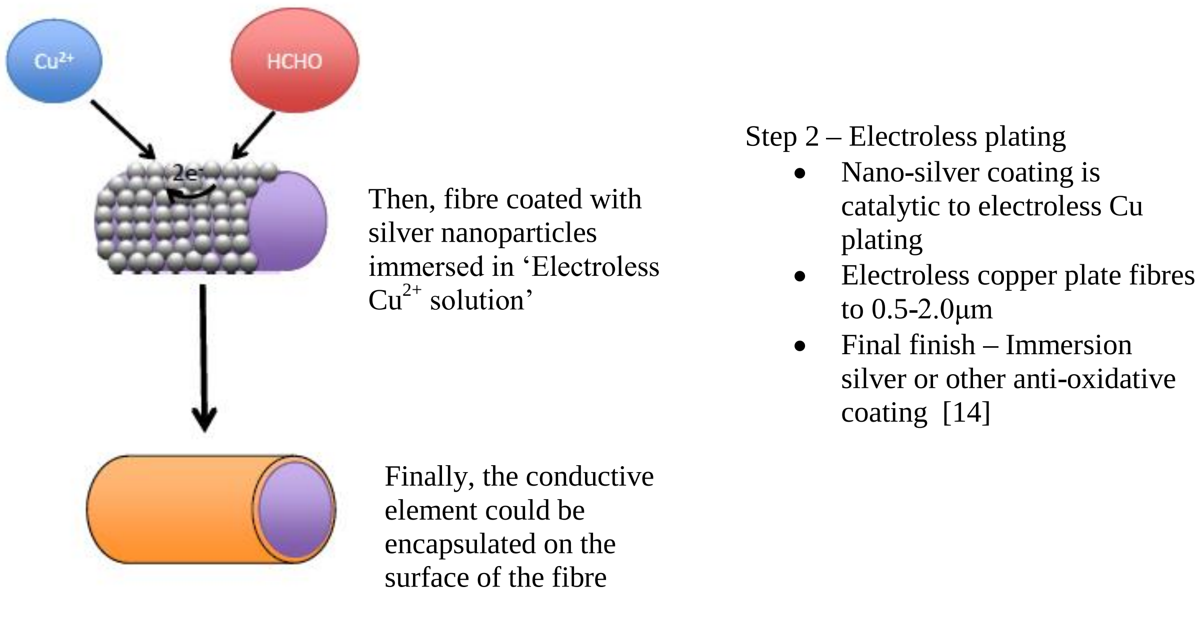
*[1,] Notes: **Figures 2.3.1** from *C. Hunt, R. Ashayer-Soltani, K. Wills, "Smart Textiles for Wearable Technology", the online PPT slides (2015)*

2.3.3 Electroless plating

The electrically conductive fibres used in the given textile sample in this project is mainly using the way of 'electroless plating'. The processing operation is detailed as follows:



Figures 2.3.3: the processing of electroless plating of the electrically conductive fibres*[1]



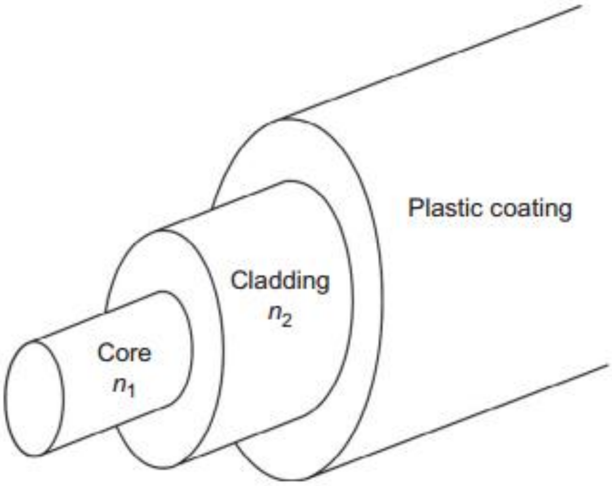
To introduce **conductivity**, a nanometal seed layer is firstly attached to the fibres, which acts as a catalyst towards a secondary electroless metal plating process. This encapsulates the fibres and the resulting textile achieves excellent resistivity depending on the textile. It demonstrates good adhesion of the coating, flexibility and is stretchable. This chemical bonding of the metal to the textile leads to it surviving more than hundred wash cycles, and repeated stretch cycles. [15]

*[1,] Notes: **Figures 2.3.3** from *C. Hunt, R. Ashayer-Soltani, K. Wills, "Smart Textiles for Wearable Technology", the online PPT slides (2015)*

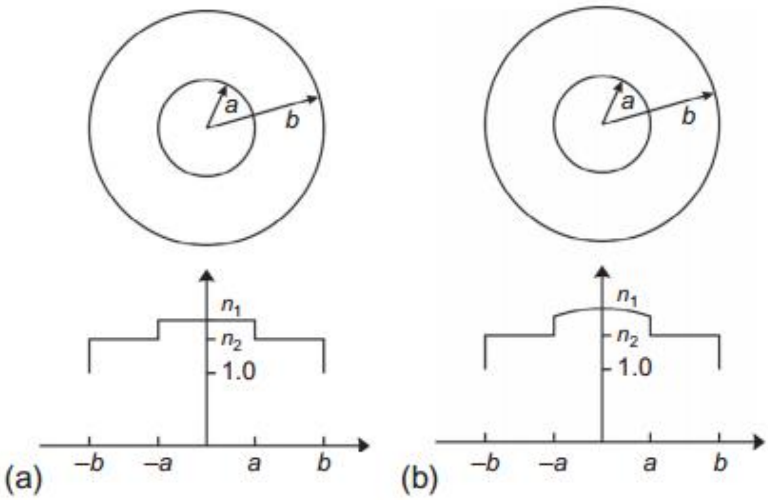
2.4 Optical fibres:

Optical fibres are optical waveguides consisting of an inner cylinder of glass with a refractive index n1, called core, surrounded by a cylindrical shell of glass or plastic of lower refractive index n2, called cladding, often covered by a plastic coating (**Figure 2.4**).

If the core, which is typically made of a silicate glass doped with germanium oxide, phosphorous oxide and other oxides in smaller quantities, has a uniform refractive index, the fibre is called 'step-index fibre'



If the core has a non-uniform refractive index that gradually decreases from the centre toward the core–cladding interface, the fibre is called a 'graded-index fibre'



(a) step-index fibre*[1] (b) graded index fibre*[2] [16]

Figure 2.4: the Dimensions and refractive indices for two kinds of fibres*[1,2]

Optical fibres could be applied to a multitude of sensing applications, as most physical properties could be sensed optically with fibres. Some application such as light intensity displacement, pressure, strain, rotation, temperature, electric field, magnetic field, radiation, flow, liquid level, vibration, etc. were just some of the properties that can be monitored. [17]

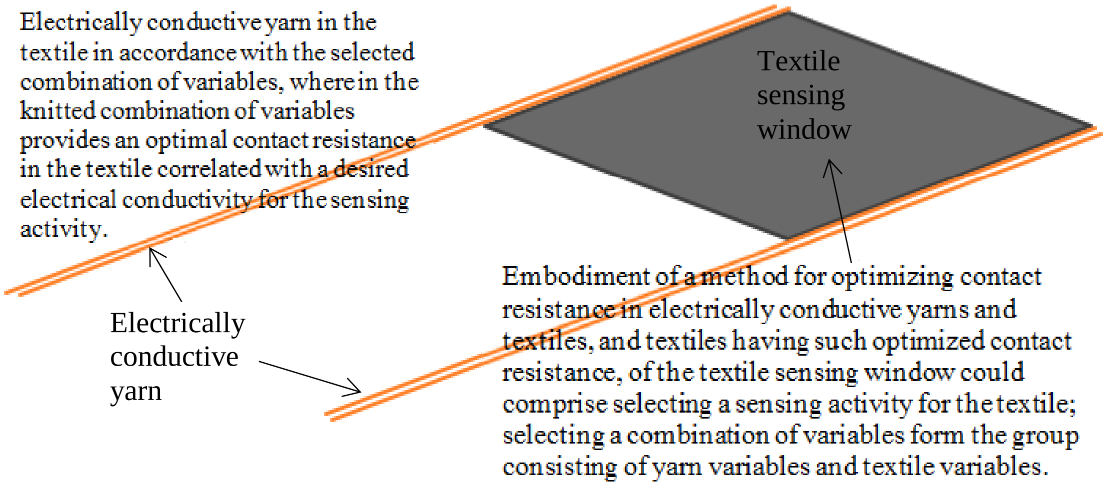
Optical fibres used in this project embroidered into textiles could measure heart rate and oxygen saturation in the reflection mode. They are placed to deliver light and receive light from the tissue in order to monitor blood volume. The "light-in and light-out" properties of the optical fibres through the **textile sensing window** enabled the spectroscopic characterization of human tissue such that out-coupling and in-coupling of light was possible. [18]

In this designed product, the optical fibre was used as a sensor for measuring the blood flow from a human finger so that the heart rate of the tester could be detected. The selected optilca fibre used in this project was 0.5mm size of radius with simple core and cladding.

*[1,2] Notes: **Figures 2,4** from *M. Ding, G. Brambilla, "Optical fibres and sensors for biomedical applications", Biophotonics for Medical Applications, Pages 53-78 (2015)*

2.5 Textile sensing window:

To introduce **textile sensing window,** there are pressure sensing fibres contained in the sensing window so that the electrical fibres could conduct different voltage levels to achieve the purpose of measuring the normal pressures on the textiles.



The textile sensing window was used to be monitor pressure under exerted by the human tissue, for example, the touch face of the human finger.

Textile sensing window:

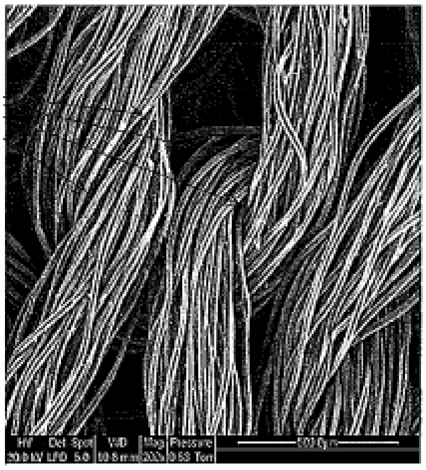


Figure 2.5a: Scanning electron microscope image of the yarn contact area for the tested given textile sample*[1]

Knitted in a '3D' layout, when a pressure is applied the shape of the knitted fibre would be changed so that the conductive behaviour would be changed. [19]

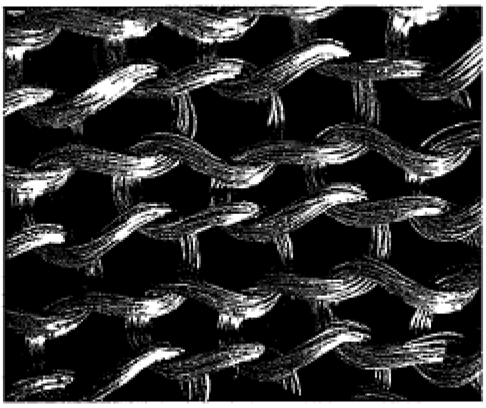


Figure 2.5b: Before pressed*[2]

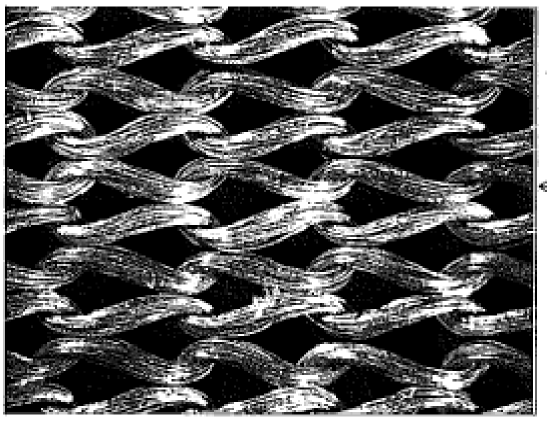


Figure 2.5c: After pressed*[3]

*[1,2,3] Notes: **Figures 2.5a-c** from the publication, *'Method for optimizing contact resistance in electrically conductive textiles', WO 2014/122619 A1 (2014)*

3. Product design

--- This chapter was written details and schematics to design and build the product. Electrical connection, optical connection and combine both works together to get an integrity system to measure the pressures and heart rate from a human finger.

3.1 Electrical connection

3.1.1 Pogo pin connection:

The electrical connection was designed to transfer the electrical signal from the textile artefacts. In order to find a suitable connection from the textile, the pogo pin connector was specifically assembled to reduce the motion artefacts with its flexible plunger and spring (shown as **Figure 3.1.1**).

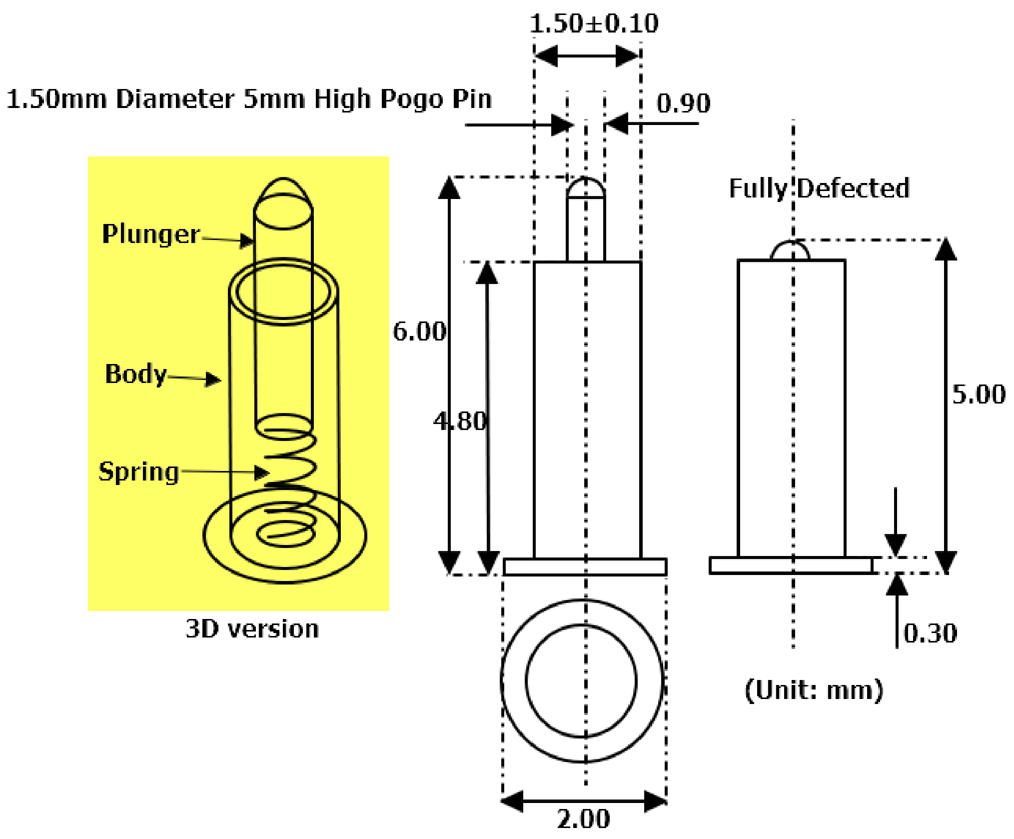


Figure 3.1.1: Schematic of 1.50mm Diameter 5mm High Pogo Pin*[1]

The pogo pin could be divided into three parts: plunger, body and spring. The plunger was connected with the spring so that the head of the plunger could be defected when applied a force on the top. The size of the pogo pin had a height of 6mm and 5mm by fully defected. Range between 5-6mm under a working condition. Contacts are gold plated and incorporate high force stainless steel springs for durability and signal integrity. The total material was made by brass.

The reason for selecting pogo pin as an electrical connection:

1. High quality of conductivity.
2. Flexible design with the spring inside the body particularly fit with the movement testing of the wearable electronics.
3. Small size, reduce the weight of the connector.
4. Durability, provide high reliability and signal integrity over 10,000 cycles.
5. Cheap and easy.

*[1]Notes: link of the data sheet of the pogo pin: http://datasheets.avx.com/PogoPin_70-9150.pdf

3.1.2 Magnet connector:

The magnet connector was used to fix the wearable electronics (the top part) with the textile plane (the bottom part). And this design was fit with a simple touching. Before the two parts was touched, the fixed magnet would attract each other and they would automatically adjust the touching position face-to-face into an immobility condition (see **Figure 3.1.2a**).

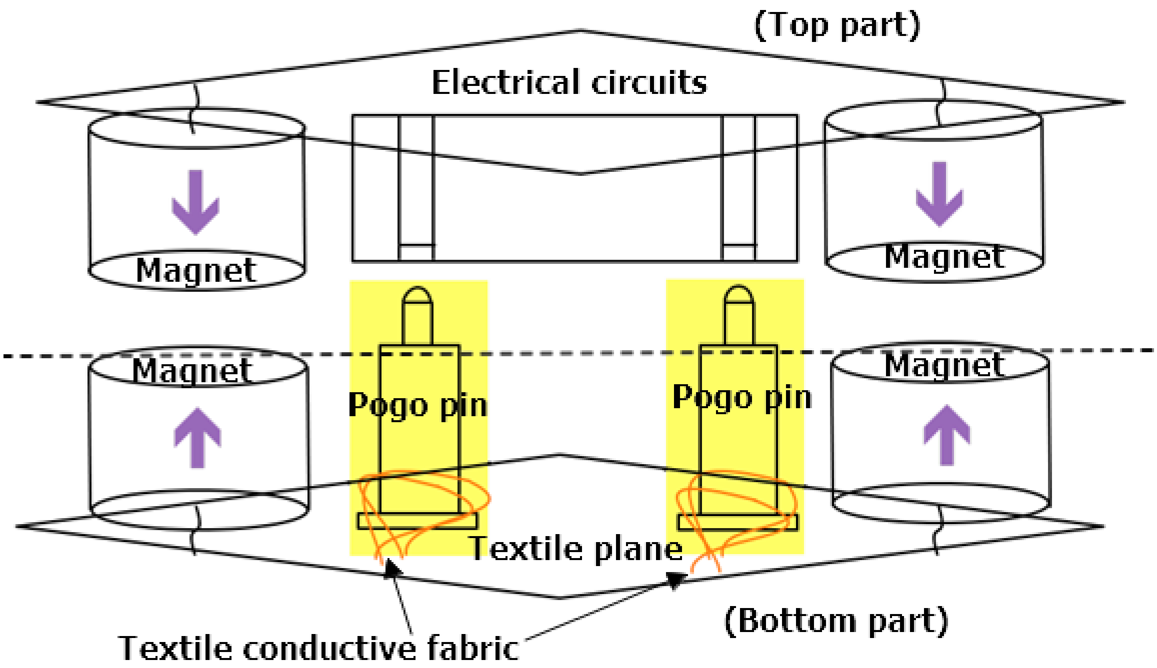


Figure 3.1.2a: Magnet connector before touching

After the magnets were touching with each other (see **Figure 3.1.2b**), the top part and the bottom part would be connected by pogo pins. The electrical signal would be transmitted from the bottom part to the top part, at the meantime the top part could send electrical signal to the bottom part to achieve a bi-direction connecting.

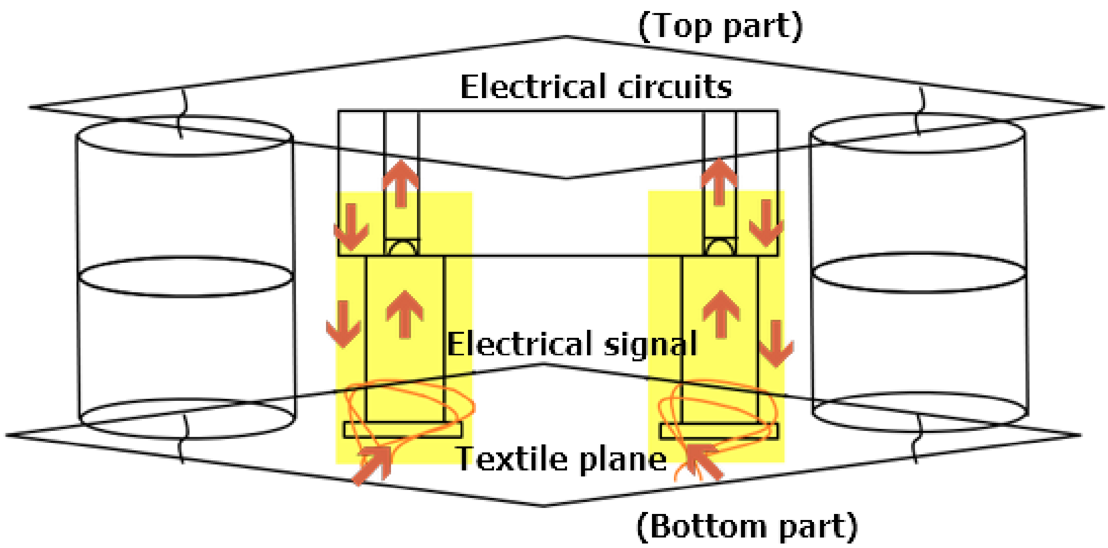


Figure 3.1.2b: Magnet connector after touching

3.1.3 Electrical circuits:

The electrical circuit was design as a simple circuit to measure the 'variable voltage' from a 'variable resistor'. Providing 5Volts DC voltage into the system, the textile sensing window would be regard as a 'variable resistor', by applying different pressures on the sensing window the total resistor between **A** and **B** would be changed within a range of 0.3kΩ-4000kΩ by a normal testing (see **Figure 3.1.3a**). The indicator light was set to indicate the pressure into a visible signal. When the pressure was applied the indicator light would get brighter as the pressure becoming larger.

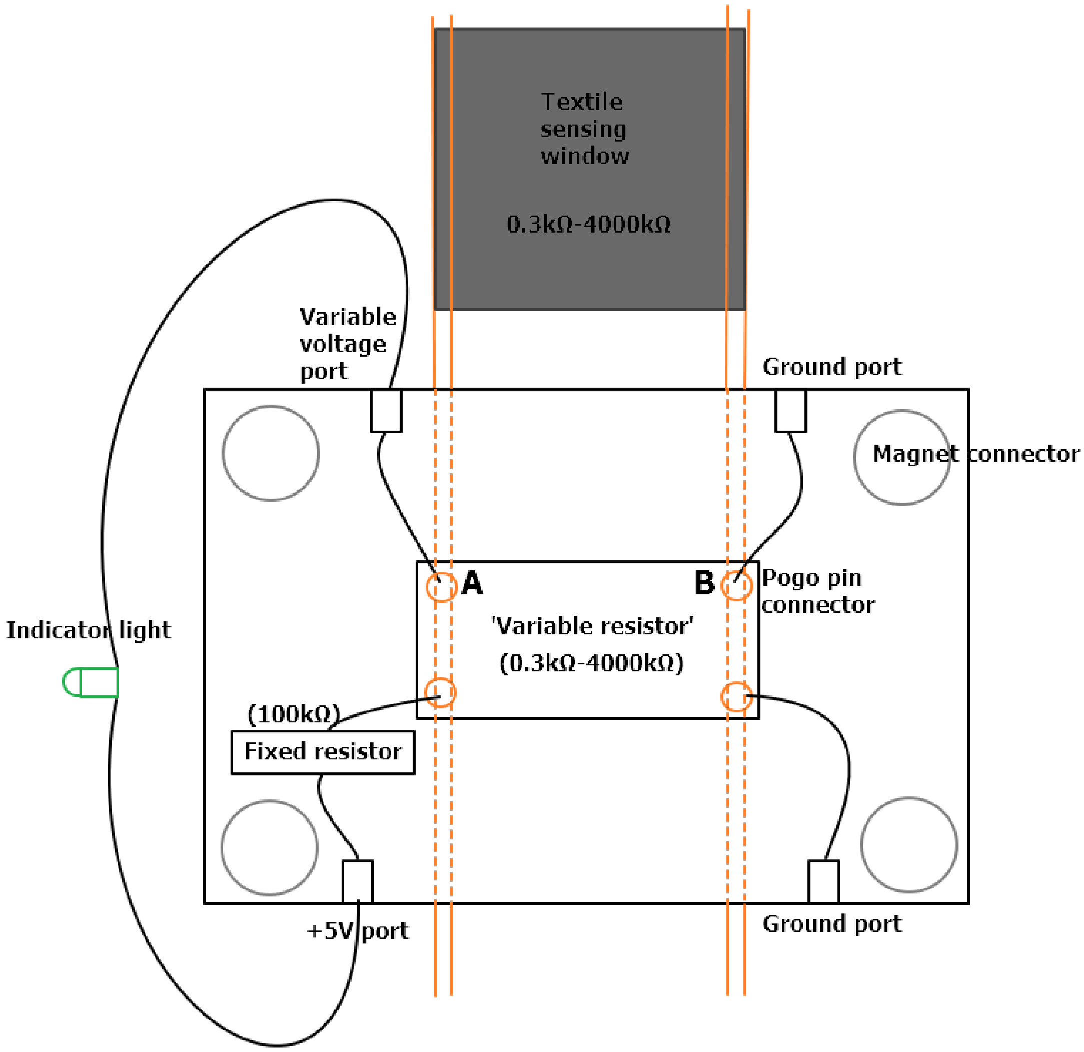
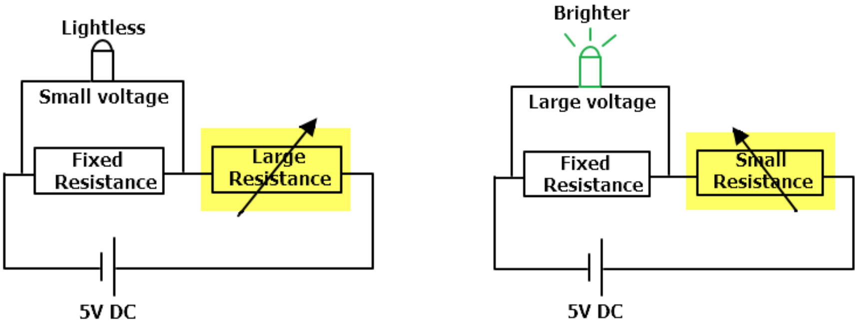


Figure 3.1.3a: Electrical pressures measuring circuits

The alternative circuits would be shown as below:

Before the pressure was applied, the resistor of the textile sensing window would be large so that the voltage gave to the indicator light was small, the light was bright less.



After the pressure was applied, the resistor of the textile sensing window would reduce so that the voltage gave to the indicator light became larger, the light was brighter.

Figure 3.1.3b: Electrical pressures measuring circuits

3.2 Optical connection:

3.2.1 LED emitter:

There were two light sources used in this project:

1. The light source used in the experiment by testing purpose was a green laser LED (wavelength= 530 nm). This kind of LED emitter could produce green light with a light power range from 0 to 3000uW.
2. The light source designed in the wearable electronics was built by serval green LED (wavelength= 530 nm) with lower power compared with the laser LED (lower 1200uW).

Both of these light sources produced the green light with the same wavelength to get an enough light power according to different utility. The laser LED was super powerful but it had a large bulk and inconvenient to take away. The green LED light could be deigned in a small circuit, but could not produce such a powerful light. The reason for choosing green LED in this project was its higher absorption by blood, therefore higher contrast. By using green LED as a light emitter could help to get a more obvious feedback signal coming back to the detected circuits.

3.2.2 Optical detector:

The optical detector circuit was designed by combining a photo diode together with its amplifier circuit. The main components used in this circuit contain: a photodiode (BPW21R*[1]), LM741 and several resistors (see **Figure 3.2.2a**). BPW21R was a planar Silicon PN photodiode which could transfer the power of light into a current signal. Due to its extremely high dark resistance, the short circuit photocurrent was linear over seven decades of illumination level. LM741 was selected to build an amplifier circuit to amplify the small photo current into a larger signal which could be easily detected by the oscilloscope. For the reason that the input of the op-amp was connected with inverting, so larger power of received light would give a lower voltage outputs on the results.

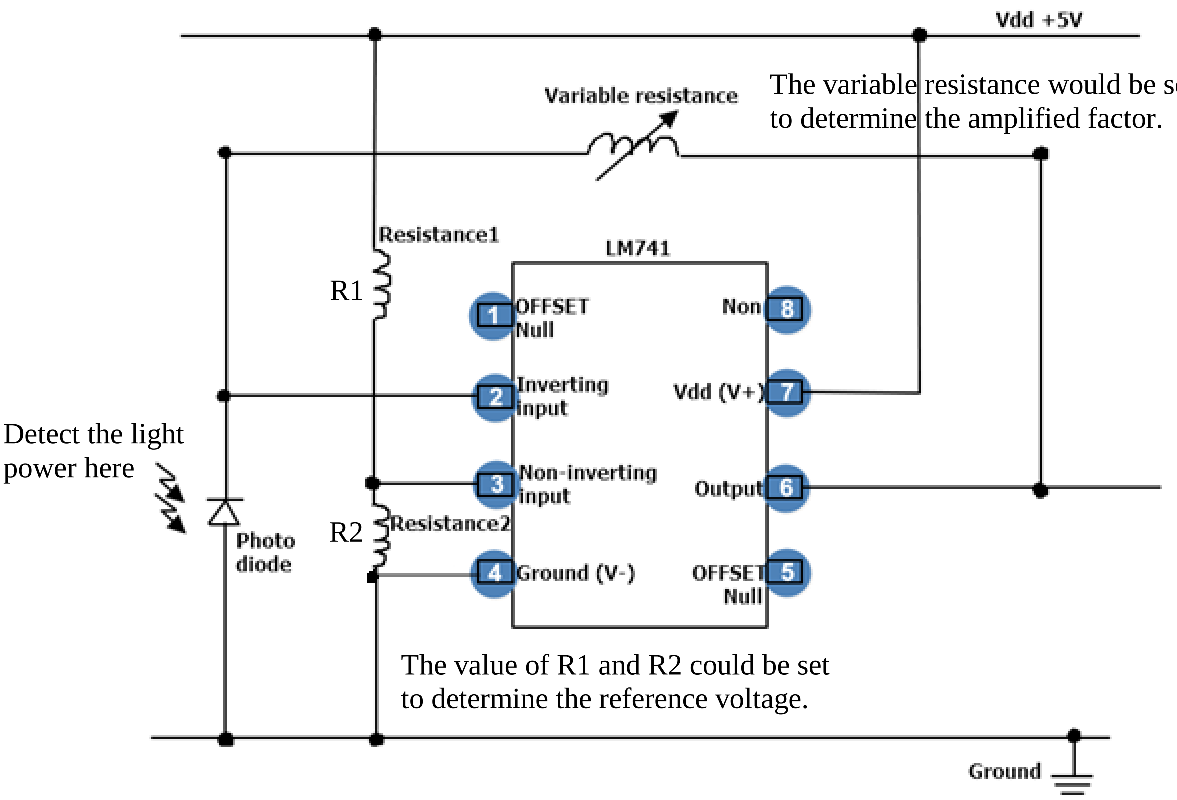


Figure 3.2.2a: Optical detector circuits

*[1]Notes: link of the datasheet of BPW21R: https://www.vishay.com/docs/81519/bpw21r.pdf

The circuits diagram showing the 'LM741' op-amp with the pin outs was shown as below:

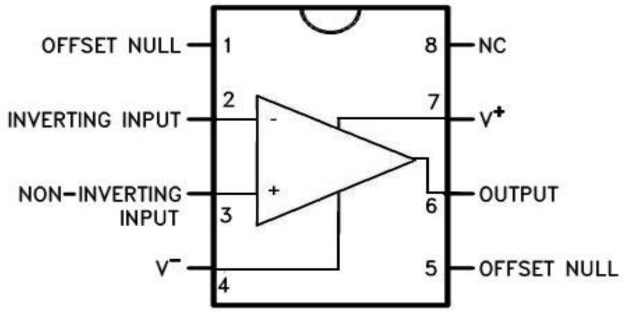


Figure 3.2.2b: LM741 pin outs diagram*[1]

In order to guide the optical fibre deliver the light signal into the photonic detecting window, there were several tries had been built on the photo diode. For example, some material such as latex, plaster and rubber, was tried to connect the optical fibre on the optical detector. But finally the 'heat' shrink tubing was implant with light blocked plasticine was designed to guide the optical fibres. Shown as **Figure 3.2.2c**, the light block material protected the photo diode from affecting by the environmental light from the outside, for example, the room light, and the computer screen.

The optical fibre was expected to be facing the photonic detecting window by 90 degrees (vertical in the cross section). The designed black tube helped to block the light from outside and fix the optical fibre standing in a vertical condition. The photonic detecting window would collect the received light power and transfer into a current signal applied in to the optical detector circuits.

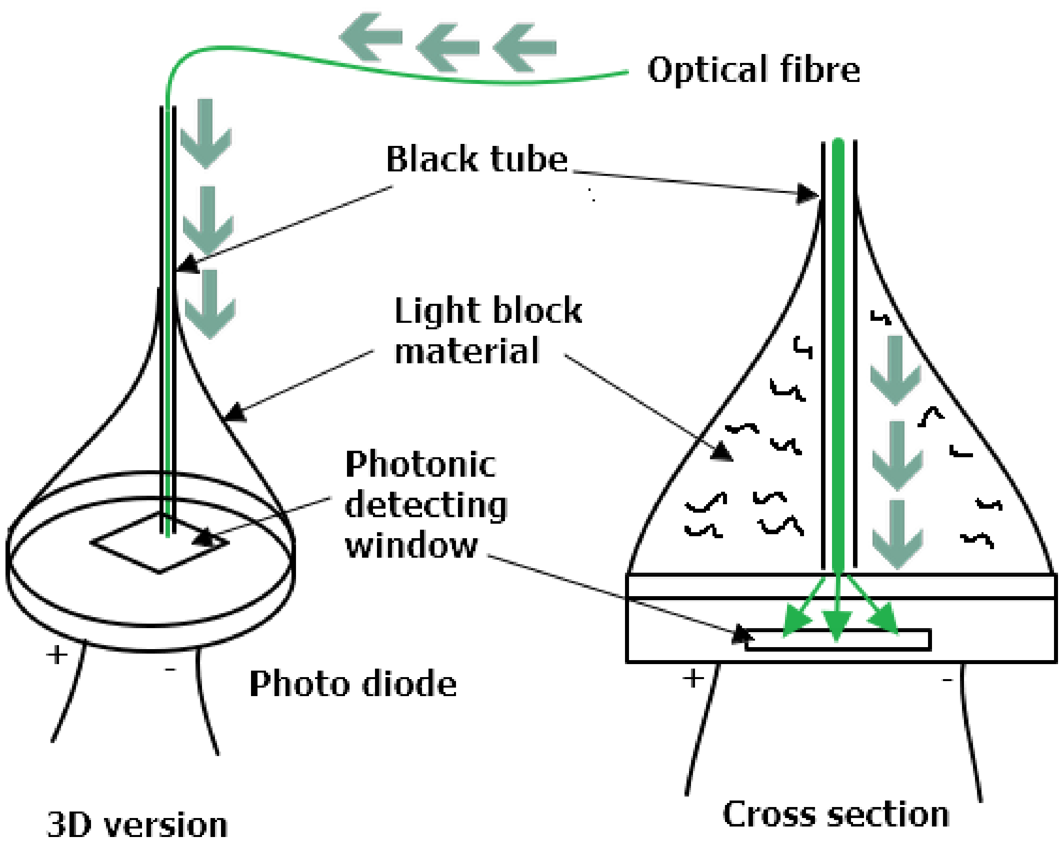


Figure 3.2.2c: Collect the light by a photodiode (block the outside light)

*[1]Notes: link of the datasheet of LM741: http://www.ti.com/lit/ds/symlink/lm741.pdf

3.2.3 Holes design:

The optical connection hole was designed to reduce motion artefacts and easy to be disassembled. The optical hole was designed to transmit optical signals from the bottom part to the top part vice versa. There were two holes need to be designed in this connector, one was used for transmitting optical signal from the LED emitter to the textile plane, and the other was used for transmitting optical signal from the textile plane to the optical detector. The main purpose of these connectors was getting an easier way to separate the textile martial and the electrical and optical circuits, to help the textile could be washable without any electronics. The design schematic was shown as **Figure 3.2.3a**.

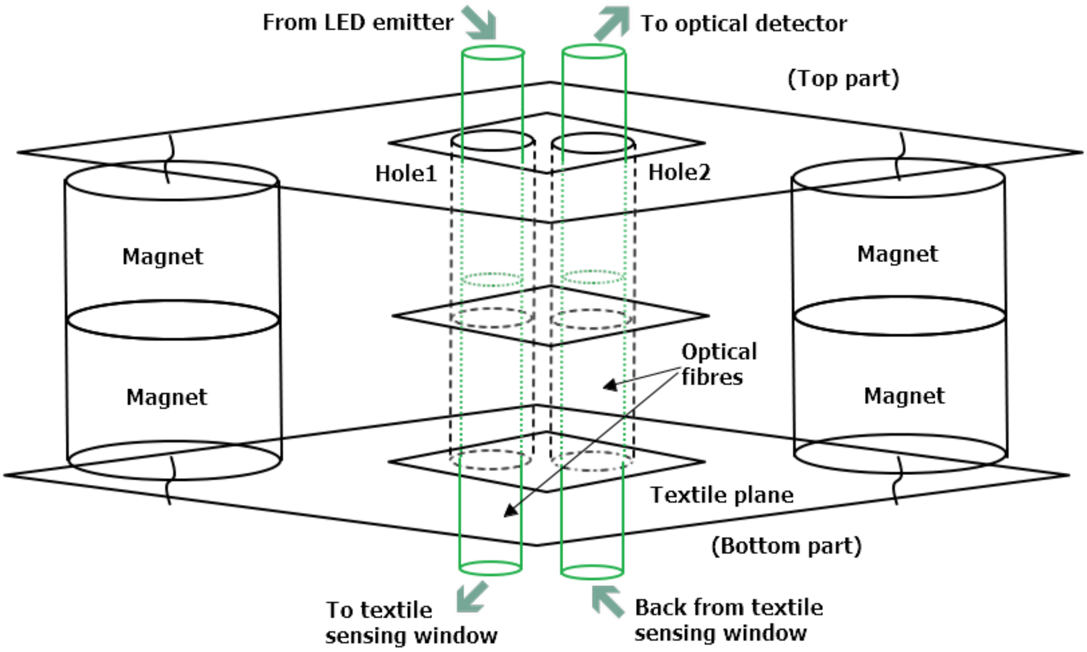


Figure 3.2.3a: Schematic of designed optical connection hole

In order to optimise the transition efficiency from one optical fibre to another, the facing and position of the optical fibre and the size of the hole was treated by three methods (see **Figure 3.2.3b**).

1. The face of the bottom part optical fibre was higher than the hole's face, and the face of the upper fibre was inside the hole's face, so that they could fit with each other even in a movable connecting.
2. The size of the hole was slightly larger than the size of the optical fibre but fixed the optical fibre to have a condition of facing centre to centre.
3. The facing of the upper optical fibre was treated by high heat and slightly larger than bottom face.

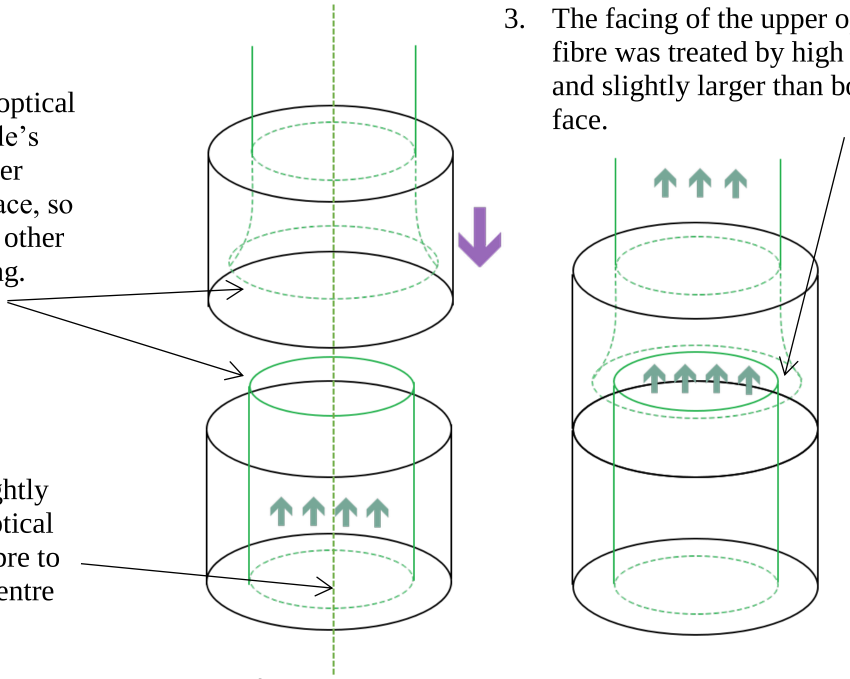


Figure 3.2.3b: Schematic of designed optical connection hole

3.3 Combinational design:

The whole system was operated with 5volts DC voltage, supplied by a normally 9volts battery with a voltage regulator (LM7805). The regulator circutit was shown as below.

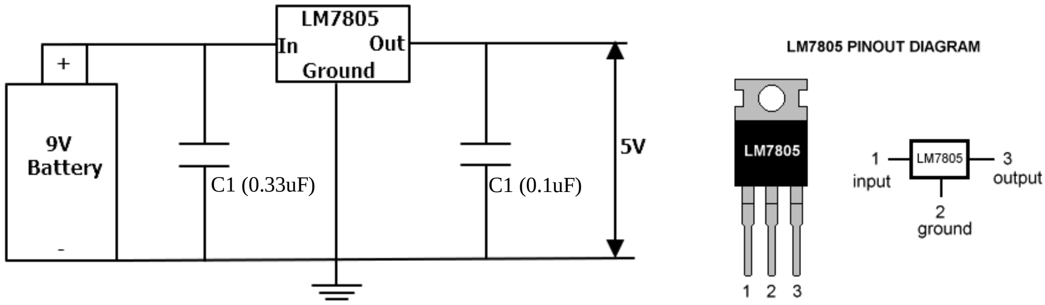


Figure 3.3a: The regulator circuits applied to the product system*[1]

The whole product was designed by three layers, from the bottom to the top to combine the electrical and optical circuits together. The first layer was the textile basic, the seconde layer was a transition layer , and the third layer was a electronic circuit.

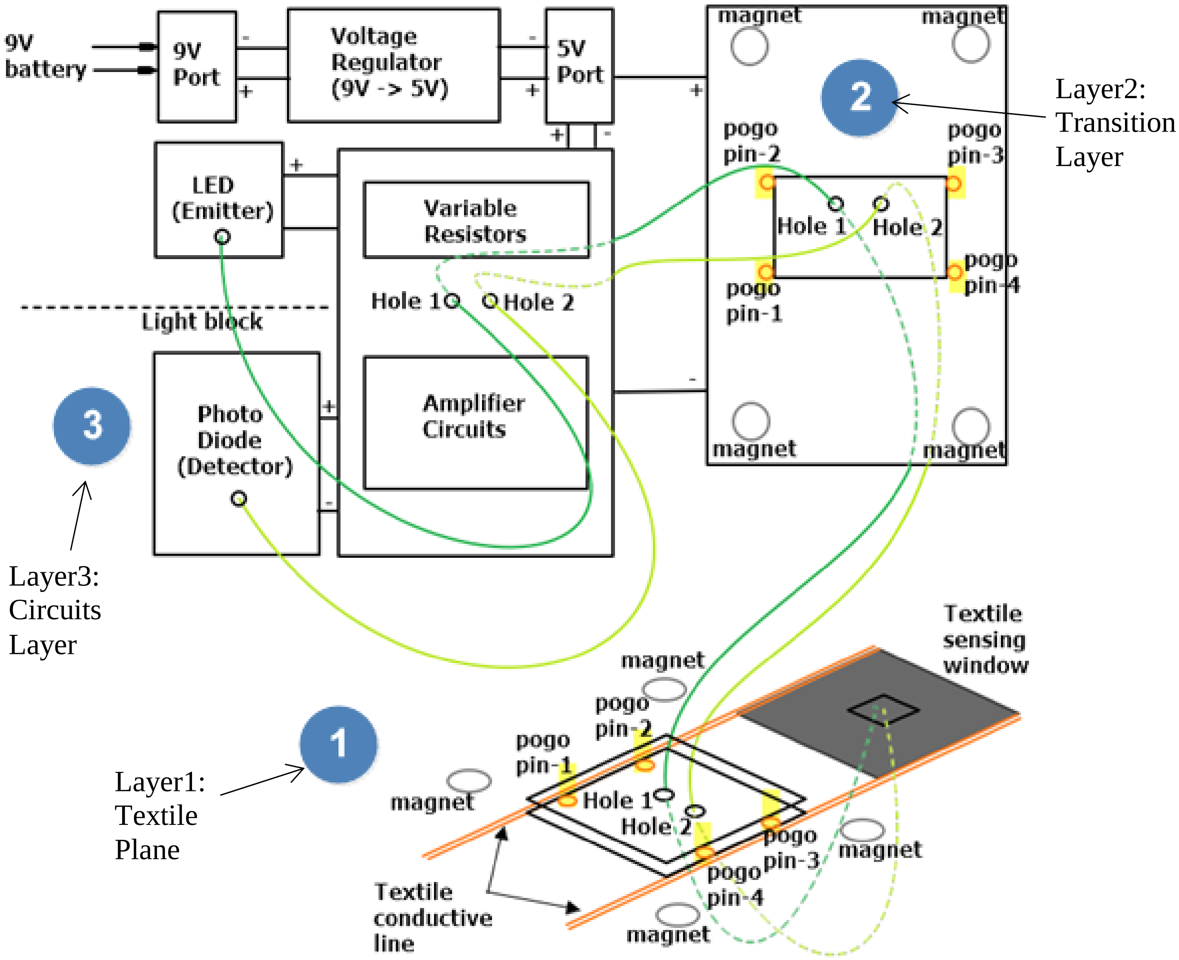


Figure 3.3b: Schematic of the designed system with the whole product

The optical fibres were coming through three layers starting from the LED emitter and ending up at the photo diode detector. The variable resistors on Layer3 was used to control the amplifier factor (see **Table3.3 & Figure 3.3b**). And the real picture of the designed product would be shown as **Figure 3.3c** with all labelled components and name of the different parts. So far the size of the product was medium, a smaller size of the product would be expected in the future design.

*[1]Notes: the datasheet of the LM7805: https://www.sparkfun.com/datasheets/Components/LM7805.pdf

Layers	Names	Components	Main Function	Size (mm)	
Layer1	Textile basic layer (Textile plane)	Textile sensing window, conductive fibric, pogo pins, magnets	Detect pressures and heart rate signal from a human finger from the textile sensing window	Width	55
				Length	105
Layer2	Transition layer	Pogo pins, magnets, bottom holes to optical fibres,	Pogo pin connection, magnet connection, holes connection	Width	37
				Length	49
Layer3	Circuits layer	Emiter, detector, upper holes to optical fibres	Provide and reveive the optical signal, analyse the results	Width	46
				Length	72

Table 3.3: Each layer's main function and sizes

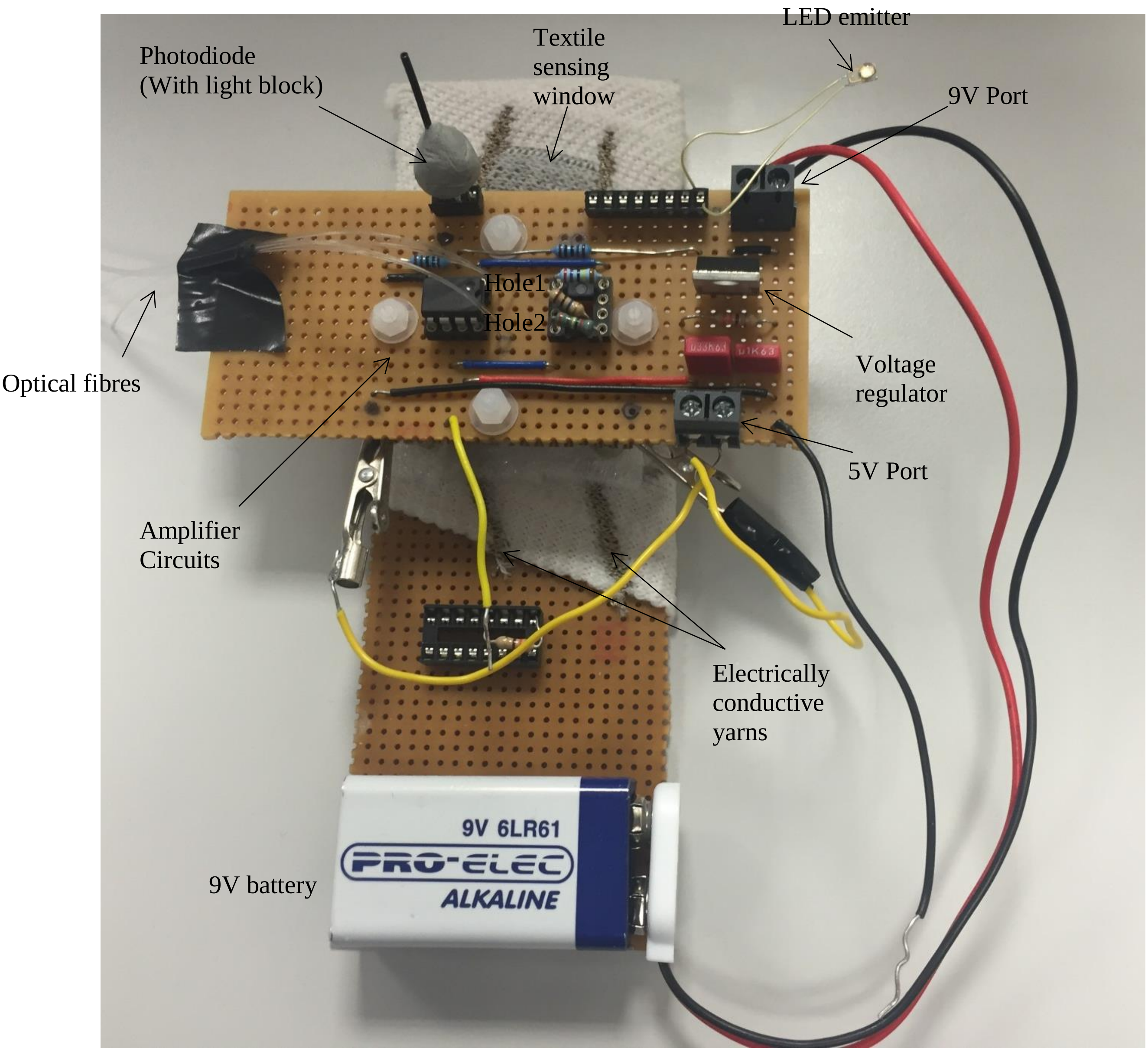


Figure 3.3c: Overview picture of the designed product

4. Experiments and results

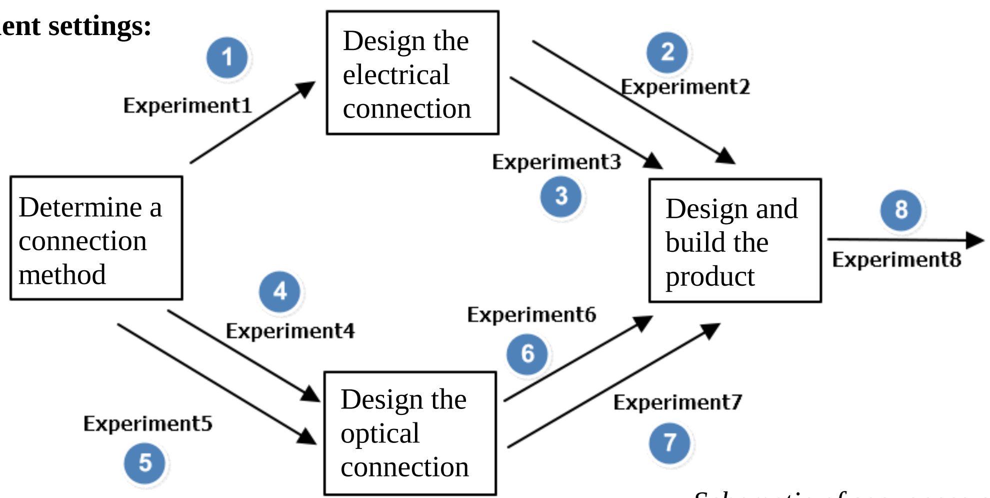
--- *This chapter contained eight separately designed experiments (Experiment1-8) to analyse the built product. Discuss the errors and give the detailed solution to overcome the challenges met in this project.*

Experiments overview: The product was designed to measure the force pressure and heart rate from a human's finger touching on the sensing window so that this function could be used in developing socks for those with diabetes to monitor blood flow and pressure under the foot.

There are eight experiments contained in this section, each experiment has its individual experiment methods to get separately purposes:

Experiment number	Name of the experiment	Aims of the experiment
Experiment 1	Comparing signal to noise ratio (SNR) for electrical connection 'directly clipped' and 'pogo pin connection'	To confirm using 'pogo pin' has no effects on noise issues to transmit electrical signals compared with normal metal wires
Experiment 2	Characterised SNR results for the textile-based circuits with robustness checking	To ensure the designed electrical connecter could enhance the robustness to movement artefacts
Experiment 3	Checking pressure response for the textile sensing window with different types of tapping	To confirm the response of the textile sample is perfectly working for different levels of forces or pressures applied on the sensing window
Experiment 4	Comparing the transmission efficiency of designed optical connector with commercial SMA connector	To confirm the designed product could achieve the most efficient optical connector on the market for the quality of the transmission efficiency
Experiment 5	Optical power transmission properties with different x, y and z distance	Analyse the tolerance of the size of the designed optical transmission holes
Experiment 6	Relationship of applying specific pressures on textile sensing window with its outcome resistance	Get a specific relationship of the applied pressure with the outcome resistance on the sensing window
Experiment 7	Measuring heart rate by optical fibres	Introduce how to measure heart rate by using optical fibres.
Experiment 8	Results for pressure test together with heart rate measuring on textile sensing window	Using the product to measure the heart rate with different level of pressures applied on the sensing window

Experiment settings:



--- *Schematic of sequences of the experiments*

4.1 Experiment 1: Comparing signal to noise ratio (SNR) for electrical connection 'directly clipped' and 'pogo pin connection'

4.1.1 Introduction (Experiment 1):

Experiment date: 20th- 25th.Oct.2015

This experiment was designed to investigate the effects of using 'pogo pin' in a basic circuit which was built by a fixed resistance, a variable resistance and a supply voltage. The variable resistance was used to simulate the function of the textile pressure sensing window whose value of the resistance could be changed when a force was applied on it. The practical function of the textile-resistance and the variable-resistance was totally different. In this case, an extra experiment was set to get a more comparable value applied on the textile based circuits. But this experiment was valuable to see the effects of using 'pogo pin' on a basic circuit to make sure that, using this method to connect a textile material was feasible.

4.1.2 Method (Experiment 1):

Two points besides the variable resistance were connected by oscilloscope, recording the voltage value vary with time. Test 1 was connected by a metal wire to get the voltage signal on the oscilloscope while test 2 using 'pogo pin' connected with the variable resistance to get the signal. Use a fixed resistance and a variable resistance here to get different level of voltage, so that this experiment could be suitable for different situation. In this experiment, 4000 values were recorded for per measure level. According to the following steps to calculate the signal to noise ratio (SNR):

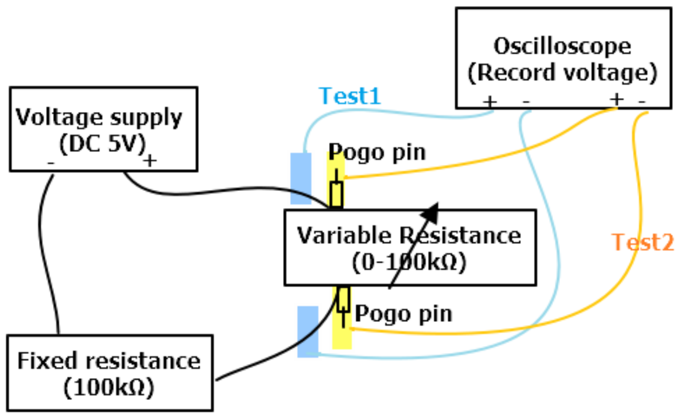


Figure 4.1.2: Tested basic circuits

Step 1- Average voltage:

$$V_{Average} = \frac{V_1+V_2+V_3+\cdots+V_{4000}}{4000}$$

Step 2- Standard deviation:

$$\sigma = \frac{\sqrt{(V_1-V_{Average})^2+(V_2-V_{Average})^2+(V_3-V_{Average})^2+\cdots+(V_{4000}-V_{Average})^2}}{4000}$$

Step 3- Calculate SNR in dB: $$SNR_{Voltage} = \frac{V_{Average}}{\sigma}$$

$$SNR\ (dB) = 20 \cdot log_{10}(SNR_{Voltage})$$

(This calculation methods was also used in '**Experiment 2**' to get SNR (dB) in **Table 4.2.3a-b**)

4.1.3 Results (Experiment 1):

There was no difference between Test1 and Test2 (by using Metal wire clipped or Pogo pin connection). The basic electrical circuits both had excellent response ($SNR_{average} \approx 80dB$) in the noise analysis when apply different voltage levels vary from 0 to 5V, and both measurements got a high average performance during the test. In a brief conclusion, using 'pogo pin' to transmit electrical signal has no effects to produce noises and works as well as a metal wire. *

*Reason for setting Expeiment1: after Experiment 1, the 'pogo pin' could be designed in the textile-based circuits to find the differences in motion artefacts (in Experiement2).

4.2 Experiment 2: Characterised SNR results for the textile-based circuits with robustness checking

4.2.1 Introduction (Experiment 2):

Experiment date: 13th.Nov - 18th.Nov.2015
This experiment was tested by basing on a 'textile sensing window' to replace the 'variable resistance' in experiment 1. The overall resistance come through the circuits would be changeable when a pressure was applied on the textile sensing window. In this case, the textile sensing window acted as a variable resistance with different pressures applied, the voltage on the oscilloscope would be recorded at different levels. There are two individual tests in this experiment, one is 'static test' and the other is 'dynamic test'. **Static test** aims to ensure the 'pogo pin' is working on the textile-based circuits and the **dynamic test** aims to get the results of how 'pogo pin' could produce better performance in a robustness test when this tested artefact is moving. In each static and dynamic test, put test 1 and test 2 at the same time to get compared results.

4.2.2 Method (Experiment 2):

For the **static test**, the circuits were put on the plate table and a **steady** normal force was given on the sensing window. The method to control the overall resistance was applying different forces on the textile sensing to get different level of voltages. The selection of the 'fixed resistance' was determined on the normal resistance produced through the textile sensing window. After a formal testing, this overall resistance come through the textile had a unit of 'kΩ' when applying a normal pressure by putting the human finger on the sensing window.

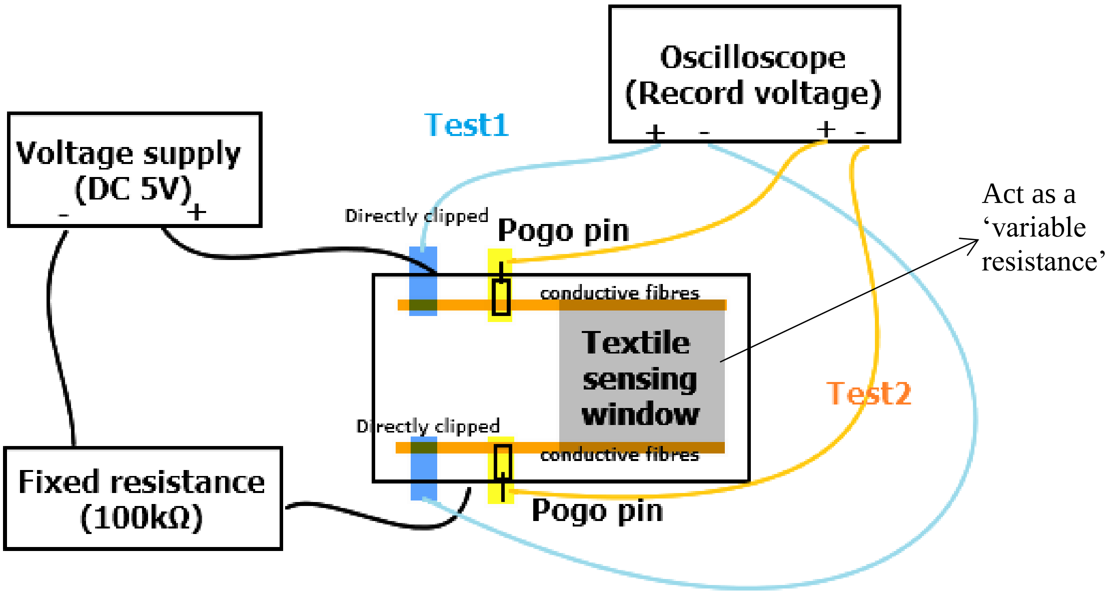


Figure 4.2.2: Tested textile-based circuits

For the **dynamic test**, the circuits were put on the plate table with some **disturbed** touching and a changeable normal force was given on the sensing window. Because this method was impossible to give a stable analysis state, several voltage levels were chosen to record without giving the specific pressures applied on the sensing window, further test would be taken in the next stages to confirm the specific relationship with the applied pressures and the outcome resistance (shown as **Experiment 6-** Relationship of applying specific pressures on textile sensing window with its outcome resistance).

4.2.3 Results (Experiment 2):

Static Test

Static test schematic diagram:

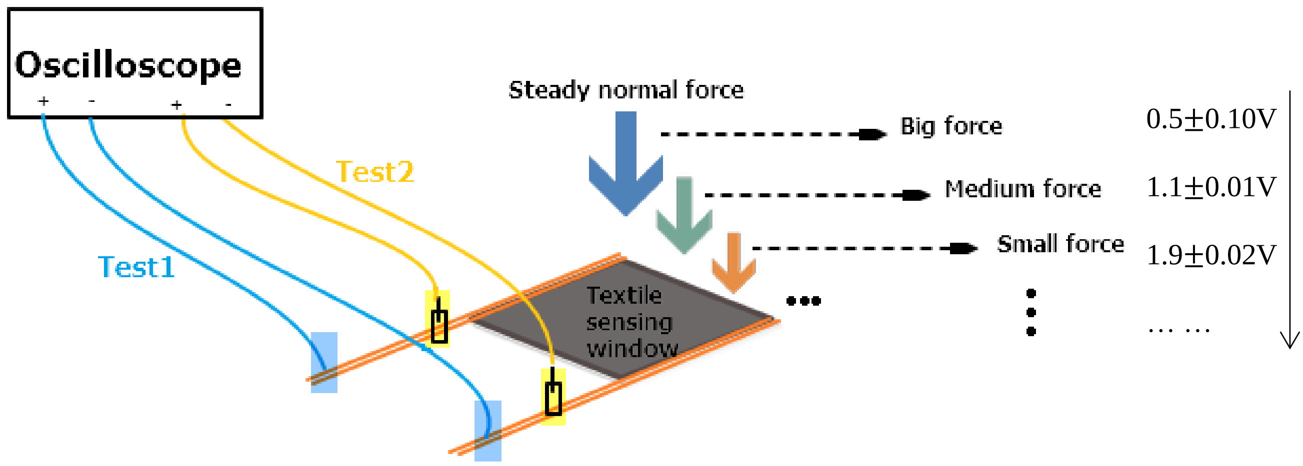


Figure 4.2.3a: schematic of static test with steady normal force

Figure 4.2.3a: Different levels of normal forces applied on the textile sensing window would produce different levels of pressure on the plane, so that the oscilloscope could record different levels of voltages as one-to-one correspondence, recorded each reading on the table as below then calculated signal to noise ratio (SNR) for every recorded voltages.

	Test1 Directly clipped		Test2 Pogo pin connection	
Voltage (V)	σ_1	$SNR_1(dB)$	σ_2	$SNR_2(dB)$
3.8±0.03	0.031005	41.8	0.024734	43.8
3.4±0.03	0.040207	38.1	0.032655	40.4
3.2±0.03	0.019143	44.5	0.015491	46.3
3.1±0.03	0.040625	37.6	0.028622	40.8
2.9±0.02	0.035704	38.2	0.019430	43.4
2.4±0.02	0.032439	37.4	0.025690	39.4
1.9±0.02	0.034273	34.9	0.013972	42.8
1.1±0.01	0.037235	29.8	0.032006	31.4
0.5±0.10	0.039844	12.4	0.029856	27.6
Average SNR	34.9(dB)		39.5(dB)	

Table 4.2.3a: static SNR test results for the textile-based electrical circuits

Table 4.2.3a: this table was recording the results of Signal to Noise Ratio (SNR) for textile-based electrical circuits in a static test. The value of $SNR_1(dB)$ and $SNR_2(dB)$ was calculated by the same method shown in the Experiment 1. From this table, 'pogo pin connection' performs **slightly** better than 'Directly clipped' on the textile-based circuits (39.5dB > 34.9dB).

The recorded value of Signal to Noise Ratio (SNR): A ratio of 10-15dB (decibels) is the accepted minimum to establish an unreliable connection; 16-24dB is usually considered poor; 25-40dB is good and a ratio of 41dB or higher is considered excellent.*[1]

*[1] Notes: this value was referenced from 'How to: Define Minimum SNR Values for Signal Coverage' tested by Jim Geier, the website information would be available from: http://www.wireless-nets.com/resources/tutorials/define_SNR_values.html

Dynamic Test

Dynamic test schematic diagram:

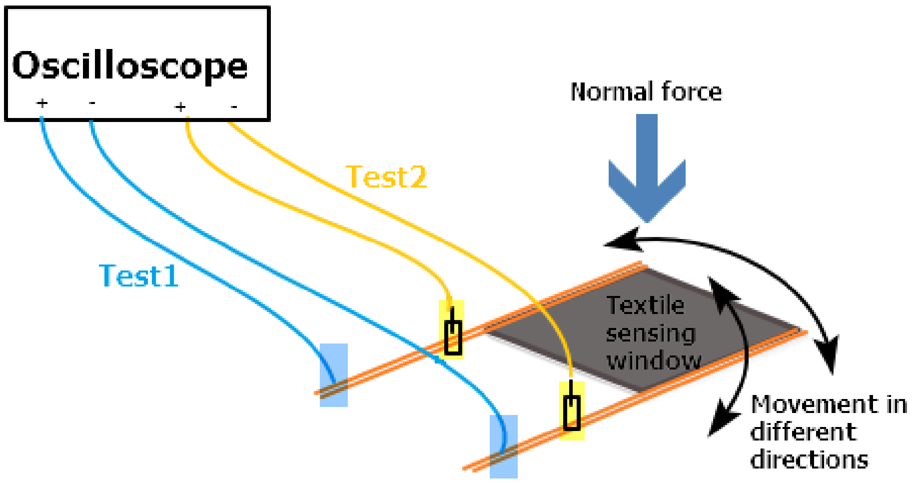


Figure 4.2.3b: schematic of dynamic test with movement

Figure 4.2.3b: The same measurement method was used as formal test, while applying the sufferable steady normal force on the textile sensing window. The plane was quivering in different directions together with the whole tested circuits (which were not shown in this figure). To keep the reading on the oscilloscope readable, then record the voltage reading from the oscilloscope for both test1 and test2 as the experiment done before to get a table as below.

	Test1 Directly clipped		Test2 Pogo pin connection	
Voltage (V)	σ_1	$SNR_1(dB)$	σ_2	$SNR_2(dB)$
3.7$\pm$0.20	0.050136	29.3	0.028432	42.4
3.4$\pm$0.20	0.050156	24.2	0.030545	41.4
3.2$\pm$0.12	0.053256	23.8	0.016441	45.3
3.1$\pm$0.15	0.050153	28.1	0.031422	40.6
2.8$\pm$0.14	0.065147	25.7	0.019532	40.0
2.4$\pm$0.14	0.051899	21.2	0.024580	39.3
1.9$\pm$0.15	0.074412	28.3	0.034893	35.1
1.1$\pm$0.16	0.064865	19.8	0.028021	30.4
0.5$\pm$0.10	0.061586	9.2	0.031843	26.3
Average SNR	23.3(dB)		37.9(dB)	

Table 4.2.3b: Dynamic SNR test results for the textile-based electrical circuits

Table 4.2.3b: the results of dynamic test shows that the 'pogo pin connection' performs **much** better than 'directly clipped' when the tested sensing window was disturbed by some movement in different directions (37.9dB > 23.3dB).

In summary, the static test shown that with the help of using 'pogo pin' connected from the textile fabric, the received signal performed better than a directly clip but the difference is not significant. While in the dynamic test, connection with 'pogo pin' had a significant improvement to enhance the robustness on the tested sample. Mentioned that the results in Experiment 1 ($SNR_{average} \approx 80dB$) would be an excellent signal, the average SNR results in Experiment 2 was lower. But it was quite tolerance because using a textile based circuits instead of the electronic components.

4.3 Experiment 3: Checking pressure response for the textile sensing window with different types of tapping

4.3.1 Introduction (Experiment 3):

Experiment date: 24th. Nov - 5th. Dec. 2015
In order to investigate the sensitive of the pressure detecting function on the textile sensing window, and transfer the pressure signal into a voltage signal so that this action could be visibly on the oscilloscope. The connecter was designed to meet a situation: different forces of tapping on the sensing window could produce instantaneous changing on the output voltage level. By this way, the behaviour of the tapping could be deduced from the output voltage diagrams.

4.3.2 Method (Experiment 3):

To do this experiment, the tested sample was placed on the flat table. The schematic could be shown as **Figure 4.3.2**. The electrical circuits was designed in Section 3, the main function of this circuits was translate changeable resistance value into voltage signal. By tapping different forces on the textile sensing window, and record the output signal in a period of time. The output voltage without any pressures was fixed around 4.0 volts. After receiving a force of tapping on the sensing window, the output voltage would reduce to a specific level, and the amount of reducing has direct proportion with the forces applied by human finger.

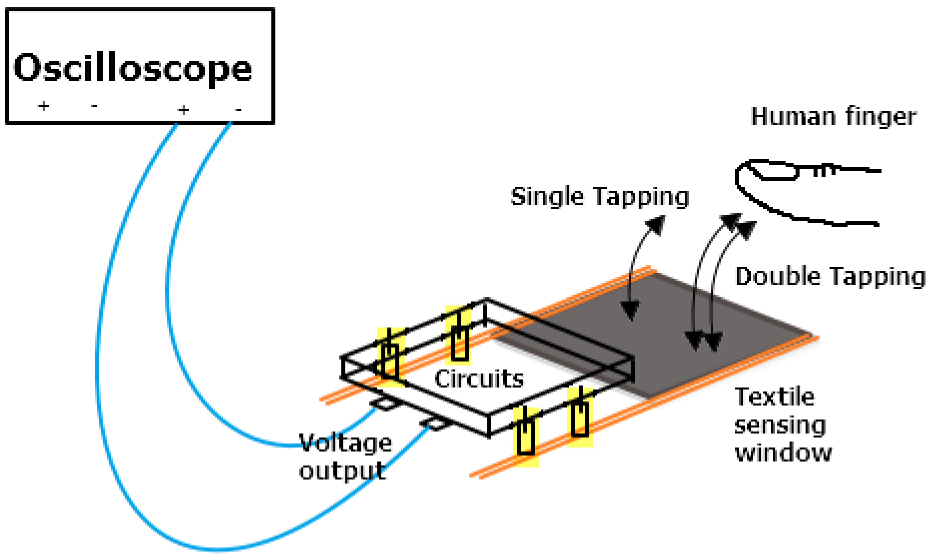


Figure 4.3.2: schematic of single and double tapping experiment

There are 3 types of tapping recorded in this experiment:

Single tapping response ---------------- **Figure 4.3.3a**
Double tapping response ---------------- **Figure 4.3.3b**
Step tapping response ----------------- **Figure 4.3.3d**

The schematic of single and double tapping were shown as above, the press and release of the human finger was completed in a short time. While the step tapping would keep the force applied on the sensing window to remain sometime before release, the schematic was shown as **Figure 4.3.3c**.

4.3.3 Results (Experiment 3):

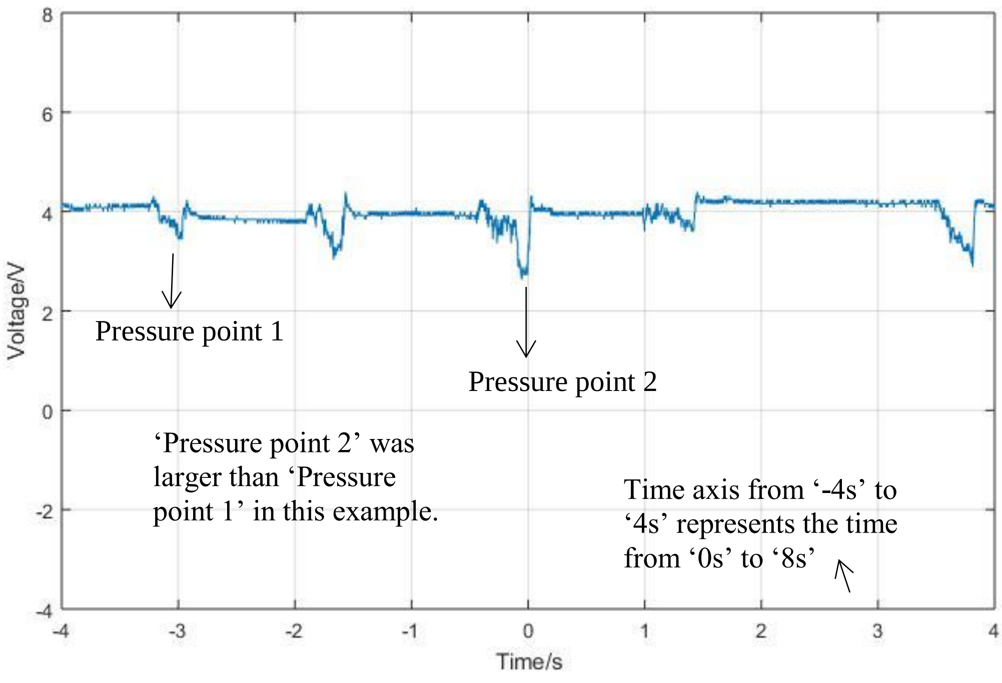


Figure 4.3.3a: Single tapping response

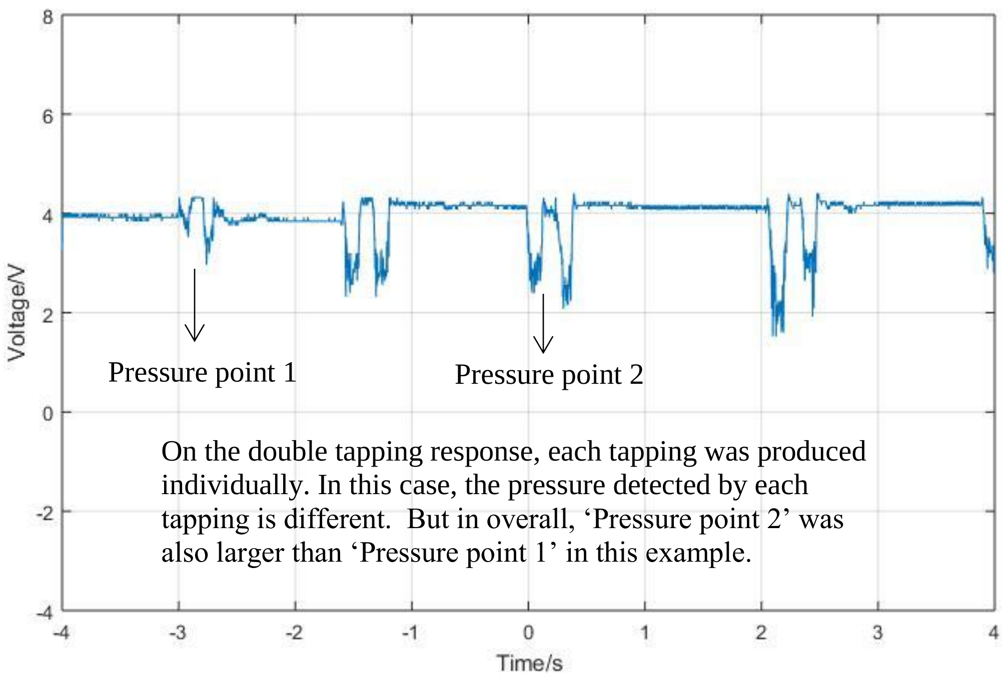


Figure 4.3.3b: Double tapping response

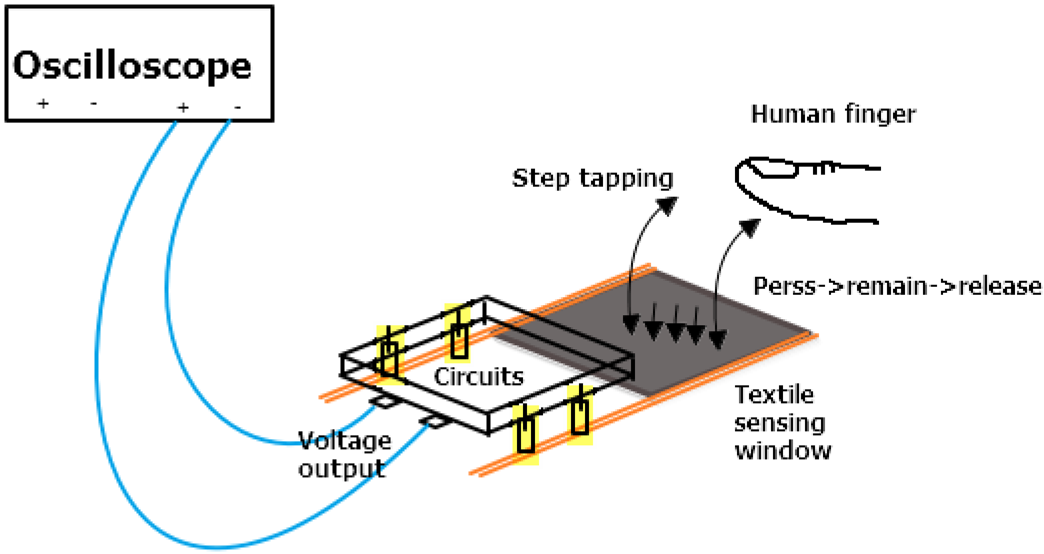


Figure 4.3.3c: schematic of step tapping experiment

Figure 4.3.3c: This type of tapping aims to find the response of a steady force applied on the textile sensing window could produce a maintained output voltage level. The output result was shown as the figure below. Each step was provided with a tolerance steady force produced by the human finger.

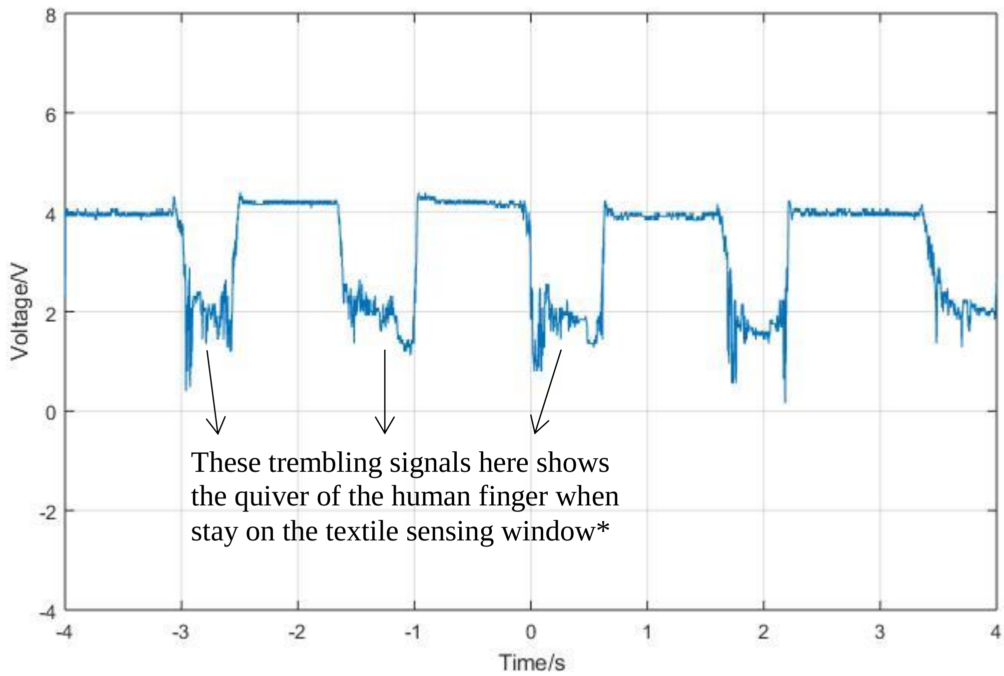


Figure 4.3.3d: Step tapping response

Figure 4.3.3d: For the reason that the force controlled by the human finger could not get a perfect steady state when it was put on the plane. The 'trembling signal' produced above perfectly verified this phenomenon on the human fingers.

*Discussion: in this experiment, tapping with a finger would produce a such 'trembling signal', in the future design, this problem could be solved by replace the human finger with an automotive piston, so that the pressures applied in each tapping would be equality and much easier to see the tapping responses.

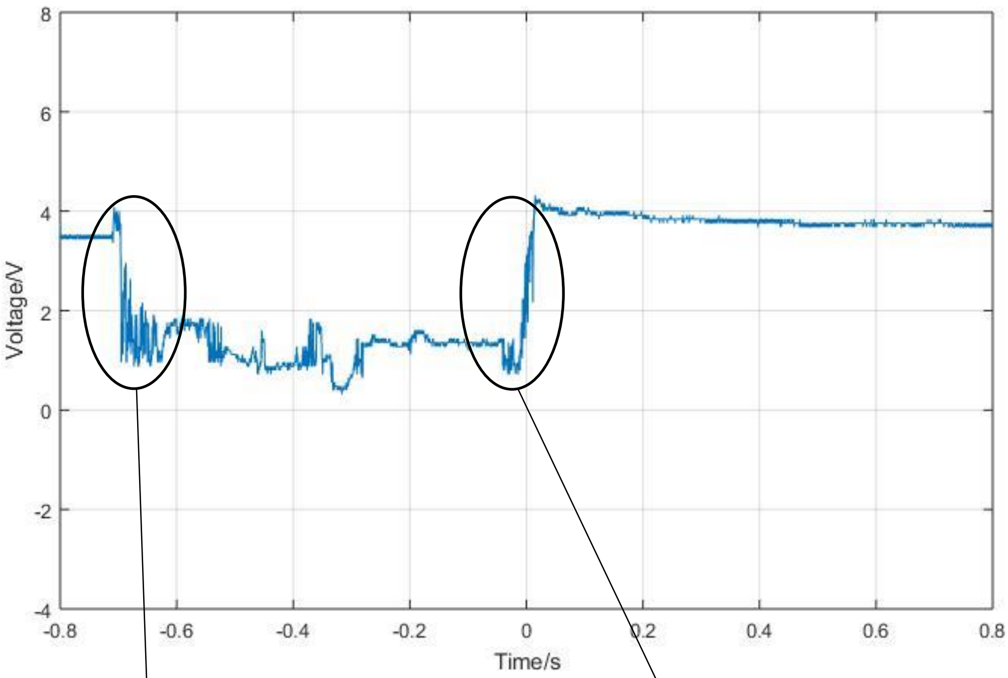


Figure 4.3.3e: Step response (Zoom in)

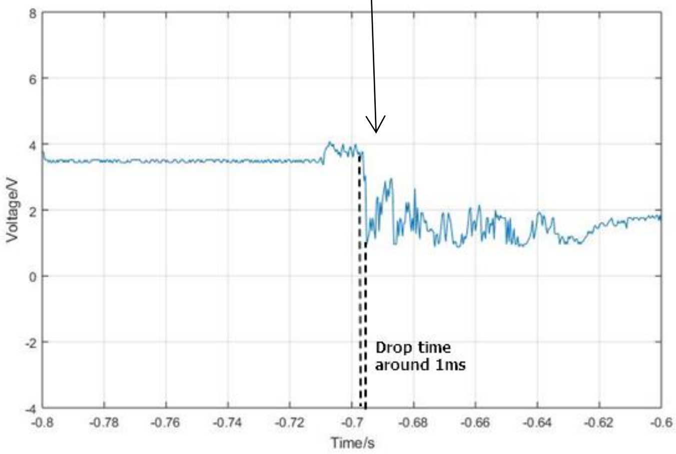


Figure 4.3.3f: Tapping response (Drop time)

Figure 4.3.3g: Tapping response (Rise time)

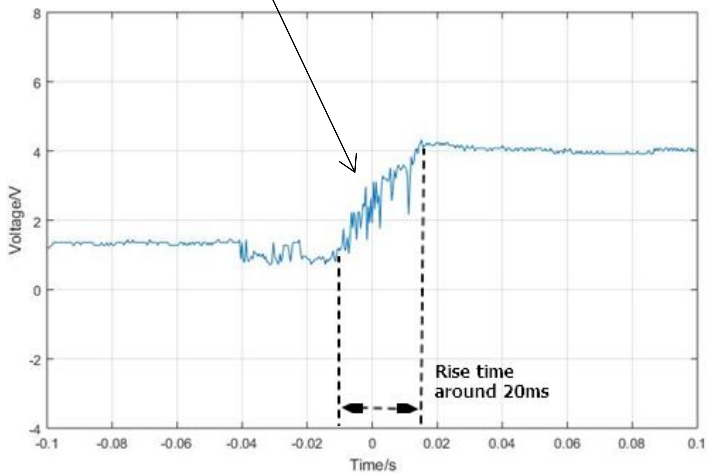


Figure 4.3.3e-g: In order to see more clearly for the step taping response, one of the example steps was zoomed in to analysis the detail behaviours of this specific step. From the results above, the finger's drop time (press) was less than 1ms and the rise time (release) was around 20ms. This was just one example of tapping response time, the analysis could be done several times to get an average results. The average results would indicate the human behaviour in a step tapping response.

In summary, the textile sensing window was sensitive for detecting different pressures. With the help of designed circuits, this kind of detecting could be easily performed with the changing of the voltage level produced from the designed circuit. By analysing the outputs diagrams, the behaviours of each kind of tapping done by human fingers could be deduced directly from the voltage output diagrams.

4.4 Experiment 4: Comparing the transmission efficiency of designed optical connector with commercial SMA connector

4.4.1 Introduction (Experiment 4):

Experiment date: 28th. Jan - 8th. Feb. 2016

The main purpose of this experiment is to make sure the designed connector could achieve an acceptable high level of transmission efficiency. This experiment recorded the data of measuring the transmission efficiency of normal SMA*[1] connector and comparing the results with designed optical connector. All the experiments would be settled in the same environment and measured in the same room temperature. Note that the connecting surface of tested optical fibres was polished in order to get a better transmission results. Two points must be cared before the test:

1. Ensure all the environmental light has been block to the sensing window of the power meter.
2. Keep the distance (D) between the measured optical fibre surface and the sensing window of the power meter to be the same level.

4.4.2 Method (Experiment 4):

The schematic of the experiment:

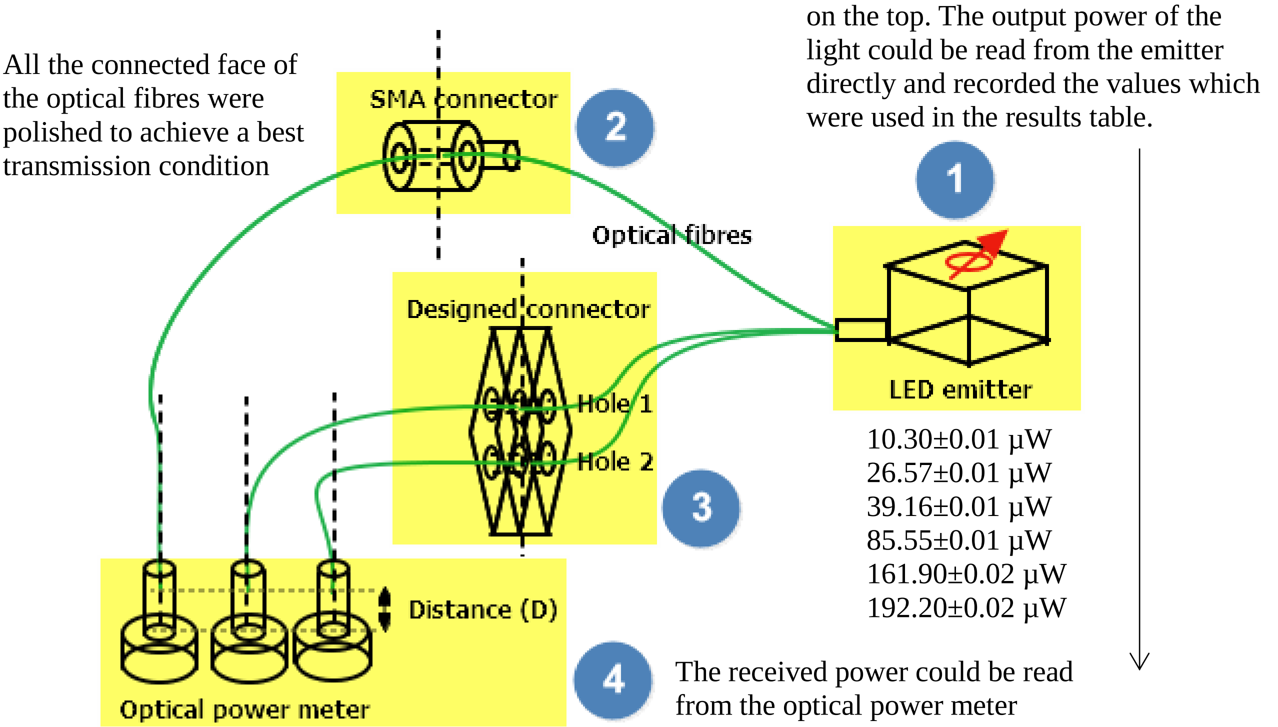


Figure 4.4.2: schematic of measuring transmission efficiency of optical connectors

Figure 4.4.2:

1. LED emitter: used LED emitter in this experiment could produce a green light photo-source with a wavelength of 530nm. Type name was 'M530F1', fibre-coupled LED.
2. SMA connector: selected SMA used in this experiment was a standard type from the commercial market, which was one of the most efficiency optical connectors on the modern market. The radius of the hole on the tested SMA was 0.5mm fit with the optical fibres (radius: 0.5mm).
3. Designed optical connector: twos hole were tested in this experiment. Each hole has little fabrication differences but with almost the same quality. Radius of the hole is 0.5mm.
4. Optical power meter: There are three meters measure the received power at the same time which were set to receive the green light especially (set received wavelength= 530 nm).

*[1]Notes: the datasheet of SMA connector could be found in: http://www.farnell.com/datasheets/1681616.pdf

4.4.3 Results (Experiment 4):

All the emitter power and received power by coming through SMA connector, designed connector hole-1and hole-2 were recorded at the same time. And the output power was come out from the same LED emitter to make sure the comparable of the following data. The transmission efficiency was calculated by the formula:

$$\text{Transmission efficiency} = \frac{\text{Received power}(\mu\text{W})}{\text{Emitter power }(\mu\text{W})}$$

SMA connector

Emitter power (μW)	Received power(μW)	Transmission efficiency (%)
10.30±0.01	5.50±0.01	0.533980583
26.57±0.01	13.65±0.01	0.513737298
39.16±0.01	20.60±0.01	0.526046987
85.55±0.01	48.20±0.01	0.563413209
161.90±0.02	85.64±0.01	0.528968499
192.20±0.02	102.20±0.02	0.531737773
Average transmission efficiency (%)		**0.532980725**

Table4.4.3a: transmission efficiency of one-SMA connector

Designed optical connector

Emitter power (μW)	Received power(μW)	Transmission efficiency (%)
10.30±0.01	4.59±0.01	0.445631068
26.57±0.01	10.69±0.01	0.402333459
39.16±0.01	16.27±0.01	0.415474974
85.55±0.01	38.60±0.01	0.45119813
161.90±0.02	67.52±0.01	0.41704756
192.20±0.02	80.54±0.01	0.419042664
Average transmission efficiency (%)		**0.425121309**

Table4.4.3b: transmission efficiency of one-designed connector (hole-1)

Emitter power (μW)	Received power(μW)	Transmission efficiency (%)
10.30±0.01	5.20±0.01	0.504854369
26.57±0.01	12.13±0.01	0.456529921
39.16±0.01	15.24±0.01	0.389172625
85.55±0.01	34.82±0.01	0.407013442
161.90±0.02	58.26±0.01	0.35985176
192.20±0.02	69.55±0.01	0.361862643
Average transmission efficiency (%)		**0.413214127**

Table4.4.3c: transmission efficiency of one-designed connector (hole-2)

Table4.4.3a-c:
SMA connector as one of the most efficient optical connectors used in optical lab but had a disadvantage of difficult to detach, if the efficiency of the designed connector could compare with a SMA connector even in a movement artefact, then the design would be much valuable. From the results above, the optical transmission efficiency of the SMA connector could achieve higher than 50%, and the designed optical connector could achieve a relatively high enough efficiency which was higher than 40% both for hole-1 and hole-2. Efficiency higher than 40% was a quite acceptable result on a more easily detachable connector.

4.5 Experiment 5: Optical power transmission properties with different x, y and z distance:

4.5.1 Introduction (Experiment 5):

Experiment date: 18th. Feb - 25th. Feb. 2016

Two optical fibre could connected with face to face linking to transmit the optical power, one is 'emitting optical fibre' which was directly connected to a light emitter, the other was 'receiving optical fibre' which could collect the optical power from the emitting fibre (See schematic below). While the different position of the 'receiving optical fibre' would affect the power transmission efficiency from one fibre to another. This experiment was designed to investigate the transmission property of the face to face linking of two fibres with different connection distance in 3D directions.

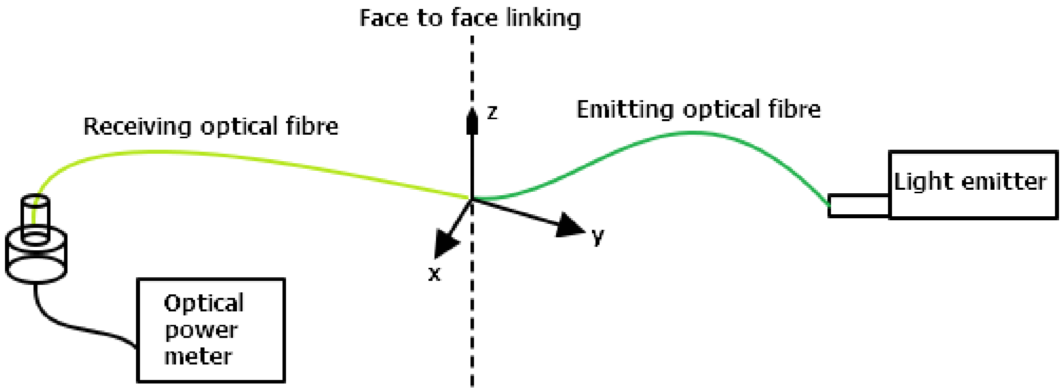
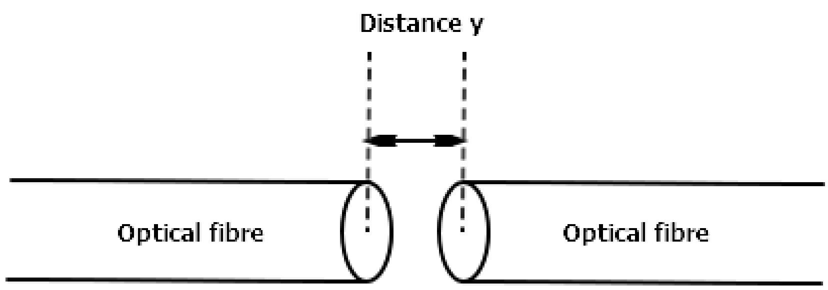


Figure 4.5.1: schematic of connecting two optical fibres

4.5.2 Method (Experiment 5):

Face to face linking of two optical fibres in 3D direction:



Notes that the 'distance x' and 'distance z' have the same property when they were investigated because the cross section of the optical fibre was a completely symmetric circle. The 'distance x' was selected in this experiment.

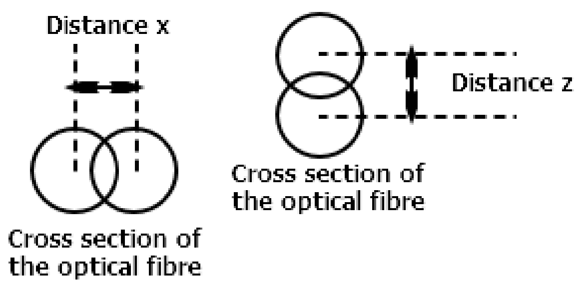


Figure 4.5.2: schematic of distances of x, y and z

The detailed methods to get each transmission result were written in the corresponding diagrams below. (See **Figure 4.5.3a-d**)

4.5.3 Results (Experiment 5):

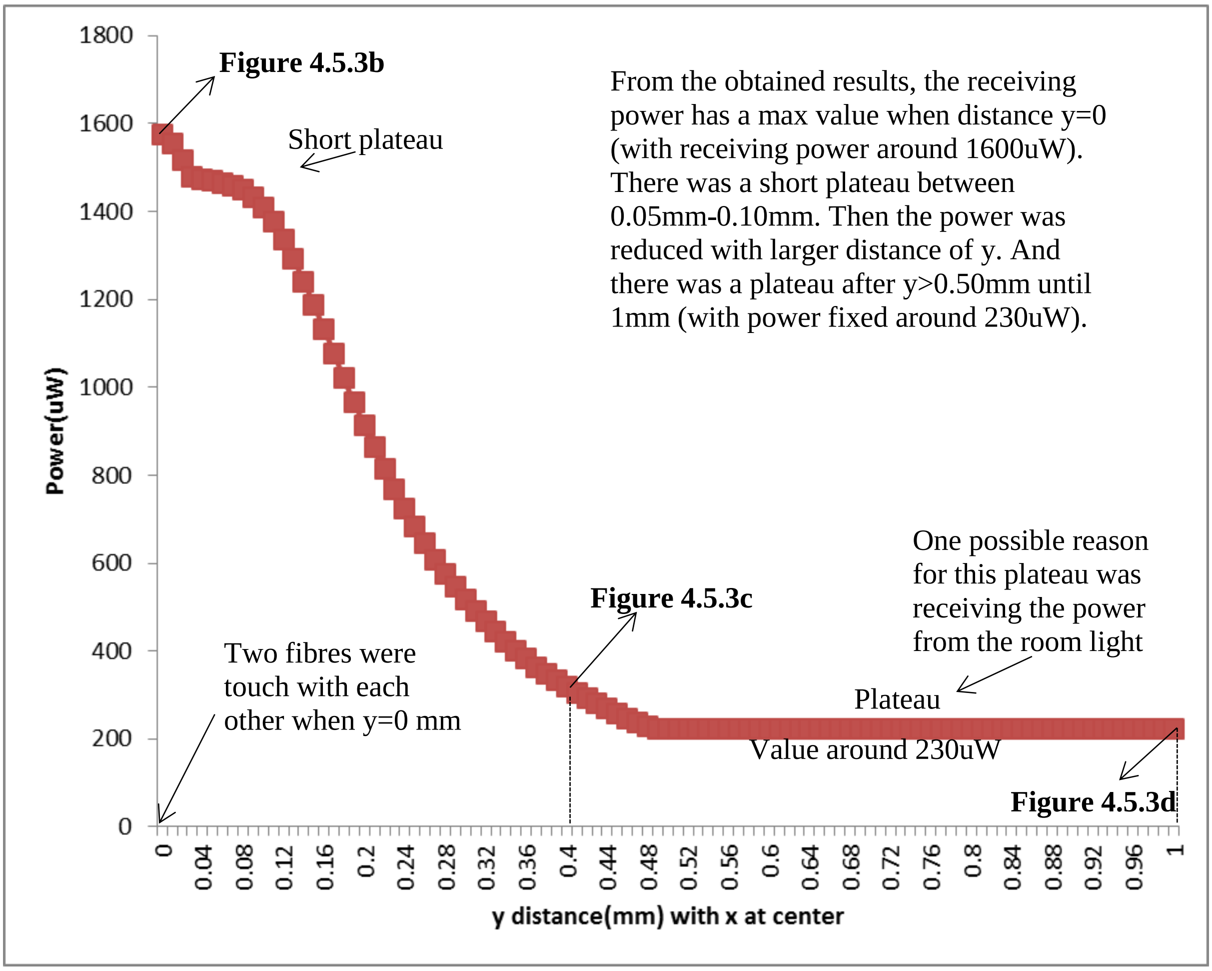


Figure 4.5.3a: power transmission efficiency with different y distance

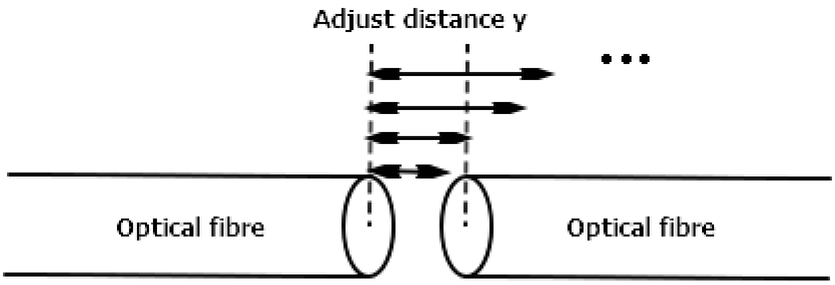


Figure 4.5.3a': schematic of changing value of distance y

Figure 4.5.3a: The distance was adjusted by a Nano-meter machine (the machine picture could be found in the Appendix- Experiment 5, the name is 'NanoMax-Ts' designed by THORLABS) which was connected with a computer. The value of the each measurement was read from the computer. To obtain this results, the distance of x and z were supposed to be fixed. Because the tested optical fibre has a ridius of 0.5mm. The adjustion of the distance was setted to 0.01mm (10um) for each step to get a recoring data. From y=0 to y=1mm with 0.01mm step setting.

The experiment for x and z distance could selected formt each step for the y distance above, for example, keep y=0mm with changing distance x to get **Figure 4.5.3b**, keep y=0.4mm with changing distance x to get **Figure 4.5.3c**, keep y=1.0mm with changing distance x to get **Figure 4.5.3d**.

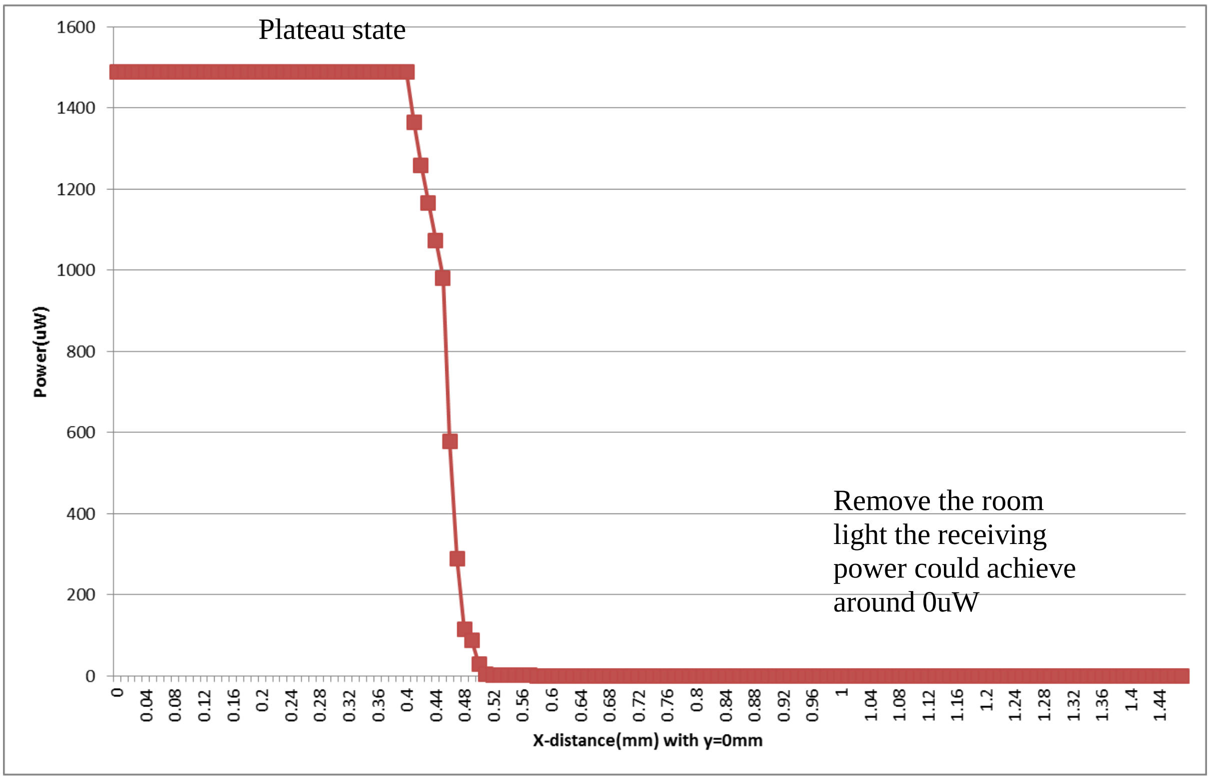


Figure 4.5.3b: power transmission efficiency with y distance = 0mm (touch together)

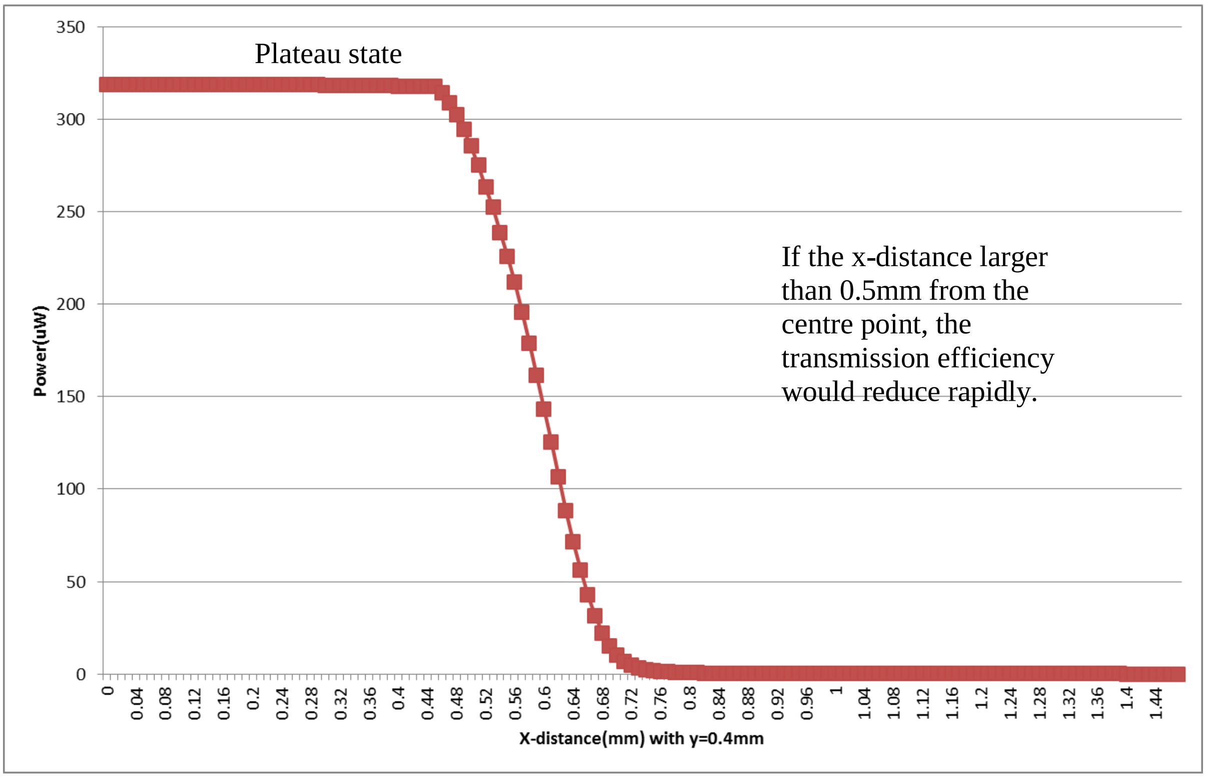


Figure 4.5.3c: power transmission efficiency with y distance = 0.4mm

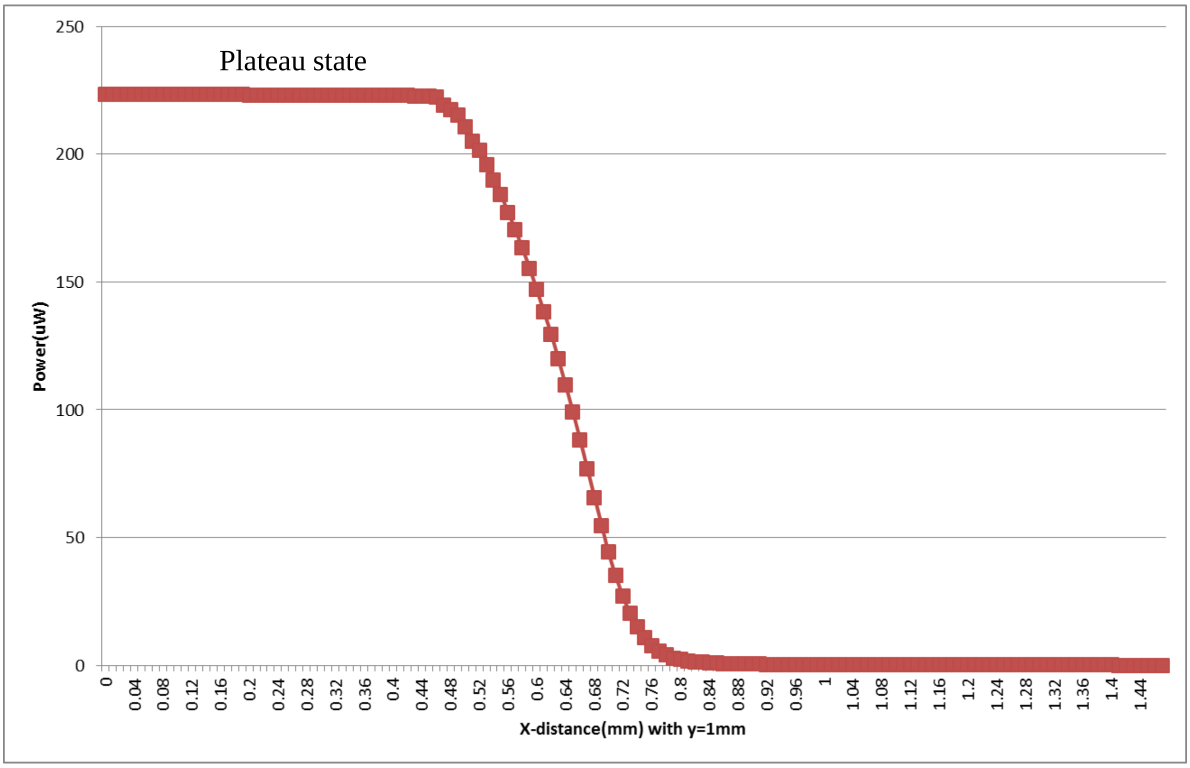
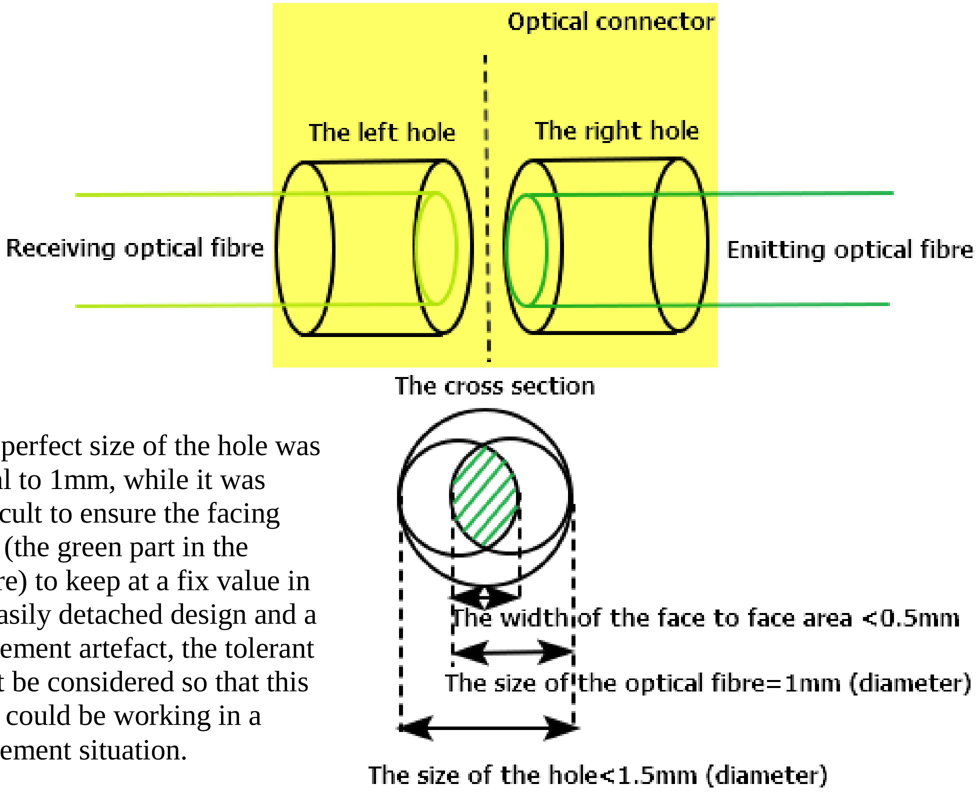


Figure 4.5.3d: power transmission efficiency with y distance = 1mm

In summary, the maximum tolerant size of the designed hole was supposed to be less than 1.5mm (diameter) to fit a 'plateau state' above to meet the condition of transmitting with a max efficiency.



The perfect size of the hole was equal to 1mm, while it was difficult to ensure the facing area (the green part in the figure) to keep at a fix value in an easily detached design and a movement artefact, the tolerant most be considered so that this hole could be working in a movement situation.

Figure 4.5.3e: Maximum size of the designed hole

4.6 Experiment 6: Relationship of applying specific pressures on textile sensing window with its outcome resistance

4.6.1 Introduction (Experiment 6):

Experiment date: 1th. Mar - 9th. Mar. 2016
This experiment aims to record the data of measuring the resistance when given a specific pressure over a unit area on textile sensing window. There were 8 samples of weights and one platform made particularly to do this experiment. The weights were made by steel from L2 laboratory in the University of Nottingham, and the platform was made by hand using some wooden and rubber (see the figure as below). The changing of the weight would change the pressure put on the textile sensing window, and then change the overall resistance come through the textile. The changing of the resistance was the main reason for changing the output voltage from the designed circuit. By doing this experiment, the relationship between pressure and output resistance would be found in a specific relevance. Then by reading the output voltage from the designed circuit, the pressed weight would be deduced.

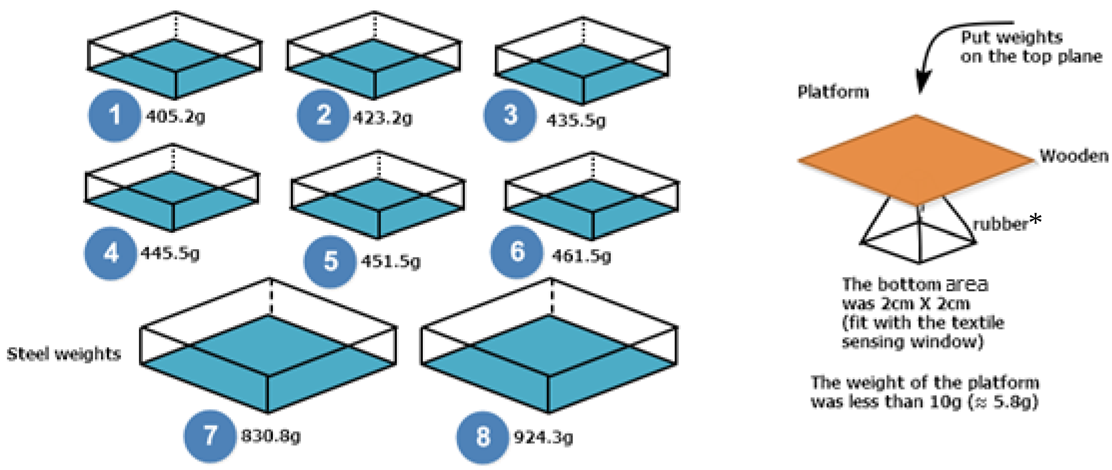


Figure 4.6.1: The 8 weights used in this experiment

*Notes: The reason for using the rubber pillar at the bottom of the platform was in order to make certain that the average pressures applied on the textile sensing window would be stressed uniformly.

4.6.2 Method (Experiment 6):

Put the textile sensing window on the flat table, ensure that the textile was in a ‘loosen state’ (which means that there was no pressed or tensile forces on the textile before the experiment). Use finger smoothly rub the textile could help the textile set in a ‘loosen state’. For the reason that the textile was easily having a deform problem when applied a force or weights on it, there were at least 10 individual tests to record a tolerant average value of each measurements. Notice that in each test and each step to add a weight on the textile, make sure the textile didn’t suffer a massive deform so that the textile could work in a normal condition.
The schematic of the experiment was shown as **Figure 4.6.2**, using a multi-meter to measure the resistance come through the textile sensing window. Notes the unit of the resistance was normally in a level of kΩ for this tested textile. The original resistance (which was no any weights on the textile) was not recorded in the tests, because the value of the original resistance had a large range from 2000 to 4000 kΩ. However, this original value had no effects on measuring the relationship between the weights and resistance. The tests were repeatedly doing in an identical environment to ensure the comparable of each test and combine together to draw the relationship diagrams.

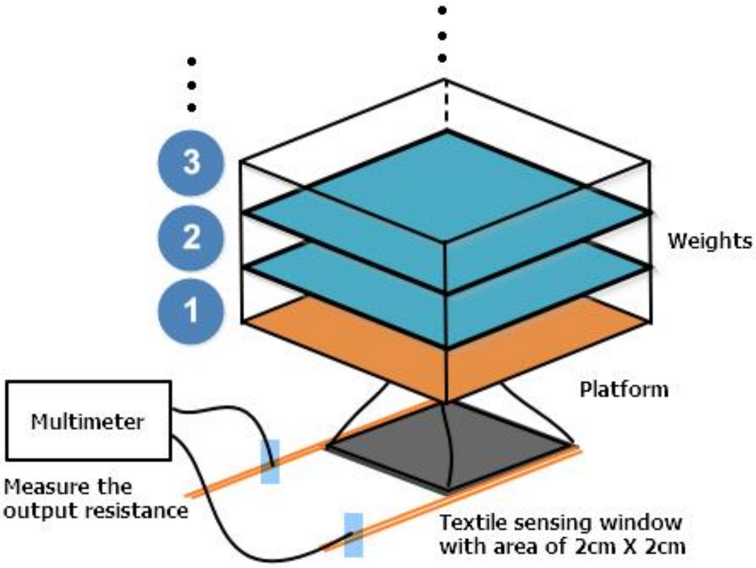


Figure 4.6.2: Schematic of adding weight on the platform

4.6.3 Results (Experiment 6):

The way to calculate pressure in per unit:

$$Pressure(N/cm^2) = \frac{Total\ weight(g) \times 9.8\ (N/kg)/1000}{textile\ sening\ window\ area\ (2\ cm\ \times 2cm)}$$

The total weights could be added by 1-8 samples of steel weight. The area of the textile sensing window was fixed. For example,
Put sample 1 on the platform:

$$Pressure(N/cm^2) = \frac{405.2 \times 9.8}{1000 \times 2 \times 2} = 0.99\ (N/cm^2)$$

Add sample 2 on the sample 1:

$$Pressure(N/cm^2) = \frac{(405.2 + 423.2) \times 9.8}{1000 \times 2 \times 2} = 2.03\ (N/cm^2)$$

Add sample 3 on the sample 2:

$$Pressure(N/cm^2) = \frac{(405.2 + 423.2 + 435.5) \times 9.8}{1000 \times 2 \times 2} = 3.10\ (N/cm^2)$$

… …

Pressure (N/cm^2)	10 individual tests output resistance through the textile sensing window (kΩ)									
	Test1	Test2	Test3	Test4	Test5	Test6	Test7	Test8	Test9	Test10
0.99	786	1100	470	670	1500	500	380	840	800	290
2.03	192	178	130	150	189	104	158	70	240	50
3.10	35	56	15	65.7	46	18.1	28	27	50	15
4.19	8	16	6	8	16.3	4.45	16	8.3	15	6
5.29	4	8	3.8	4.8	4.2	4	6	5.1	6	2
6.42	1.5	1.3	1.6	2.2	2.2	2.33	2.3	3.5	1.7	1
8.46	0.8	0.9	1.1	1.03	0.96	1.2	1.7	2.3	0.8	0.5
10.72	0.5	0.56	0.55	0.53	0.52	0.52	0.6	0.58	0.4	0.3

Table 4.6.3a: Pressure test on textile sensing window ($2 \times 2\ cm^2$)

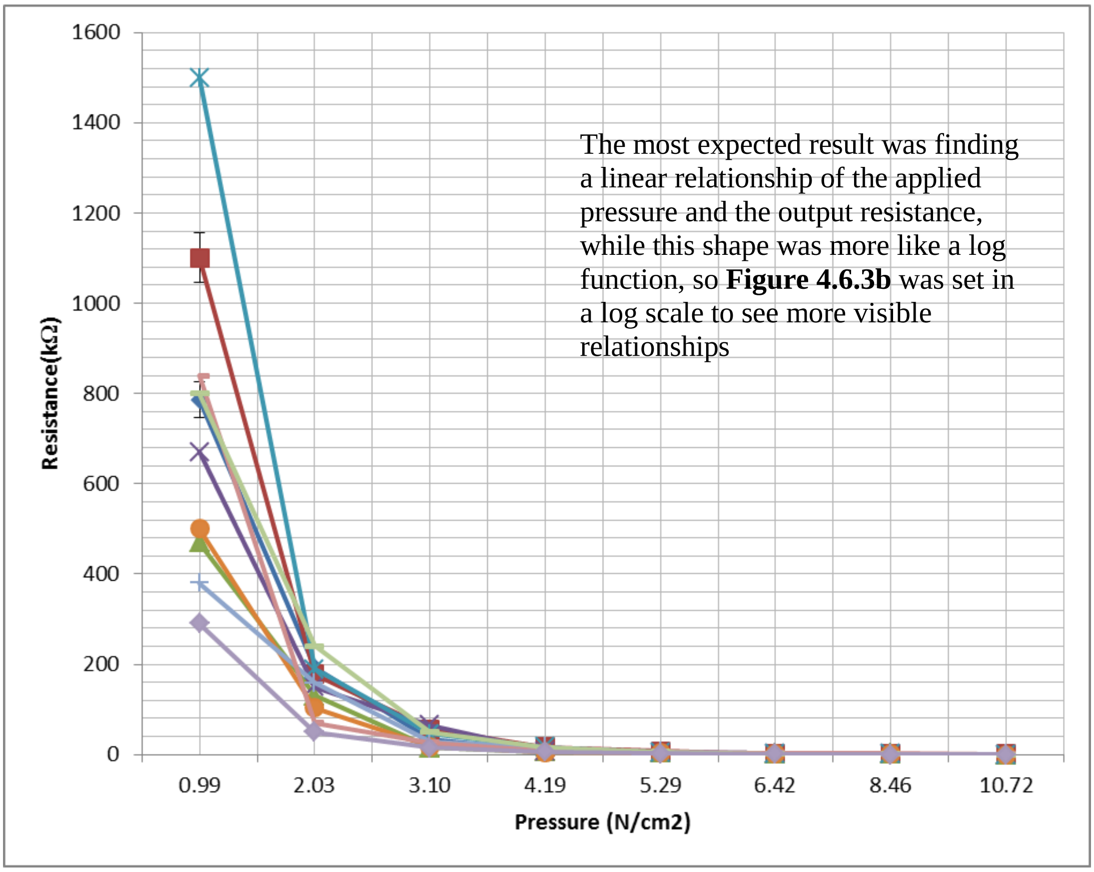


Figure 4.6.3a: Pressure test on textile sensing window ($2 \times 2\ cm^2$) - normal scale

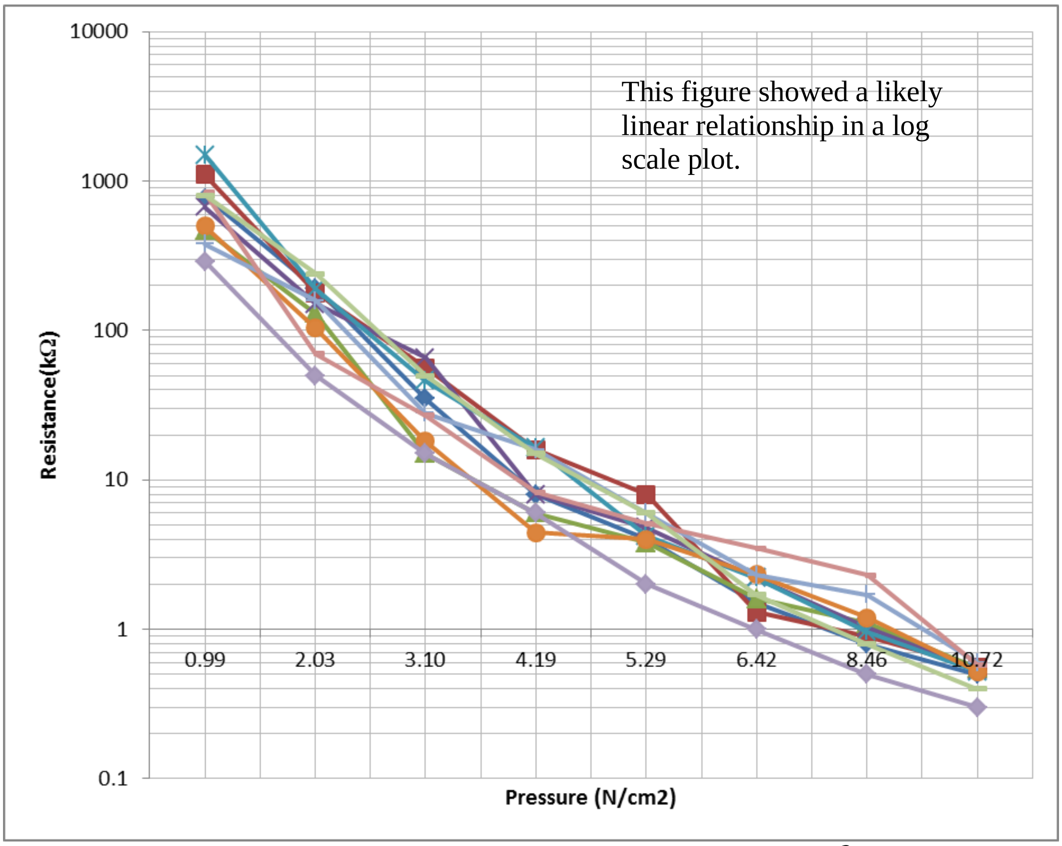


Figure 4.6.3b: Pressure test on textile sensing window ($2 \times 2\ cm^2$) – log scale

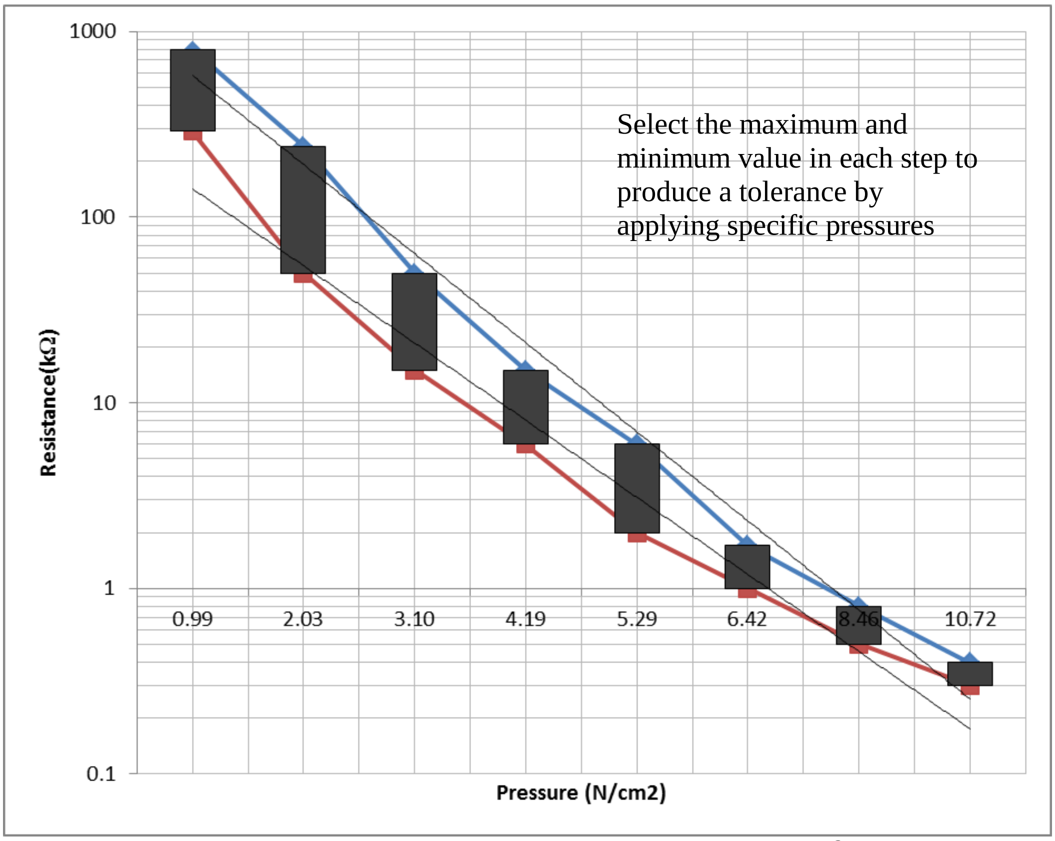


Figure 4.6.3c: Pressure test on textile sensing window ($2 \times 2\ cm^2$) – tolerance

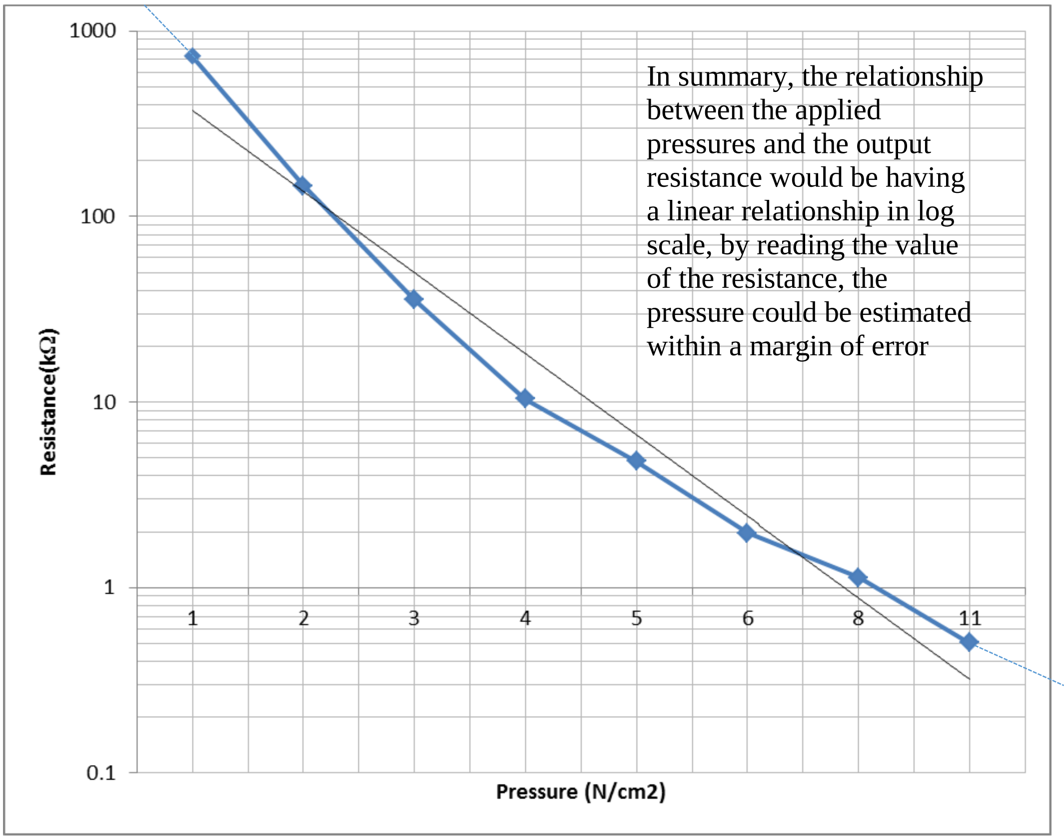


Figure 4.6.3d: Average results Pressure test on textile sensing window ($2 \times 2\ cm^2$) – average value

4.7 Experiment 7: Measuring heart rate by optical fibres

4.7.1 Introduction (Experiment 7):

Experiment date: 10th. Mar - 18th. Mar. 2016
This experiment was designed to measure the heart rate from the human finger using two lines of optical fibres. The main working principle of the measurement was detecting the varying optical power collected form the receiving fibre. This varying optical power was transfer to a varying current signal by photo diode in the detector circuit. Then the current signal would change into a voltage signal which could be displayed on the oscilloscope screen. The oscilloscope was connected to a computer, and the final figure in the results was produced by the MATLAB software. By reading the information from the results, the heart rate could be estimated in a very accurate way.

4.7.2 Method (Experiment 7):

There were four main parts in this system (see **Figure 4.7.2a**):
1. LED emitter: the optical power produced by the LED emitter could be adjusted.
2. Optical connector: two holes were designed to transmit optical power between separate fibres, one for emitting, and the other for receiving.
3. Heart rate measuring window: the detail schematic was shown as **Figure 4.7.2b**, the face of the optical fibre exposed on the measuring window had been polished and treated as a cant to give a larger facing area on the top.
4. Optical detector circuit: this circuit was designed in section 3 and the main function of the circuit was transferring the optical power into an electrical signal which could be measured by the oscilloscope.

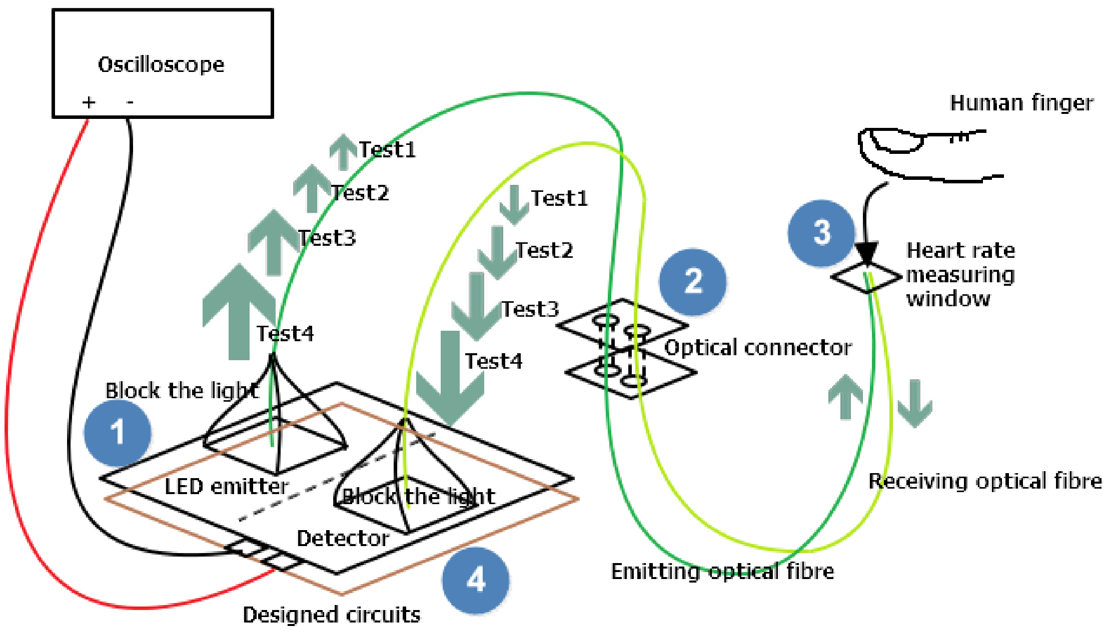
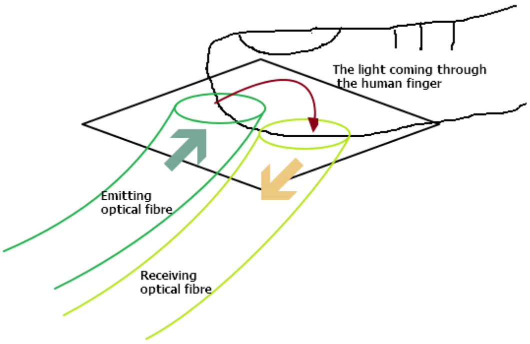


Figure 4.7.2a: Schematic of measuring heart rate with different optical emitting power



The received power from the emitting light would be affected by the blood flow through the human finger, which was pumped by the human heart. Recording the difference of the receiving power could measure the human heart rate. [20]

Figure 4.7.2b: Schematic of heart rate measuring window

4.7.3 Results (Experiment 7):

	Test1	Test2	Test3	Test4	Heart rate measured by heart monitor
Optical power (uW)	300	600	900	1200	
Average voltage (V)	3.58	3.47	3.42	3.34	
Heart rate (bits/min)	≈92	≈92	≈92	≈92	92*

Table 4.7.3: output voltage of heart rate with different optical power

*[1] Notes: the heart rate monitoring was measured by a heart monitor by many times to verify the accuracy. The test was measured at the same time by putting another finger on the optical fibres.

Calculation of the heart rate from the signals:

$$\text{Heart rate} = \frac{Number\ of\ the\ pecks}{16\ seconds} \times 60\ seconds/min = \frac{24.5}{16} \times 60 \approx 92\ bits/min$$

Compare the calculated results with the heart rate measured by heart monitor, the heart rate measured by using optical fires were accurate. So the designed circuit was working for detecting the heart rate.

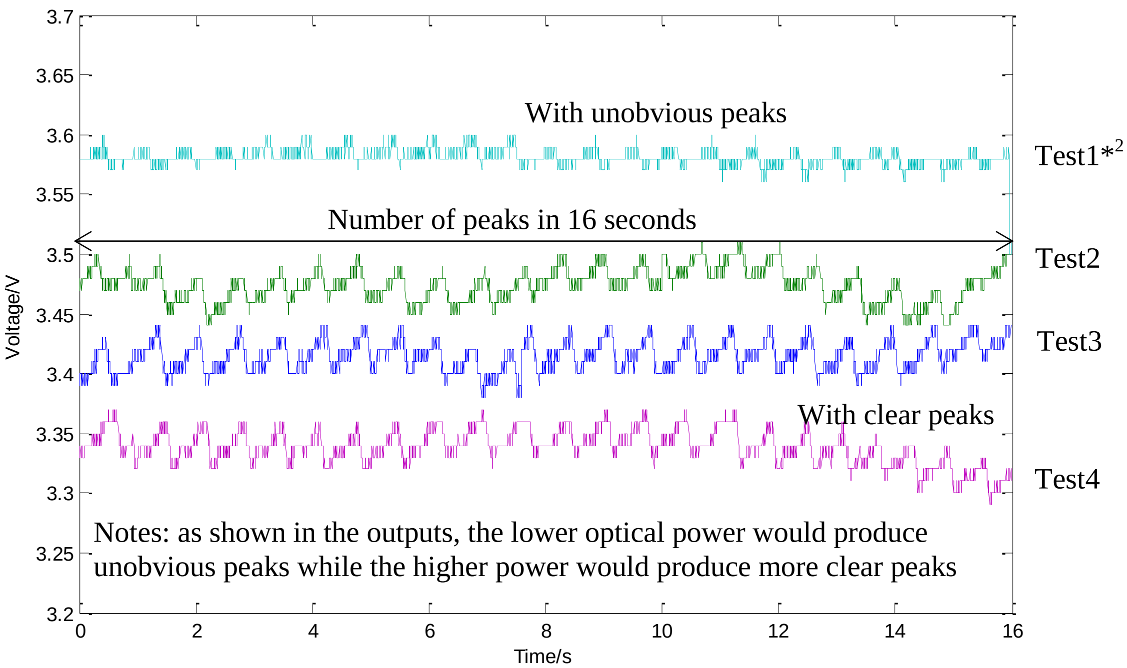


Figure 4.7.3: output voltage of heart rate with different optical power

*[2] **Discussion**: it could be found that the results of Test1 worked as the data was so noisy, one of the possible reasons was that, the optical power provided by the light emitter was not strong enough. So that the feedback signal from the tested human finger was weak and not easy to get an obvious changing. One method could be used to solve this problem was adjusting a larger amplifier factor in the amplifier circuits.

4.8 Experiment 8: Results for pressure test together with heart rate measuring on textile sensing window

4.8.1 Introduction (Experiment 8):

Experiment date: 20th. Mar - 30th. Mar. 2016

This experiment was a final test for combination of the electrical and optical connection of the designed product. The final designed product expected to measure the pressure and the heart rate by putting the human finger on the textile sensing window. The pressure signal was transferred by the electrical connection into a steady DC voltage signal. And the heart rate signal was transferred by the optical connection into a quivering voltage signal. For the overall design, the electrical signal was easily transmitted through the 'pogo pin' clipped on the 'textile conductive line'. The optical signal was transmitted through the combined connector, and then fed into the optical detecting circuits (see **Figure 4.8.2**).

4.8.2 Method (Experiment 8):

This experiment combined the experiment 6 and experiment 7 together. The designed product was placed on the flat table, in order to measure the pressure and heart rate at the meantime. The optical fibre was set on the textile sensing window. The detecting faces of the optical fibres were paralleling with the window plane. There were two detecting faces, one for emitting the optical power and the other for receiving. Both pressure signal and heart rate signal would be transferred into voltage signal which could be shown on the oscilloscope. The electrical and optical connection was settled by the combined connector and both related to the designed circuits to analysis the final output signals.

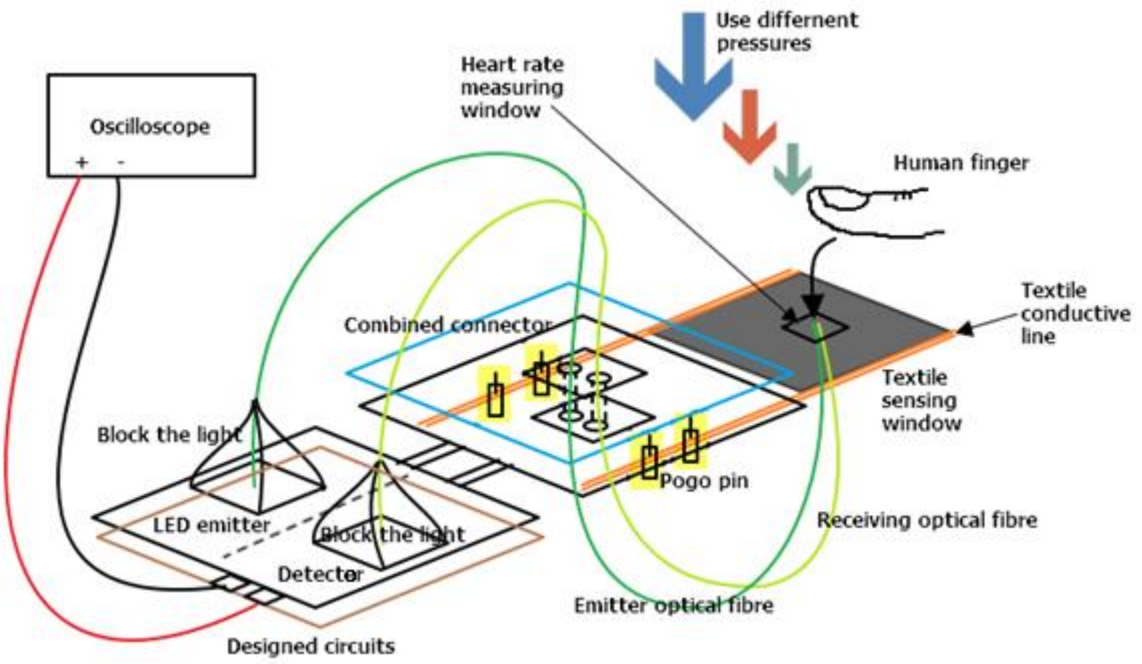


Figure 4.8.2: Schematic of measuring heart rate from a human finger with different pressures

By putting finger on the top of the 'heart rate measuring window' with different pressures, the output signal from the designed circuits were expected to produce different levels of voltage with the same frequency of the heart rate. There were ten different measurements tested in this experiment and recorded in a period of 40 seconds for per individual testing. In order to get a better comparable data, the tester would be in a normal mood and all the measurements had been coupled in **Figure 4.8.3a-e** (each figure contains two Heart rate signals (the **colourful line**) and two different outputs (The **dot lines**) represented a different level of pressures* applied).

*Notes: The method to estimate pressures would be according to the results in Experiment 6, and the example calculation had been shown in **'4.8.4: The way to estimate the pressures applied on the sensing window'**.

4.8.3 Results (Experiment 8):

There were 10 tests results shown in this experiment, which were measured in 5 days (2 tests in each single day). The user was using different levels of forces pressed on the sensing window. For the reason that the forces produced by the human finger affected by the natural trembling, the applied force couldn't be controlled with a fixed value, the pressures output voltage had been produced in a average value (see **dot lines**). However, it could be found that the small quiver of the signal was almost the same because the quivering frequency of the heart rate signal (see **colourful lines**) measured was similar from the same tester. There were more clear comparisons of the signals by selecting two of them from each day shown in the following figures (**Figure 4.8.3a-e**).

The heart rate for each example test could be estimated by finding the number of peaks within per minutes. In order to count the peaks number more accurately, every example comparison figure had been zoomed into a 10 seconds to find the peaks in this period of time. The heart rate results for each individual test had been shown as the table below.

	Day 1		Day 2		Day 3		Day 4		Day 5	
Test No.	Test1	Test2	Test3	Test4	Test5	Test6	Test7*	Test8	Test9	Test10
Peaks in 10 sec	14.5	14	15	14	15.5	14.5	/	14.5	14	15
Peaks in 40 sec	58	56	60	56	62	58	/	58	56	60
Heart rate (Beats/min)	87	84	90	84	93	87	/	87	84	90

Table 4.8.3a: output data of heart rate detected on the textile sensing window (5 Days)

For each individual test, the pressures applied on the sensing window would affect the contact resistances for the textile so that the average output voltage would stay in different values. The applied pressures had been recorded as tables below:

Day 1	Test 1	Test 2
Average voltage (V)	4.15	1.59
Resistances($k\Omega$)	488.24	46.63
Pressures(N/cm^2)	1.3	2.6

Day 2	Test 3	Test 4
Average voltage (V)	3.21	1.12
Resistances($k\Omega$)	179.33	28.87
Pressures(N/cm^2)	1.8	2.8

Day 3	Test 5	Test 6
Average voltage (V)	3.38	2.86
Resistances($k\Omega$)	208.64	133.64
Pressures(N/cm^2)	1.7	2.1

Day 4	Test 7*	Test 8
Average voltage (V)	4.74	2.47
Resistances($k\Omega$)	1823.08	97.63
Pressures(N/cm^2)	0.5	2.4

Day 5	Test 9	Test 10
Average voltage (V)	2.54	1.86
Resistances($k\Omega$)	103.25	59.24
Pressures(N/cm^2)	1.6	2.5

Table 4.8.3b: output data of different pressures applied on the textile sensing window (5 Days)

(*Note: Test 7 was not clear to show the peaks, one of the possible reasons was, the applied pressures were too small and the sensing window could not detect the light signal clearly. Details had been discussed in **Figure 4.8.3**, the results of Test 7)

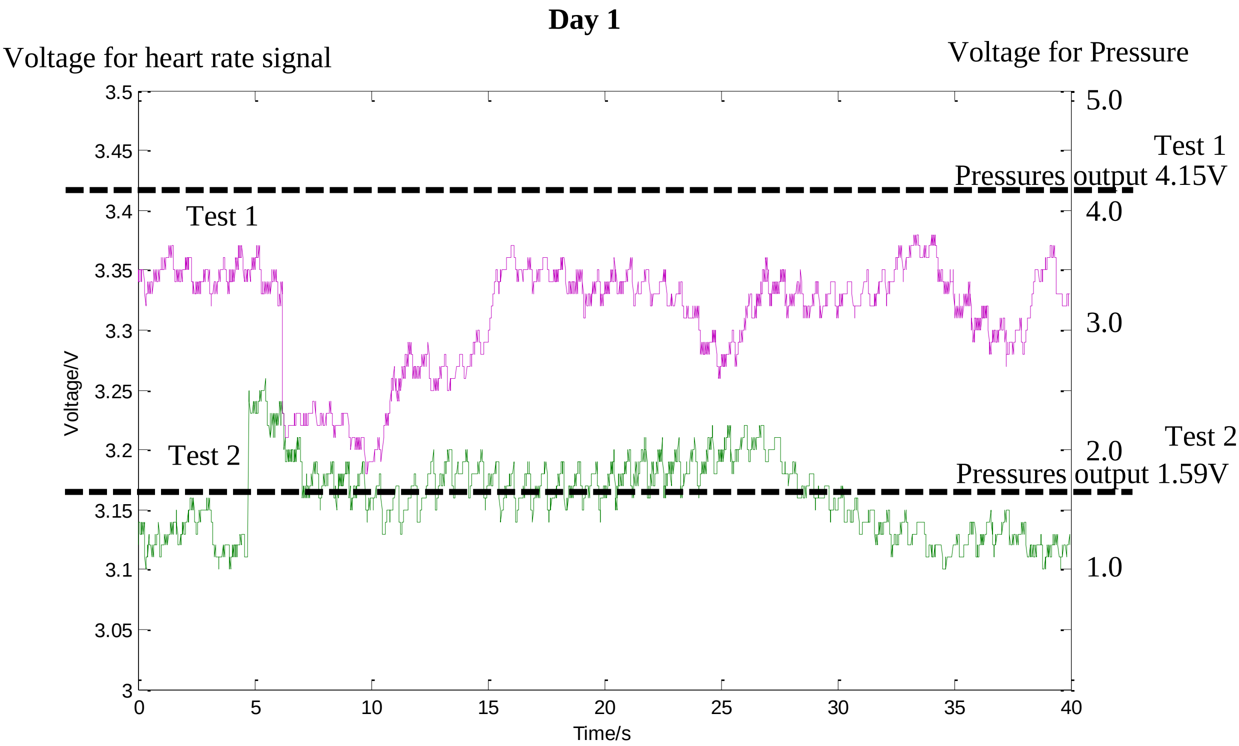


Figure 4.8.3a: heart rate signals from a human finger with different pressures (Test1&2)

Figure 4.8.3a-the way to read the results: two individual tests had been recorded in the same figure, one for smaller pressures and the other for larger pressures. The y-axis on the left side was reading for 'hate rate signal (the **colourful lines**)' while the y-axis on the right would be the **average** reading for pressures (the **dot lines**).

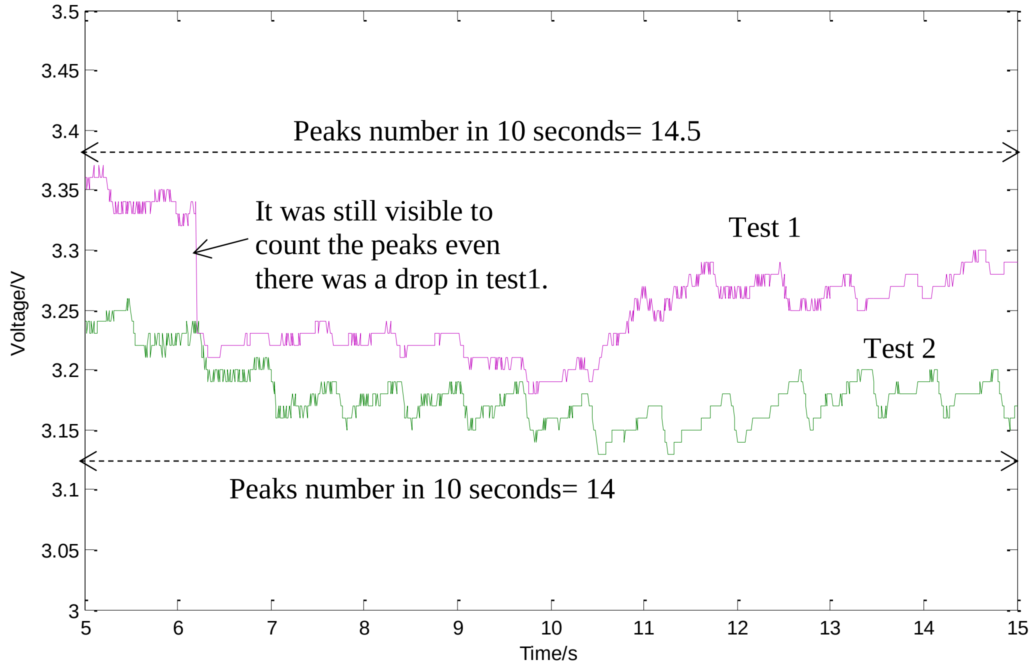


Figure 4.8.3a': heart rate signals from a human finger zoomed in (Test1&2)

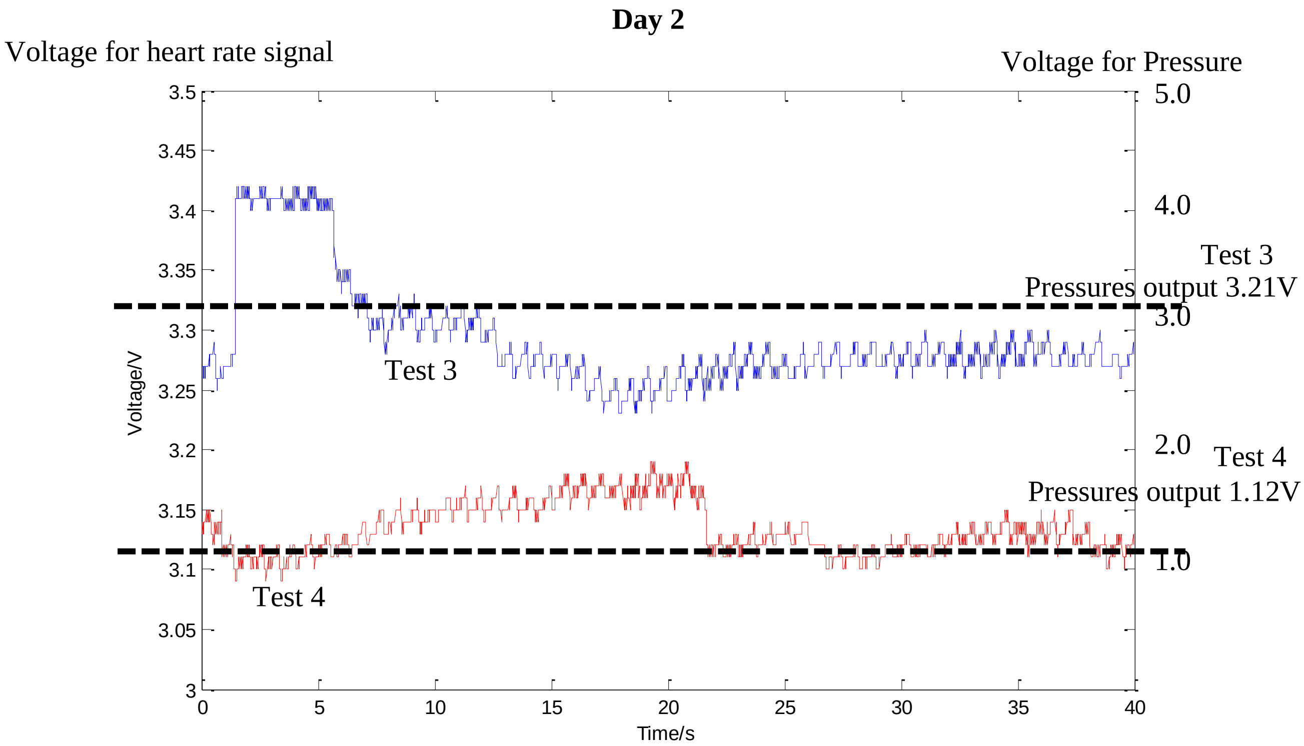


Figure 4.8.3b: heart rate signals from a human finger with different pressures (Test3&4)

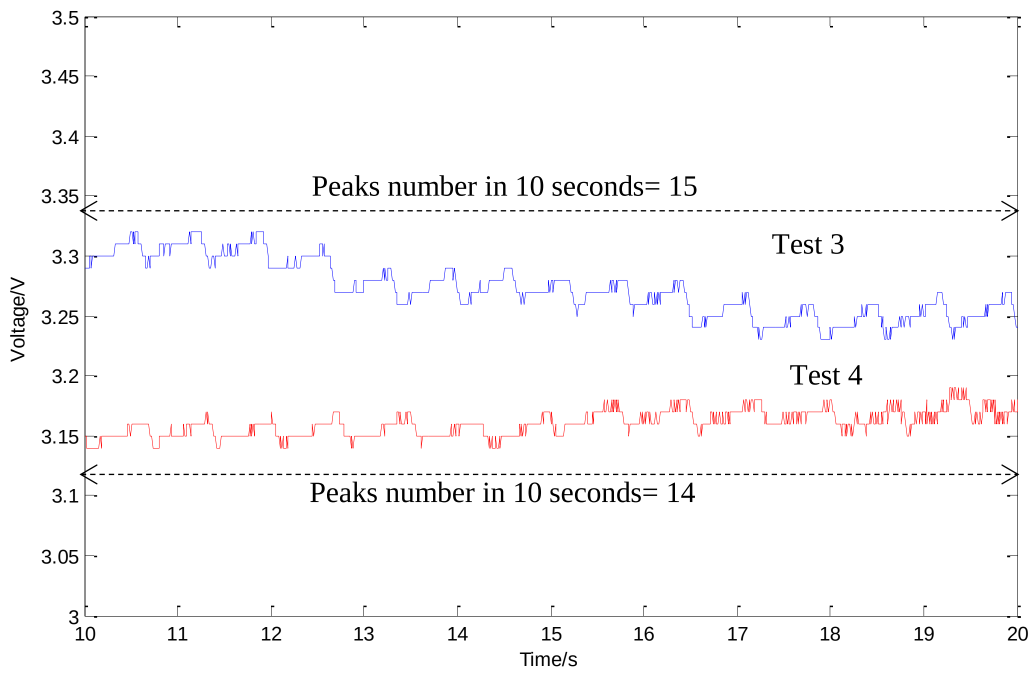


Figure 4.8.3b': heart rate signals from a human finger zoomed in (Test3&4)

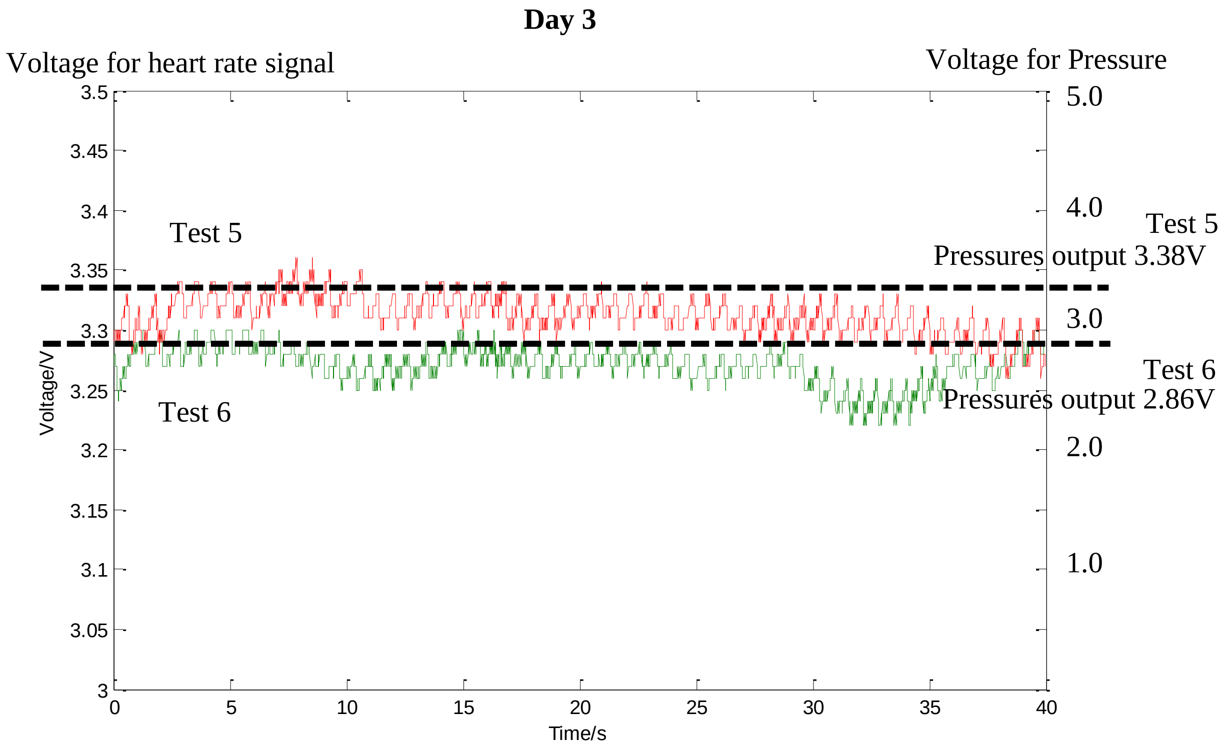


Figure 4.8.3c: heart rate signals from a human finger with different pressures (Test5&6)

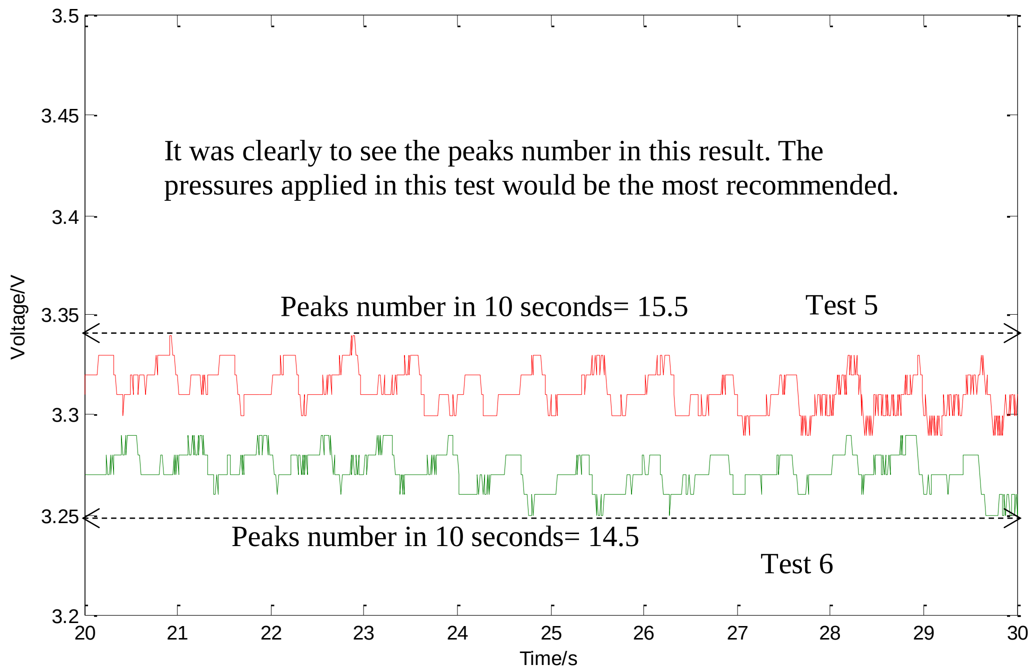


Figure 4.8.3c': heart rate signals from a human finger zoomed in (Test5&6)

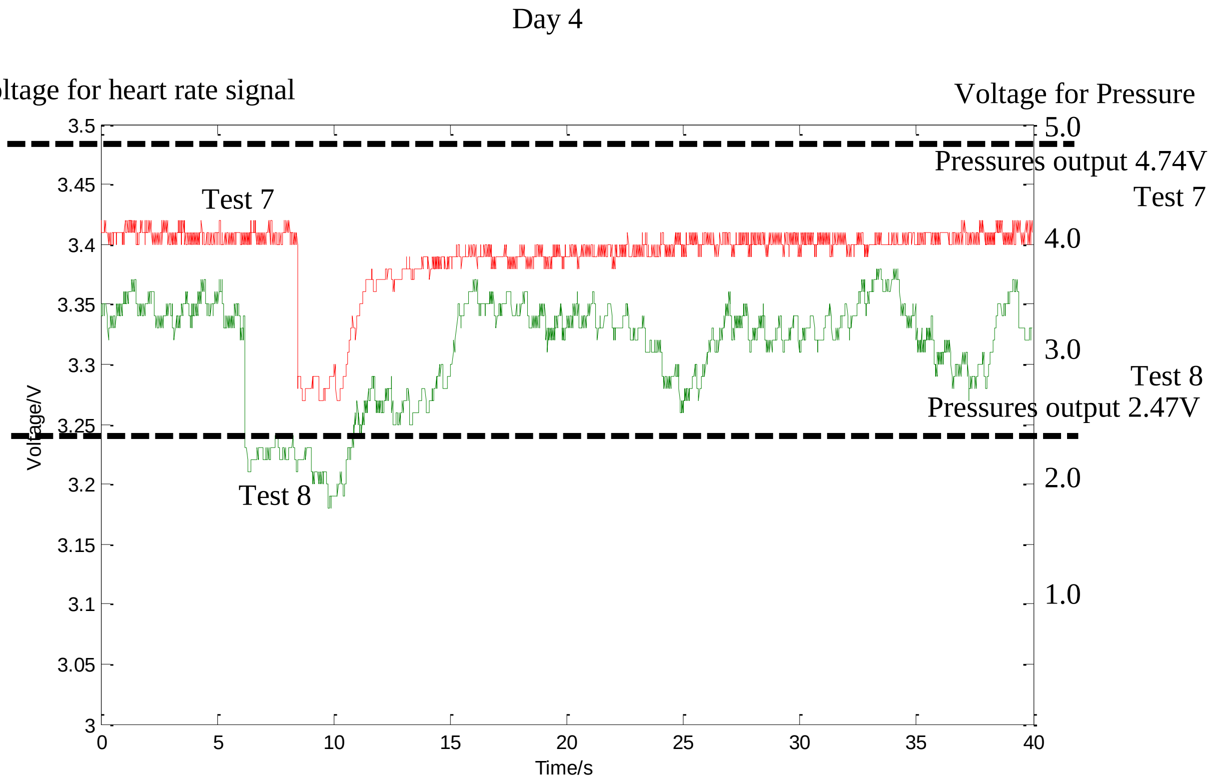


Figure 4.8.3d: heart rate signals from a human finger with different pressures (Test7&8)

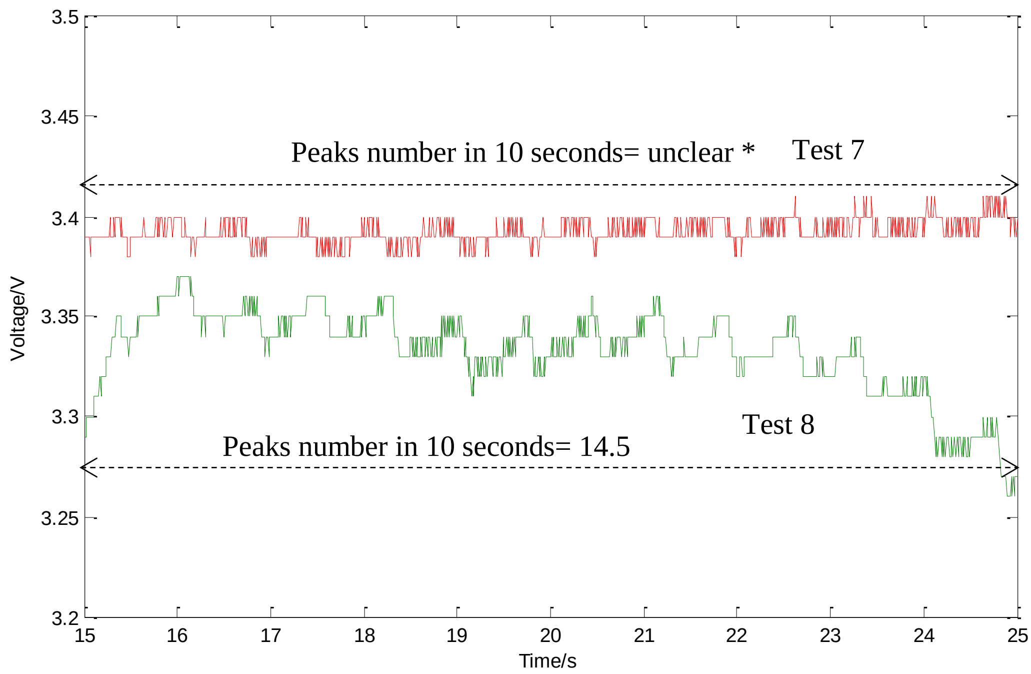


Figure 4.8.3d': heart rate signals from a human finger zoomed in (Test7&8)

*Discussion (Test7): it could be seen that the peaks were unclear to count from the results in test 7. As the applied pressure in this test was the smallest one compared with other tests (which was 1.6N/cm^2 shown in **Table 4.8.3b**). In order to get a clear signal, the pressures larger than 1.6N/cm^2 was recommended, or a larger amplifier factor could be set in the future design to get more obvious peaks changing.

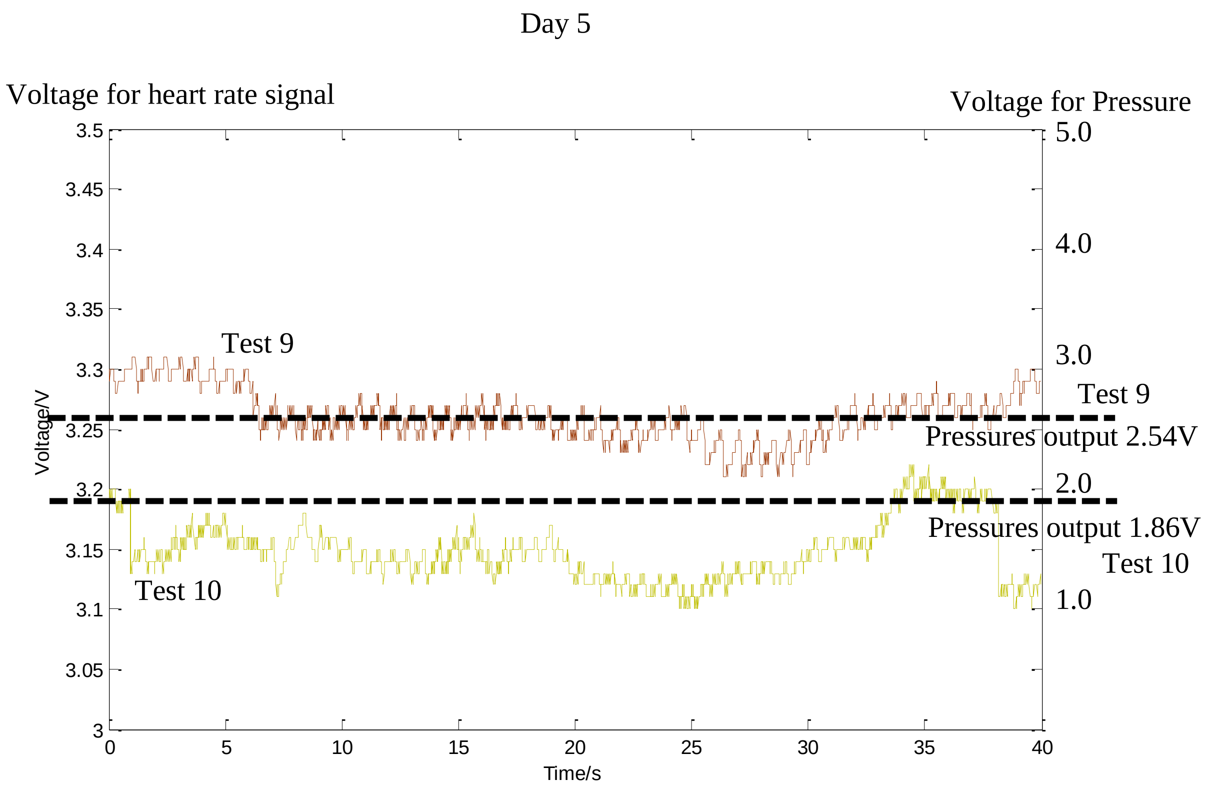


Figure 4.8.3e: heart rate signals from a human finger with different pressures (Test9&10)

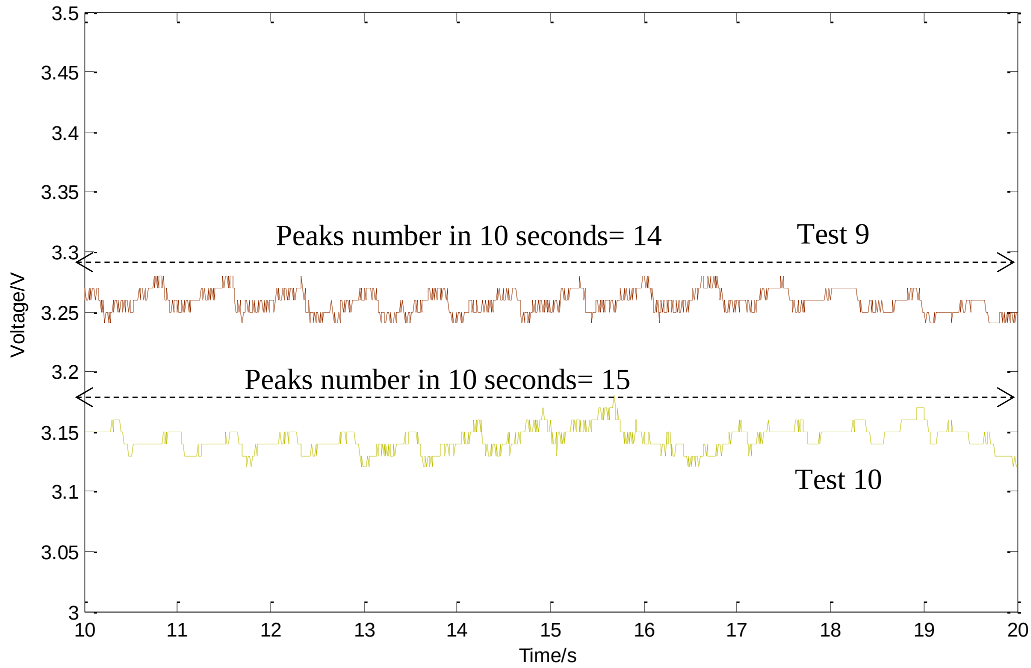
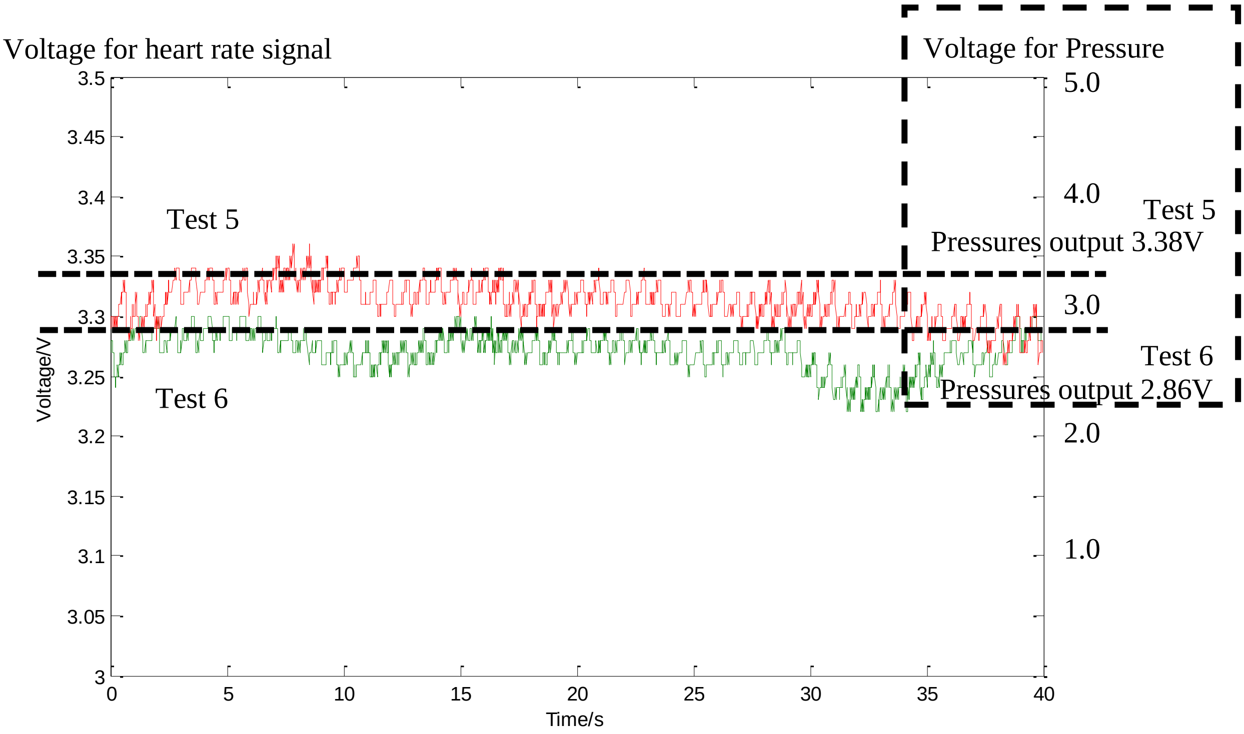


Figure 4.8.3e': heart rate signals from a human finger zoomed in (Test9&10)

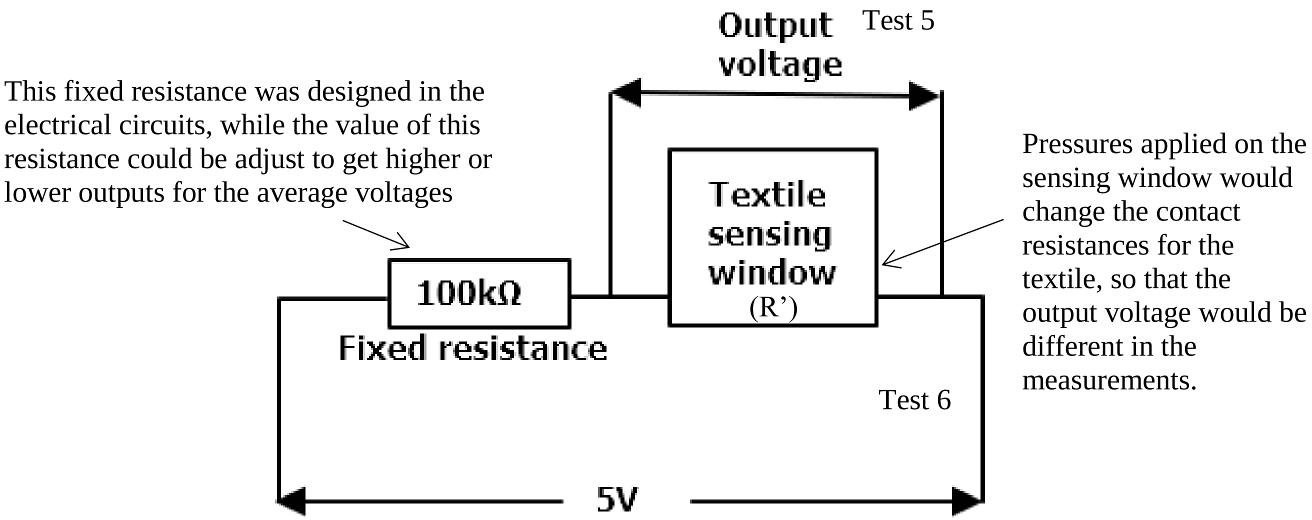
4.8.4 The way to estimate the pressures applied on the sensing window:

Take Test 5 and Test6 as an example to calculate the applied pressures:

Step 1, record the average voltage of the pressures output signal



Step 2, according to the pressures output voltage, calculate the overall contact resistance of the textile sensing window. The fixed resistance used in the circuits was 100 $k\Omega$, and the overall voltage applied to the system was around 5V, than the resistance of the textile sensing window could be calculated be the formula below:



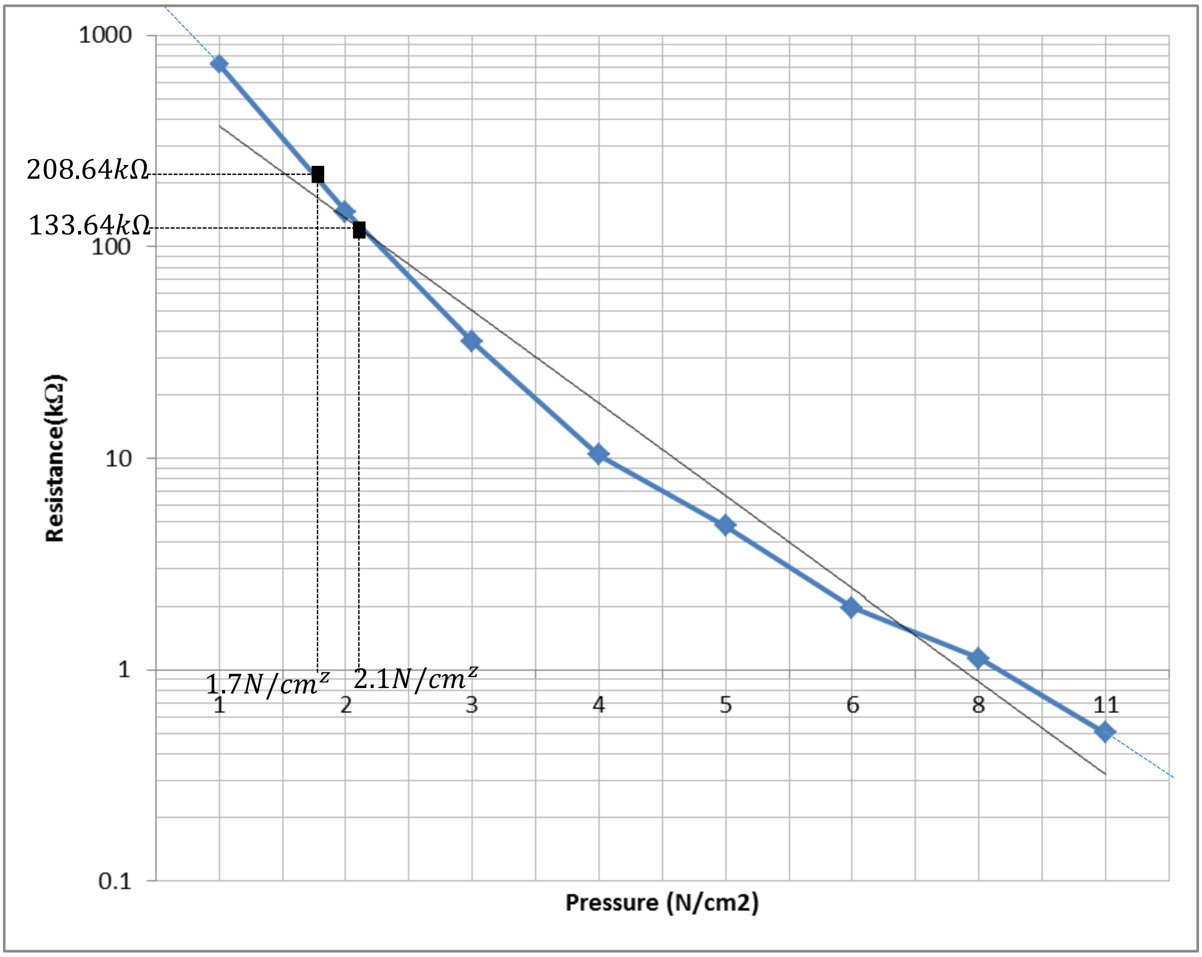
Test5:

$$\frac{R'}{R'+100k\Omega} = \frac{3.38V}{5V} \rightarrow 1.62R' = 338k\Omega \rightarrow R' = \frac{338}{1.62}k\Omega = 208.64k\Omega$$

Test6:

$$\frac{R'}{R'+100k\Omega} = \frac{2.86V}{5V} \rightarrow 2.14R' = 286k\Omega \rightarrow R' = \frac{286}{2.14}k\Omega = 133.64k\Omega$$

Step 3, using the calculated resistance in **Step 2**, compare the resistance value with the '**Figure 4.6.3d**: Average results Pressure test on textile sensing window ($2 \times 2\ cm^2$)', estimate the corresponding pressures applied by this specific test. From the reading the estimated pressures applied in Test 5 and Test 6 were $1.7N/cm^2$ and $2.1N/cm^2$.



Results of estimate pressures applied on the textile sensing window:

Pressures Test	Test 5	Test 6
Average voltage (V)	3.38	2.86
Resistances($k\Omega$)	208.64	133.64
Pressures(N/cm^2)	1.7	2.1

Table 4.8.4: Results of estimate pressures applied on the textile sensing window (Test5&6)

The results shown in **Figure 4.8.3b** would use the calculation method as above. By using the same method, the average pressure applied on the textile sensing window would be estimated for each individual test. In this experiment, the minimum pressure was shown in **Test 7 ($0.5N/cm^2$)** and the maximum was shown in **Test 4 ($2.8N/cm^2$)**. While the unclear heart rate signal was shown in Test7, it could be prospected that the most suitable pressure applied on this textile sensing window would have its suitable range to measure the heart rate signal from the human finger. For example, the most recommended pressures applied in this experiment were **>$0.5N/cm^2$ (>5kpa)**. And compare with the results, the optimal signals was shown when the pressures **<$2.0N/cm^2$**. However, there was a huge approximating data in each step of calculation, and the tested textile sample would also suffer from a deform problem when applied larger pressures. From this case, the method to calculate such pressures was just a reference results and there was no accuracy guarantee.

5. Conclusion:

--- *This chapter gave a final summary of the whole thesis, analysis the merits and shortages, with possible development and the future work of the product, and contained the reflection of the time plan and how effective the project was completed in time.*

Brief conclusion:

It could be concluded that the product would be useful to measure the pressures and human heart rate from a simple human finger touching. The electronic part and the textile base could be easily despatched. This product would be propitious to a movement situation with flexible designing of the connection holes and 'pogo pin' with helping of the magnet connectors. The efficient of the optical connection for transmitting the optical power would over 40% and it was a very acceptable efficiency level by using a simple optical fibre connecting. The overall output of the product produced a clear voltage signal with low level of noise issues, the heart rate frequency could be found by finding the number of peaks in a specific period. It was clearly to see and quite visible directly from the screen of the oscilloscope. The further optimise could be done by adding a better low pass filter after getting the voltage signal from the designed circuits, even further optimise could be done by adding digital filter by collecting the data in the MATLAB software. The relationship between the applied forces on the textile sensing window and the contact resistance in electrically conductive yarns and textiles also had been investigated in an individual experiment. By analysing the output voltage from then textile sensing window, the recommended applied pressure to measure the heart rate from a human finger could be estimated within a tolerant range of 0.5N/cm^2 ~2.0N/cm^2(5kpa~20kpa).

Future works:

Current states	Improvements
So far, all the designed circuits were built in three layers of PCB board including the textile sample. And the overall size of the designed product would be expected to be smaller as a wearable device.	Could use printed board replace the PCB board so that the electronic components used in the circuits could be smaller and the size of the product would be smaller.
There was no outer packing for the designed product. The circuits and connector had been designed in a suitable three layers case, while the electronic components were still exposed in the surroundings.	The outer packing of the product could be re-designed to locking all the electronic circuits in a little box and re-built with a wearable fashion, for example, using streamlined design.
The output signals had to be seen from an oscilloscope screen, there was no directly reading for the measured heart rate and pressures value. All the results was calculated and estimated by a roughly way.	A separate LED display screen could be added on the product to show the pressure and heart rate directly rather than using an oscilloscope to show the results. For example could use a PIC board to control the display and design the corresponding software code to show the values directly.
The light emitter was not powerful enough by using LEDs and the connection from the emitter and the optical fibres were crude and light block for the LED emitter need to be improved.	Modulating the light source and using lock in detection so that the light emitter could be immune to environmental light.

The designed product in this project was able to monitor the heart rate from a human finger, while the further purposes would meet with the function of monitoring the heart rate built for socks, for example, engagement with end users such as clinicians and people with diabetes. Higher technical improvements for this application were expected in the future developments to achieve.

Time plan reflection

The original time plan was printed on an A3 page in the final pages of the thesis, and the renewed time plan had been discussed in a comparable version with all the completed progressing.

There are two time plan Gantt chart in the finial of the thesis, one is the original time plan and the other is the 'renewed' version based on the same procedure. Compared to the 'renewed' one with the original plan there are several differences be mentioned as below:

	Original time plan	Renewed time plan
Research work	All settled	An additional research work had been done during the designed part, more advanced research about 'the mechanism of textile sensing window', and what is the suitable
Stage 1 Electrical part	Progressing on schedule	Rearrange the experiment to check the electrical connection to the experiment part in Stage 4.
Stage 2 Optical part	Progressing on schedule	More optical connection work had been added to optimise the transmission efficiency of from the optical fibre to another.
Stage 3 Combination part	Progressing on schedule	The combination designed had been settled and a further design of the outer package of the product was designed but not produced in this thesis, some ideals show in the future work.
Stage 4 The advantage work and experiments	The experiment for checking the electrical and optical connection was set in Stage 1 and Stage 2 separately to make sure the designed circuits could keep regular work. And additional experiments were set in the 'Stage 4: advanced work'.	All the experiment was designed in 8 separate actions. Perfectly match the experiments results from experiment 1 to experiment 8 in the Chapter 4 of the thesis. Each individual experiment has its own purposes, methods, discussions and conclusions. The finish time for the experiments were matching the original expects.
Thesis written	The time for the draft typed thesis was expected to be finished early April and the final edition would be finished before May 1st.	The actually finishing time for the thesis writing was May 5th, it took a longer time to re-edit and modify the final assessment work.

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