DEVELOPMENT AND ANALYSIS OF ELECTROCARDIOGRAPHY CIRCUIT ON FLEXIBLE POLYMERS

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DEDICATION

This thesis is dedicated to:

My beloved parents, ***Sahar Sahlan*** *and* ***Rosiah Marni***

My lovely husband, ***Mohd Faizal Zakaria***

My cute children, ***Muhammad Wafiy Yusuf*** *and* ***Noor Anis Afina***

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ABSTRACT

Recently, flexible printed circuit (FPC) technology is utilized in electronic industry to reduce the device size and weight. Electrocardiography (ECG) device is one of the healthcare devices needed in small size as to give comfort to user. There are various technique of fabricating circuit on flexible substrate were proposed such as etching, screen printing, and inkjet printing. However, the conductive traces fabricated using those techniques were easily cracked and led to loose of circuit continuity. Thus, the aim of this study is to find the best flexible material to be used with copper tape as conductive traces to replace the method of using nano-scale particle material. ECG circuit is integrated and fabricated on flexible substrate material using vinyl cutting technique. There were three different materials chosen to be used in this study; silicone rubber sheet, Thermoplastic Polyurethane (TPU) and Polyethylene Terephthalate (PET). Material characterization analysis such as Atomic Force Microscopy (AFM), contact angle and peel adhesion test were done on these materials to know the best material suit to be used with conductive copper tape (Copper tape 1181 from 3M). From that, this study has found that PET is the most suitable material to be used because its peel adhesion strength is the highest. Then, ECG circuit was developed using vinyl cutting technique and the circuit performance between flexible substrate and rigid substrate were compared. In the data processing stage, ECG data were denoised using sym20 from Wavelet Transform tool in MATLAB. Signal to noise ratio (SNR) parameter was calculated and used as the signal quality indicator. The data then further analyzed using statistical ANOVA to determine the significant features. Results showed that vinyl cutting method is a successful method to fabricate circuit on PET substrate as the performance of the flexible ECG circuit is comparable with rigid ECG circuit.

ABSTRAK

Kebelakangan ini, teknologi litar bercetak fleksibel (FPC) digunakan dalam industri elektronik bagi mengurangkan saiz peranti dan beratnya. Peranti Elektrokardiografi (ECG) ialah salah satu alat penjagaan kesihatan yang memerlukan saiz yang kecil untuk memberi keselesaan kepada pengguna. Terdapat pelbagai teknik pembuatan litar pada bahan fleksibel yang dicadangkan seperti goresan, percetakan skrin, dan percetakan inkjet. Namun, aliran konduktif yang dibuat menggunakan teknik-teknik tersebut mudah retak dan menyebabkan kehilangan sambungan litar. Maka, tujuan kajian ini adalah untuk mencari bahan fleksibel yang terbaik untuk digunakan dengan pita tembaga sebagai aliran konduktif untuk menggantikan kaedah penggunaan bahan zarah berskala nano. Litar ECG dicantum dan dibina pada lapisan bahan fleksibel menggunakan teknik potongan vinil. Terdapat tiga bahan fleksibel yang dipilih; lembaran getah silikon, Poliuretana Termoplastik (TPU) dan Polietilena Terephthalate (PET). Pencirian bahan seperti AFM, sudut sentuhan dan ujian lekatan dilakukan pada bahan-bahan ini untuk mengenalpasti bahan terbaik sesuai digunakan bersama pita tembaga konduktif (pita Tembaga 1181 dari 3M). Daripada itu, kajian ini mendapati PET adalah bahan yang paling sesuai digunakan kerana kekuatan lekatannya yang tertinggi. Kemudian, litar ECG telah dibangunkan menggunakan teknik pemotongan vinil dan prestasi litar antara bahan fleksibel dan bahan tegar telah dibandingkan. Dalam peringkat pemprosesan data, data ECG dinyahbising menggunakan sym20 dari alat Wavelet Transform dalam MATLAB. Parameter nisbah isyarat kepada hingar (SNR) dikira dan digunakan sebagai penanda aras kualiti isyarat peranti. Data kemudiannya dianalisa menggunakan analisis statistik ANOVA untuk menentukan ciri kesan ketara. Dapatan menunjukkan bahawa kaedah potongan vinil adalah kaedah yang berjaya untuk membuat litar pada lapisan PET kerana prestasi litar ECG fleksibel adalah setanding dengan litar ECG tegar.

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LIST OF ABBREVIATIONS

ADC	-	Analogue Digital Converter
AFE	-	Analogue Front End
AFM	-	Atomic Force Microscopy
Ag	-	Silver
Ag/AgCl	-	Silver/ Silver-Chloride
ANOVA	-	Analysis of Variance
BW	-	Baseline Wander
CHD	-	Coronary Heart Disease
CMRR	-	Common Mode Rejection Ratio
DC	-	Direct Current
DIM	-	Diiodomethane
DSP	-	Digital Signal Processing
ECG	-	Electrocardiography
ERC	-	Electrical Rule Check
FIR	-	Finite Impulse Response
FPC	-	Flexible Printed Circuit
GO	-	Graphene Oxide
HPF	-	High Pass Filter
IC	-	Integrated Circuit
IIR	-	Infinite Impulse Response
Li-Po	-	Lithium-Polymer
LMS	-	Least Mean Square
LNA	-	Low Noise Amplifier
PCB	-	Printed Circuit Board
PDMS	-	Polydimethylsiloxane
PET	-	Polyethelene Terephthalate
PRD		Percent Root-mean- squared Difference
PSA	-	Pressure Sensitive Adhesive
PTF	-	Polymer Thick-Film
SCA	-	Sudden Cardiac Arrest

SFE	-	Surface Free Energy
SMD	-	Surface Mount Device
SNR	-	Signal to Noise Ratio
SoC	-	System on Chip
SWT	-	Stationary Wavelet Transform
TPU	-	Thermoplastic Polyurethane
VDM	-	Vacuum Deposition Method
WT	-	Wavelet Transform

LIST OF SYMBOLS

γ_s	-	SFE of a solid substrate
γ_l	-	SFE of a liquid drop
γ_{sl}	-	Interfacial free energy between solid substrate and liquid drop
θ	-	Contact angle between solid-liquid interface
W_a	-	Work of adhesion
R_a	-	Arithmetic mean roughness
R_q	-	RMS roughness
l	-	Sampling length of profiles
$y(x)$	-	Profile heights measured from reference line
${\gamma_l}^d$	-	Dispersion component of surface tension of liquid
${\gamma_l}^p$	-	Polar component of surface tension of liquid
${\gamma_s}^d$	-	Dispersion component of surface tension of solid
${\gamma_s}^p$	-	Polar component of surface tension of solid

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Any disorder related to the heart is known as heart disease. Heart disease can affect different parts of the organ and can occur in different ways. The main cause of Coronary Heart Disease (CHD) is the accumulation of cholesterol in the artery walls which will narrow the flow of blood to the heart. This condition can lead to heart attack and stroke (Leys *et al.*, 2002). Therefore, heart attack can be referred to as a blood circulation problem. In contrast, sudden cardiac arrest (SCA) can be attributed to electrical signal problems in the heart.

Most SCA cases are caused by irregular heart rhythms called arrhythmias. Common symptoms of SCA are fainting and the absence of heartbeat detection. Some people may exhibit very fast heartbeat, dizziness or light-headedness just before fainting, while some may have chest pain, shortness of breath, nausea or vomiting. This could lead to ventricular fibrillation and disruption of blood flow to all parts of the body. Subsequently, as less oxygen is received by the brain, a person may lose consciousness and could possibly die if no emergency treatment is given within the next five minutes.

According to a press release by the Department of Statistics Malaysia regarding the statistics on causes of death in Malaysia, 2014, ischemic heart disease was reported as the highest cause of death in the last ten years from year 2005 to 2014 (Department of Statistics, 2016). Figure 1.1 shows ischemic heart disease as the highest contributor to the death percentage which is 13.5 percent (10432 deaths) in year 2014 only. Even in a finding, researchers discussed about acute ischemic event is a trigger to SCD (Thygesen and Uretsky, 2004).

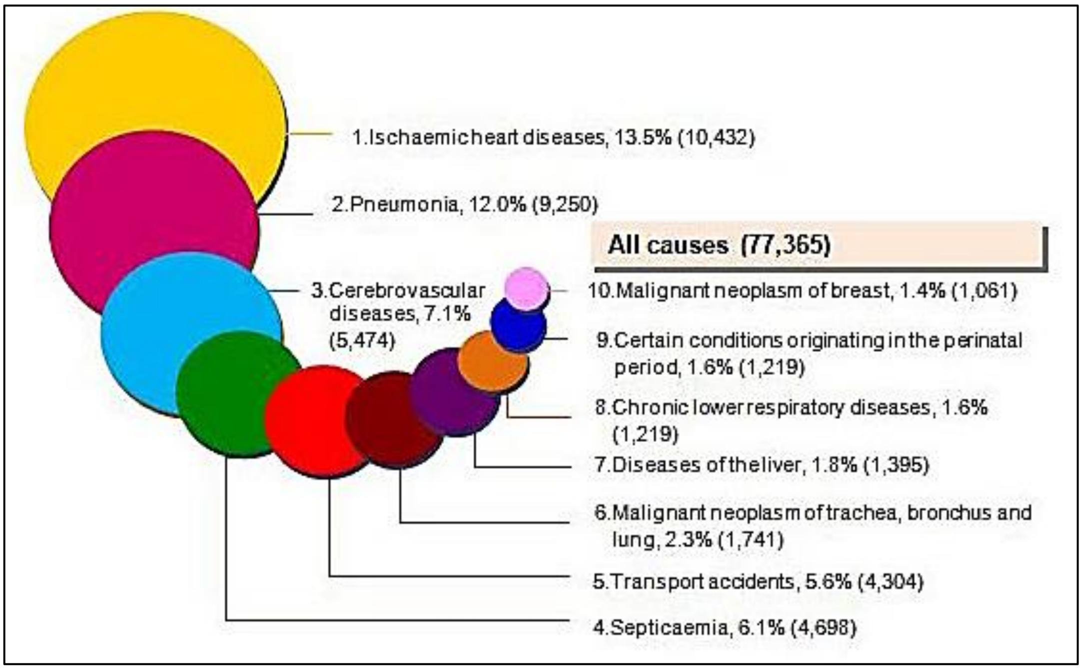

Figure 1.1 Statistical data on causes of death in Malaysia, 2014 (Department of Statistics, 2016)

Another statistic on the CHD mortality rates based on sex and age among Malaysians is shown in Figure 1.2. The mortality rate of CHD among males starts to increase at the age of 30 (Abdullah *et al.*, 2017). From this figure, it shows that the number of heart disease cases in Malaysia is increasing, and these cases are observed among adults aged as early as 30. According to the summary of risk factors for CHD in Malaysia, hypertension has been found to be the leading risk factor (Seong and John, 2016). Although one research stated that the chances of youths developing heart disease and CHD are low (Schmied and Borjesson, 2014), the statistical finding is still a major concern as these young adults carry responsibilities towards their family, society and country.

Heart disease is caused by blockage of the coronary arteries, and poor supply of nutrients and oxygen to the heart. Examples of lifestyle habits and conditions that could increase the risk of heart disease are junk-food diet practice, smoking, being overweight and diabetic, high blood pressure and cholesterol, and family history. The most important thing is to practice a healthy lifestyle by exercising regularly, eating a healthy and balanced diet, and performing regular medical checkup.

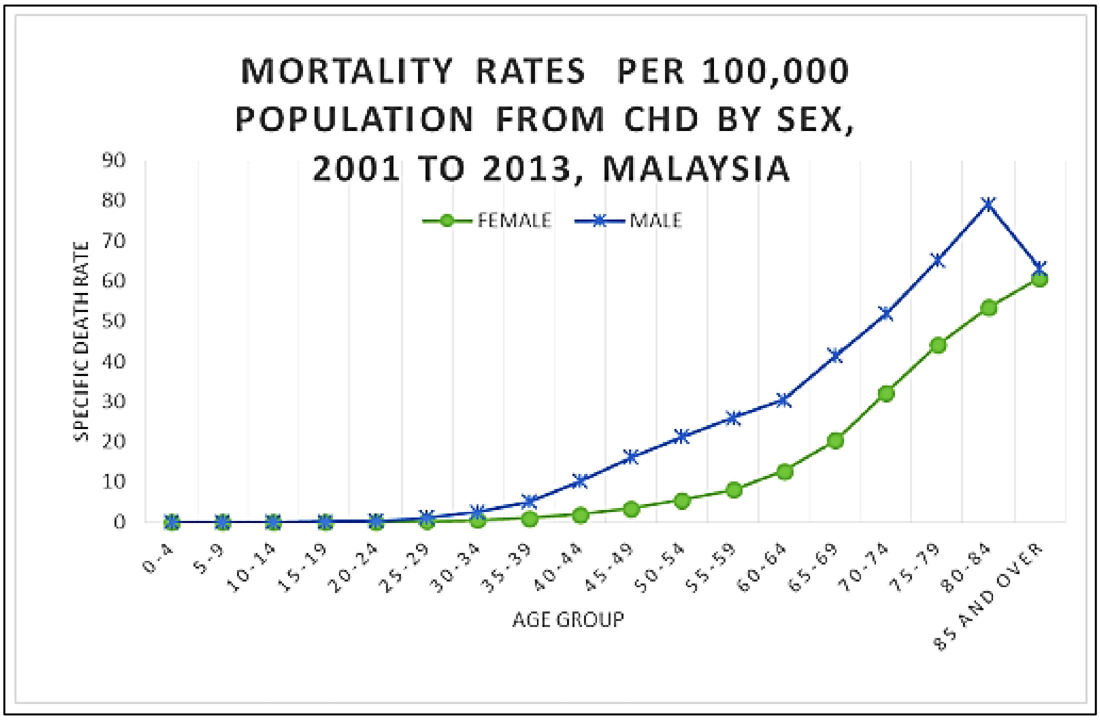

Figure 1.2 Mortality rates of CHD in Malaysia (Abdullah *et al.*, 2017)

As a suggestion, regular health check-ups should be done at least once a year to ensure individuals are screened for many types of diseases. By doing this, potential diseases and problems can be identified at an early stage. If any chronic diseases like heart disease, diabetes and high blood pressure are discovered early, it can be prevented and treated before it worsens. In Malaysia, there are a lot of companies and even government entities which provide health check-ups such as blood test, eye test, general test and scans to identify the health status of a person. However, screenings for heart disease are often neglected as the prices are expensive.

In heart screening, individuals with no symptoms of coronary artery disease may be evaluated based on their family history, blood pressure, blood sugar level, cholesterol level, weight and their lifestyle. The doctor may recommend additional testing such as the Electrocardiography (ECG) monitoring if there is presence of symptoms or risk factors for coronary artery disease.

In the past few years, heart rate monitors have received increasing attention from people throughout the world. Based on Figure 1.3, the value of smart medical devices, including heart rate monitors, are forecasted to increase from 2014 to 2025.

Smartphones play an important role in the healthcare industry. The increase in smartphone usage is in parallel with the rising demand for wireless and smartphone-compatible medical devices. This in turn promotes awareness and focus on health and fitness, and demand-led growth for home healthcare (Grand View Research, 2017). Heart rate measurement could be calculated by using the distance between QRS complexes in the ECG signal (Ruha *et al.*, 1997). Thus, the focus of this study is to develop a wireless ECG monitoring device which is small, flexible, and equipped with wireless communication.

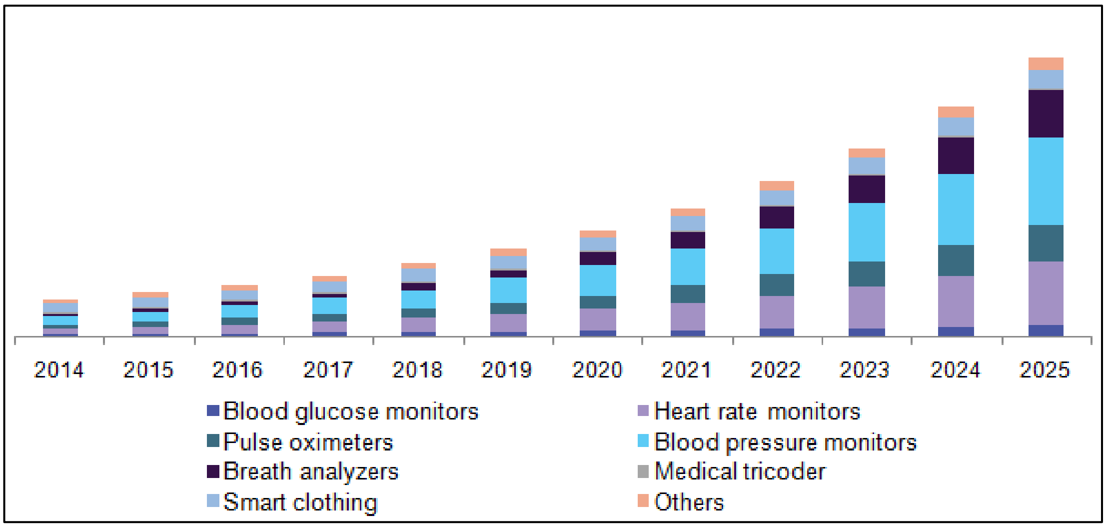

Figure 1.3 United State smart medical devices market by product, 2014-2025 (Grand View Research, 2017)

In this study, flexible circuit was used in developing the ECG device. Flexible circuit is an invention and improvement from a Printed Circuit Board (PCB). The purpose of having this flexible circuit are to cut cost and minimize the design of an application. Most of the time, flexible circuit are applied on automotive manufacturing, camcorders, mobile phone, hand calculator and SLR cameras. Common method used in fabrication of flexible circuit is by screen printing or well known as polymer thick-film (PTF) method (Macleod, 2002). This method has been used for decades in manufacturing to produce high volume goods. This flexible circuit technology started to develop in 1960's. The process in improving the fabrication method of conductive traces on a substrate continuing until today.

1.2 Problem Statement

The conventional method of ECG monitoring practiced in hospitals or other fixed-clinical settings is not convenient for continuous monitoring. This is due to the bulkiness of the device itself which limits user mobility and device portability. Although technological improvements have been made for this device such as the development of the Holter monitor for ambulatory ECG monitoring (Jovanov, 2016), the extensive wire connections of this device often cause discomfort in the user. This problem is especially significant when the user wants to carry out daily activities such as walking as they need to carry along the device. As technologies in the healthcare field improve with time, this may result in the increase of development cost and subsequently the price of wearable devices, making them less affordable for people in developing countries.

In this study, we focus on the method used to fabricate circuit on a flexible substrate. Based on the review of previous studies, researchers have used screen printing (Merilampi and Ruuskanen, 2009), inkjet printing and direct writing (Hyun *et al.*, 2013), (Chem, 2011) methods. However, there are some drawbacks when using these methods such as causing environmental pollution and difficulties in repairing defective products. The process involved in screen printing causes wastage of silver paste and is susceptible to having micro-cracks and loss of continuity (Bossuyt *et al.*, 2012). Moreover, the inkjet printing method requires high cost for maintenance as micron-sized nozzles are prone to getting clogged due to the accumulation of nanoparticles at the nozzle opening.

In order to overcome some of the drawbacks mentioned above, this study focuses on fabricating conductive traces of a circuit on a flexible substrate using the vinyl cutting method. Therefore, the aim of the study was categorized into two parts, hardware and software.

1.3 Objectives of the Study

In order to overcome the drawbacks as stated in problem statement, three objectives were constructed as follows;

i. To investigate the adhesion strength of copper tape towards polymer substrate through characterization testing

ii. To integrate and fabricate an ECG circuit on the flexible substrate with copper tape as the conductive traces using vinyl cutting method to print the circuit traces

iii. To compare performance of the flexible ECG circuit with a rigid ECG circuit using signal-to-noise ratio (SNR) measurement

1.4 Scope of Study

This study is divided into three parts: (part 1) characterization of substrate material, (part 2) fabrication of an ECG circuit and (part 3) analysis of the ECG data performance. Therefore, both software (part 3) and hardware (part 1 and part 2) aspects were incorporated to complete this study.

In the first part of this study, material characterization for substrate is needed to identify the most suitable substrate that can be used with the 3M copper foil tape. Three flexible substrates were chosen to be compared which were Thermoplastic Polyurethane (TPU), Polyethelene Terephthalate (PET) and silicon rubber.

In the process of developing the device, the CADSoft Eagle software was used to design the wireless ECG circuit. The HC05 Bluetooth module was used for transparent wireless serial connection setup while the BMD101 microchip, which is a System-on-a-Chip (SoC), acted as a digital bio-signal detection and processing module. The ECG circuit was then fabricated on the chosen flexible substrate which acted as the circuit base. In this study, copper tape and conductive epoxy glue were used as the conductive traces and solder replacement, respectively. The traces were cut using a vinyl cutter machine.

Once the circuit was completed, the device was ready for circuit performance analysis, which is the third objective of this study. The device performance and signal quality were analyzed using the MATLAB software by computing the Signal-to-Noise Ratio (SNR). Differences between the two circuits were tested for statistical significance using the Sigma Plot software.

1.5 Significance of Study

This study has introduced new fabrication method on flexible substrate for electronics circuit. Contribution and improvement found are:

i. Fabrication of copper tape as conductive traces on polymer-based using vinyl cutting method

ii. The performance level of fabricated circuit using vinyl cutting method is as good as circuit fabricated using standard manufacturing process

1.6 Thesis Organization

This thesis is divided into five chapters. Following this introductory chapter is Chapter 2 which is on Literature Review. There are several subsections in Chapter 2. Subsection 2.1 is a brief description on the whole of Chapter 2. Subsection 2.2 presents background information on related researches concerning wireless ECG monitoring systems. ECG artifacts and conventional preprocessing methods are explained in Subsection 2.3. Subsection 2.4 is a review of flexible materials suitable for circuit fabrication and methodologies used in previous researches. In Subsection 2.5, factors affecting peel adhesion of Pressure-Sensitive Adhesive (PSA) to another substrate are discussed.

Chapter 3 consists of seven subsections which construe the research methodology employed in this study for characterization of substrate material, component selection, circuit design, method of circuit fabrication, data acquisition and data analysis. In Chapter 4, findings from this study are discussed in detail. Lastly, Chapter 5 summarizes this thesis, including the conclusions, and some limitations and recommendations observed in this study. This chapter is followed by list of references and several appendices.

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LIST OF APPENDICES

Appendix A Matlab Codes for ECG Denosing Process and SNR Calculation

```
%insert original signal%
subplot(3,1,1);
plot(VarName1, 'r');
title('Original Signal');
xlim ([0 3000]);
ylabel ('mV');
xlabel ('Samples');

%apply filter%
sigDEN1 = func_denoise_dw1d(VarName1);
subplot(3,1,2);
plot (sigDEN1,'b');
title('Denoised Signal');
xlim ([0 3000]);
ylabel ('mV');
xlabel ('Samples');


%SNR calculation%
sigDEN=sigDEN1';
SNR = snr(sigDEN,VarName1- sigDEN);
subplot(3,1,3);
plot (VarName1,'r'); hold on;
plot (sigDEN1,'b');
title('Overlapped of Original Signal & Denoised Signal');
xlim ([0 3000]);
ylabel ('mV');
xlabel ('Samples');
```

Appendix B Result of Two Way Repeated Measures ANOVA run on Sigma Plot

Two Way Repeated Measures ANOVA (Two Factor Repetition) Wednesday, April 03, 2019, 3:28:59 PM

Data source: Data 1 in Notebook2

Balanced Design

Dependent Variable: SNR

Normality Test (Shapiro-Wilk): Passed (P = 0.910)

Equal Variance Test (Brown-Forsythe): Passed (P = 0.777)

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Subject	9	1173.337	130.371		
Circuit Type	1	25.422	25.422	2.017	0.189
Circuit Type x Subject	9	113.410	12.601		
Activity	6	2.601	0.433	0.271	0.948
Activity x Subject	54	86.304	1.598		
Circuit Type x Activity	6	5.528	0.921	1.477	0.203
Residual	54	33.680	0.624		
Total	139	1440.283	10.362		

The difference in the mean values among the different levels of Circuit Type is not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in Activity. There is not a statistically significant difference (P = 0.189).

The difference in the mean values among the different levels of Activity is not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in Circuit Type. There is not a statistically significant difference (P = 0.948).

The effect of different levels of Circuit Type does not depend on what level of Activity is present. There is not a statistically significant interaction between Circuit Type and Activity. (P = 0.203)

Power of performed test with alpha = 0.0500: for Circuit Type : 0.148
Power of performed test with alpha = 0.0500: for Activity : 0.0500
Power of performed test with alpha = 0.0500: for Circuit Type x Activity : 0.179

Least square means for Circuit Type :

Group	**Mean**
Flexible	32.104
FR4	32.956

Std Err of LS Mean = 0.424

Least square means for Activity :

Group	**Mean**
Rest	32.783
0deg 1km/h	32.378
0deg 2km/h	32.544
0deg 3km/h	32.567
3deg 1km/h	32.335
3deg 2km/h	32.587

3deg 3km/h 32.517
Std Err of LS Mean = 0.283

Least square means for Circuit Type x Activity :

Group	**Mean**
Flexible x Rest	32.422
Flexible x 0deg 1km/h	31.562
Flexible x 0deg 2km/h	32.412
Flexible x 0deg 3km/h	32.075
Flexible x 3deg 1km/h	31.828
Flexible x 3deg 2km/h	32.309
Flexible x 3deg 3km/h	32.120
FR4 x Rest	33.143
FR4 x 0deg 1km/h	33.194
FR4 x 0deg 2km/h	32.676
FR4 x 0deg 3km/h	33.059
FR4 x 3deg 1km/h	32.842
FR4 x 3deg 2km/h	32.865
FR4 x 3deg 3km/h	32.915

Std Err of LS Mean = 0.250

All Pairwise Multiple Comparison Procedures (Bonferroni t-test):

Comparisons for factor: **Circuit Type**

Comparison	**Diff of Means**	**t**	**P**	**P<0.050**
FR4 vs. Flexible	0.852	1.420	0.189	No

Comparisons for factor: **Activity**

Comparison	**Diff of Means**	**t**	**P**	**P<0.050**
Rest vs. 3deg 1km/h	0.448	1.120	1.000	No
Rest vs. 0deg 1km/h	0.405	1.013	1.000	Do Not Test
Rest vs. 3deg 3km/h	0.265	0.664	1.000	Do Not Test
Rest vs. 0deg 2km/h	0.238	0.596	1.000	Do Not Test
Rest vs. 0deg 3km/h	0.216	0.540	1.000	Do Not Test
Rest vs. 3deg 2km/h	0.196	0.491	1.000	Do Not Test
3deg 2km/h vs. 3deg 1km/h	0.252	0.629	1.000	Do Not Test
3deg 2km/h vs. 0deg 1km/h	0.209	0.523	1.000	Do Not Test
3deg 2km/h vs. 3deg 3km/h	0.0692	0.173	1.000	Do Not Test
3deg 2km/h vs. 0deg 2km/h	0.0423	0.106	1.000	Do Not Test
3deg 2km/h vs. 0deg 3km/h	0.0196	0.0490	1.000	Do Not Test
0deg 3km/h vs. 3deg 1km/h	0.232	0.580	1.000	Do Not Test
0deg 3km/h vs. 0deg 1km/h	0.189	0.474	1.000	Do Not Test
0deg 3km/h vs. 3deg 3km/h	0.0496	0.124	1.000	Do Not Test
0deg 3km/h vs. 0deg 2km/h	0.0227	0.0568	1.000	Do Not Test
0deg 2km/h vs. 3deg 1km/h	0.209	0.524	1.000	Do Not Test
0deg 2km/h vs. 0deg 1km/h	0.167	0.417	1.000	Do Not Test
0deg 2km/h vs. 3deg 3km/h	0.0269	0.0672	1.000	Do Not Test
3deg 3km/h vs. 3deg 1km/h	0.182	0.456	1.000	Do Not Test
3deg 3km/h vs. 0deg 1km/h	0.140	0.350	1.000	Do Not Test
0deg 1km/h vs. 3deg 1km/h	0.0427	0.107	1.000	Do Not Test

Comparisons for factor: **Activity within Flexible**

Comparison	**Diff of Means**	**t**	**P**	**P<0.050**
Rest vs. 0deg 1km/h	0.860	1.825	1.000	No
Rest vs. 3deg 1km/h	0.594	1.260	1.000	Do Not Test
Rest vs. 0deg 3km/h	0.347	0.736	1.000	Do Not Test
Rest vs. 3deg 3km/h	0.302	0.641	1.000	Do Not Test

Rest vs. 3deg 2km/h	0.113	0.240	1.000	Do Not Test
Rest vs. 0deg 2km/h	0.00958	0.0203	1.000	Do Not Test
0deg 2km/h vs. 0deg 1km/h	0.851	1.805	1.000	Do Not Test
0deg 2km/h vs. 3deg 1km/h	0.584	1.240	1.000	Do Not Test
0deg 2km/h vs. 0deg 3km/h	0.337	0.715	1.000	Do Not Test
0deg 2km/h vs. 3deg 3km/h	0.292	0.620	1.000	Do Not Test
0deg 2km/h vs. 3deg 2km/h	0.104	0.220	1.000	Do Not Test
3deg 2km/h vs. 0deg 1km/h	0.747	1.585	1.000	Do Not Test
3deg 2km/h vs. 3deg 1km/h	0.481	1.020	1.000	Do Not Test
3deg 2km/h vs. 0deg 3km/h	0.233	0.495	1.000	Do Not Test
3deg 2km/h vs. 3deg 3km/h	0.189	0.400	1.000	Do Not Test
3deg 3km/h vs. 0deg 1km/h	0.558	1.184	1.000	Do Not Test
3deg 3km/h vs. 3deg 1km/h	0.292	0.620	1.000	Do Not Test
3deg 3km/h vs. 0deg 3km/h	0.0448	0.0949	1.000	Do Not Test
0deg 3km/h vs. 0deg 1km/h	0.513	1.089	1.000	Do Not Test
0deg 3km/h vs. 3deg 1km/h	0.247	0.525	1.000	Do Not Test
3deg 1km/h vs. 0deg 1km/h	0.266	0.565	1.000	Do Not Test

Comparisons for factor: **Activity within FR4**

Comparison	**Diff of Means**	**t**	**P**	**P<0.050**
0deg 1km/h vs. 0deg 2km/h	0.517	1.098	1.000	No
0deg 1km/h vs. 3deg 1km/h	0.352	0.746	1.000	Do Not Test
0deg 1km/h vs. 3deg 2km/h	0.329	0.698	1.000	Do Not Test
0deg 1km/h vs. 3deg 3km/h	0.279	0.591	1.000	Do Not Test
0deg 1km/h vs. 0deg 3km/h	0.135	0.286	1.000	Do Not Test
0deg 1km/h vs. Rest	0.0501	0.106	1.000	Do Not Test
Rest vs. 0deg 2km/h	0.467	0.991	1.000	Do Not Test
Rest vs. 3deg 1km/h	0.301	0.640	1.000	Do Not Test
Rest vs. 3deg 2km/h	0.279	0.592	1.000	Do Not Test
Rest vs. 3deg 3km/h	0.229	0.485	1.000	Do Not Test
Rest vs. 0deg 3km/h	0.0847	0.180	1.000	Do Not Test
0deg 3km/h vs. 0deg 2km/h	0.383	0.812	1.000	Do Not Test
0deg 3km/h vs. 3deg 1km/h	0.217	0.460	1.000	Do Not Test
0deg 3km/h vs. 3deg 2km/h	0.194	0.412	1.000	Do Not Test
0deg 3km/h vs. 3deg 3km/h	0.144	0.305	1.000	Do Not Test
3deg 3km/h vs. 0deg 2km/h	0.239	0.506	1.000	Do Not Test
3deg 3km/h vs. 3deg 1km/h	0.0729	0.155	1.000	Do Not Test
3deg 3km/h vs. 3deg 2km/h	0.0503	0.107	1.000	Do Not Test
3deg 2km/h vs. 0deg 2km/h	0.188	0.400	1.000	Do Not Test
3deg 2km/h vs. 3deg 1km/h	0.0225	0.0478	1.000	Do Not Test
3deg 1km/h vs. 0deg 2km/h	0.166	0.352	1.000	Do Not Test

Comparisons for factor: **Circuit Type within Rest**

Comparison	**Diff of Means**	**t**	**P**	**P<0.050**
FR4 vs. Flexible	0.722	1.056	0.308	No

Comparisons for factor: **Circuit Type within 0deg 1km/h**

Comparison	**Diff of Means**	**t**	**P**	**P<0.050**
FR4 vs. Flexible	1.632	2.388	0.031	Yes

Comparisons for factor: **Circuit Type within 0deg 2km/h**

Comparison	**Diff of Means**	**t**	**P**	**P<0.050**
FR4 vs. Flexible	0.264	0.386	0.705	No

Comparisons for factor: **Circuit Type within 0deg 3km/h**

Comparison	Diff of Means	t	P	P<0.050
FR4 vs. Flexible	0.984	1.439	0.171	No

Comparisons for factor: **Circuit Type within 3deg 1km/h**

Comparison	Diff of Means	t	P	P<0.050
FR4 vs. Flexible	1.014	1.484	0.159	No

Comparisons for factor: **Circuit Type within 3deg 2km/h**

Comparison	Diff of Means	t	P	P<0.050
FR4 vs. Flexible	0.556	0.814	0.429	No

Comparisons for factor: **Circuit Type within 3deg 3km/h**

Comparison	Diff of Means	t	P	P<0.050
FR4 vs. Flexible	0.795	1.163	0.263	No

A result of "Do Not Test" occurs for a comparison when no significant difference is found between two means that enclose that comparison. For example, if you had four means sorted in order, and found no difference between means 4 vs. 2, then you would not test 4 vs. 3 and 3 vs. 2, but still test 4 vs. 1 and 3 vs. 1 (4 vs. 3 and 3 vs. 2 are enclosed by 4 vs. 2: 4 3 2 1). Note that not testing the enclosed means is a procedural rule, and a result of Do Not Test should be treated as if there is no significant difference between the means, even though one may appear to exist.

LIST OF PUBLICATIONS

Indexed Journal

1 **NS Sahar**, NA Abdul-Kadir, FKC Harun. 2020. Vinyl Cutting Technique for Flexible ECG Circuit Fabrication and Application. International Journal of Electrical and Computer Engineering. [Scopus] Accepted.

2 **NS Sahar**, NA Abdul-Kadir, WH Chan, SLM Eileen, FKC Harun. 2018. Wireless ECG Circuit on Flexible Material: A Preliminary Study. Journal of Telecommunication, Electronic and Computer Engineering. 10 (1-17). pp43-46. [Scopus, Q4]

Indexed Conference Proceedings

1 **NS Sahar**, NA Abdul-Kadir, FKC Harun. 2019. Flexible Wireless ECG Circuit Fabrication Technique. The International Biomedical Instrumentation and Technology Conference (IBITeC). Yogyakarta, Indonesia. 24-25th Oct 2019. [Scopus]. Accepted.

2 NA Abdul-Kadir, **NS Sahar**, WH Chan, FKC Harun. 2018. A Portable WiFi ECG. 38th International Electronics Manufacturing Technology Conference (IEMT2018). Melaka, Malaysia. 4-6th Sept 2018. [Scopus]

Non-Indexed Conference Proceedings

1 NA Abdul-Kadir, **NS Sahar**, SM Saleh, SM Jusob, FKC Harun, WH Chan. A Wearable Internet-of-Things: Electrocardiograph. Joint Workshop for Global Engineers in Asia (JWGEA) 2017. Surabaya, Indonesia. 24-26th July 2017.

2 NA Abdul-Kadir, FSA Wahab, **NS Sahar**, FKC Harun. 2017. A Wearable ECG Device using A Neurosky Cardio Module. International Medical Device

and Technology Conference (iMEDiTEC2017). Malaysia. 6-7th September 2017. pp260-262.

Book Chapter

1 NA Abdul-Kadir, NM Safri, MA Othman, FKC Harun, **NS Sahar**, AM Embong. 2019. Domain Analysis for AF Features Extraction: A Review, in: Biomedical Instrumentation and Signal Processing. Universiti Teknologi Malaysia, Johor Bahru, Malaysia: UTM. Accepted.

2 SM Saleh, SM Jusob, **NS Sahar**, NA Abdul-Kadir, FKC Harun, DHB Wicaksono. 2018. Fabrication of Cotton Fabric as Flexible Electrode in Electrocardiography Monitoring, in: Lecture Notes on Multidisciplinary Research and Application. Malaysia Technical Scientist Association: Malaysia. pp97-106.