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3d Printed Bio-potential Dry Electrodes

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Abstract— **The most commonly used bio-potential electrodes are silver/silver chlorides gel-electrodes (Ag/AgCl electrodes). However, wet electrodes are not suited for daily usage and long-term monitoring. Dry electrodes are the best choice for long-term measurements. Dry electrodes can be fabricated using various methods and materials; one of these methods is three dimensional (3d) printing. 3d printing is a cost-effective method and can be easily used in mass production. This paper will present 3d printed bio-potential dry electrodes using five different commercially available fused deposition modeling (FDM) electrically conductive filaments. Then, these printed electrodes will be tested and validated using electrocardiogram (ECG) portable acquisition system. Three out of five filaments were printed successfully. Collected ECG data from these electrodes showed acceptable quality with Signal to Noise Ratios (SNRs) ranging around 20 dB when compared with wet electrodes collected raw data as a reference. In conclusion, this study designed and printed a 100% 3d printed electrodes from three different FDM filaments which could be used efficiently for ECG signal monitoring in resting position.**

I. Introduction

Wet electrodes are less suited for long-term use, since the electrolytic gel will cause skin irritation and allergic reactions. Also, the gel will dehydrate over time and this will decrease the quality of the signal. Therefore, dry electrodes are the best choice for long-term measurements. Dry electrodes could be reusable and are more convenient to be used and integrated in any configurations as conductive gel might cause short-circuiting if multiple wet electrodes are placed close to each other. Dry electrodes can be fabricated using various methods such as conductive fabrics, screen printing, and three dimensional (3d) printing. 3d printing is a cost-effective method and can be easily used in mass production. Also, 3d printing could be used to directly print assistive devices and prostheses which incorporate individually designed sensors and actuators without the need for additional post-processing steps. [1, 2, 3, 4, and 5].

Fused Deposition Modeling (FDM) is one of the most popular 3d printing techniques. The numbers of commercially available FDM materials have grown significantly in recent years, while the cost continues to decrease. The commonly used materials are thermoplastic filaments such as Polylactic Acid (PLA), Acrylonitrile butadiene styrene (ABS), thermoplastic polyurethane (TPU), and polyvinylidene fluoride (PVDF) [6]. Conductive filaments usually made of conductive polymer composites. These composites consist of a thermoplastic base material blended with carbon-based materials [7]. Table I lists the most popular commercially available conductive filaments.

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There have been some studies which developed 3d FDM printed bio-potential electrodes using conductive filament. Abdou et. al showed that the performance of the proposed 3d printed dry electrocardiogram (ECG) electrode is reliable for monitoring heart rate calculations [5]. Stopforth demonstrated that 3d printed ECG electrodes could be reusable and disinfected with chemical agents. He also showed that these electrodes could be used with magnetic resonance imaging (MRI) machines [8]. Hnat produced 3d printed semi-wet ECG electrode and showed that this electrode has lower resistivity when compared to commercially available wet and dry electrodes [9]. Foster et. al developed a 3d printed ECG electrode which could be used in the interaction between a therapy dog and human patient in a clinical Animal-assisted therapies setting [10]. Espadinha developed and tested 3d printed electromyography (EMG) electrode that could be integrated into the cuffs of 3d printed orthotic devices [11]. Kim et. al created a 3d printed EMG electrode to be used with cooperative healthcare sensing robots. [12]. Wolterink et. al designed, printed, and tested a 3d soft EMG sensing structures enables the creation of personalized sensing structures that can be potentially integrated in prosthetic, assistive and other devices [1].

The goal of this study is to explore the potential use of 3d printed dry electrodes made of conductive FDM filaments. Five different filaments were purchased and printed. Successfully printed electrodes were tested by acquiring ECG and comparing their performance to wet electrodes.

TABLE I. Commercially Available Conductive Filaments

Filament	Properties		
	Base material	***Doping material***	***Resistivity provided by manufacturer***
Proto pasta[13]	PLA	Carbon black	(x/y): 30 Ω.cm (z): 115 Ω.cm
Black Magic Graphene[14]	PLA	Graphene	0.6 Ω.cm
Palmiga PI-ETPU 95-250[15]	TPU	Carbon black	Less than 800 Ω.cm
Conductive Filaflex[16]	TPU	not mentioned	3.9 Ω.cm
Multi3D Electrifi[17]	Biodegradable Polyester	Copper	0.006 Ω.cm
Amolen[18]	PLA	not mentioned	1.42 Ω.cm
NinjaTek Eel[19]	TPU	Carbon black	1.5 × 103 Ω.cm
Koltron G1[20]	PVDF	Aros Graphene	2.0 Ω.cm
Filoalfa Alfaohm[21]	PLA	Carbon Nanotubes	(x/y): 15 Ω.cm (z): 20 Ω.cm
Sunlu ABS[22]	ABS	not mentioned	10^3 to 10^5 Ω.cm
3dkonductive[23]	PLA	Carbon black	(x/y): 23 Ω.cm (z): 53 Ω.cm
BlackMagic Flexible TPU[24]	TPU	Graphene	Less than 1.25 Ω.cm

II. MATERIALS AND METHODS

A. 3d Model

Fig. 1 illustrates electrode design with dimensions in millimeters. The goal was to design bio-potential electrode with knop that could be connected to the leads of ECG reading module. SolidWorks was used to create this model.

B. Printing Material and Printer

This study tested five commercially available conductive filaments. These filaments are Proto-pasta, Filaflex, Palmiga, Multi3D, and Sunlu. Proto-pasta is one of the most popular conductive filaments. It consists of a combination of milled carbon fibers and high-performance heat treatable PLA [13]. Filaflex is a flexible, electrically conductive TPU filament with 92A shore hardness. According to manufacturer [16], it is a good filament for the creation of wearable devices. Palmiga is a flexible, rubber-like, TPU filament filled with carbon fiber which makes it electrically conductive. It possesses 95A shore hardness [15]. Multi3D is a non-hazardous, proprietary metal-polymer composite that consists primarily of biodegradable polyester and copper [17]. Sunlu ABS holds good mechanical properties and toughness [22]. All five filaments were printed using 3d FDM printer called Qidi Tech X-Plus and its corresponding slicer program [25 and 26]. It is an enclosed printer with two interchangeable direct drive extruders. The default extruder is capable of printing general material such as PLA, ABS, and TPU. The second extruder is a high temperature extruder (printing temperature up to 300 °C) which designed to print advanced material such as nylon and carbon fiber. Table II explains printing settings were used for each filament. At least 3 electrodes were made for each filament.

C. Data Collection and Signal Quality Calculations

ECG data was collected using an integrated signal conditioning module called AD8232 [27] and Arduino Mega 2560 as a microcontroller. AD8232 will read ECG data using electrodes then sends the data to the microcontroller. The collected raw data will be stored in the pc using serial output function of the Arduino (Arduino sampling frequency for this experiment = 8 ms) then transferred to MATLAB. Signal-to-noise ratio (SNR), Peak signal-to-noise ratio (PSNR), mean squared error (MSE), and mean absolute error (MAE) values were calculated using MATLAB given that wet electrodes data was also collected in the same settings and used as a reference for these calculations. All data was collected from 1 subject in resting sitting position with minimum movement. The chest area was chosen to place ECG electrodes.

TABLE II. PRINTING SETTINGS

Settings	Filament				
	Protopasta	***Filaflex***	***Palmiga***	***Multi3D***	***Sunlu***
nozzle temperature	206°C	250°C	220°C	160°C	240°C
printing speed	45 mm/s	20 mm/s	30 mm/s	15 mm/s	50 mm/s
build plate temperature	60°C	60°C	60°C	60°C	110°C
retraction speed	30 mm/s	40 mm/s	30 mm/s	40 mm/s	30 mm/s
retraction distance	2 mm	2 mm	1.5 mm	1.5 mm	1.5 mm

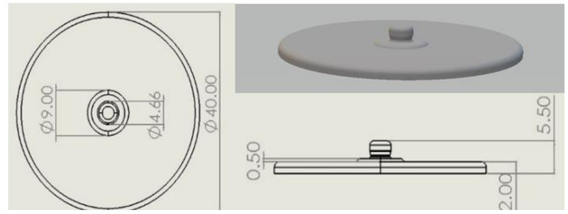

Figure 1. 3d design and dimensions in mm of the electrode.

D. Electrodes Resistance Values

The resistance values of 3d printed electrodes were measured using smart digital multimeter (GVDA GD128, resolution 0.1 Ω for values below 1 kΩ and accuracy ± 1%+5) [28]. These measurements has been done by placing multimeter leads; one on the knop and the other in the opposite side usually in the middle of electrode base. Resistance values were calculated for each filament using resistivity information given by manufacturers as shown in Table I, model dimensions presented in Fig. 1, and resistance law (resistance=resistivity*length/area). Cross sectional area was calculated using circle area law ($\pi * r^2$) for all electrodes including Protopasta in z direction. Protopasta electrode in x/y direction was assumed to be a half rectangle when the model being vertically divided in the middle (diameter*thickness/2). The 3d model was divided to 3 sections; electrode base, knop base, and the knop.

III. RESULTS

Fig. 2 shows sample of 3d printed electrodes and Fig. 3 displays a portion equals to 8 seconds of the collected ECG raw data. Table III demonstrates the results of SNR, PSNR, MSE, and MAE values for each filament except Palmiga and Multi3D as their knops were not printed successfully and data could not be collected from their electrodes.

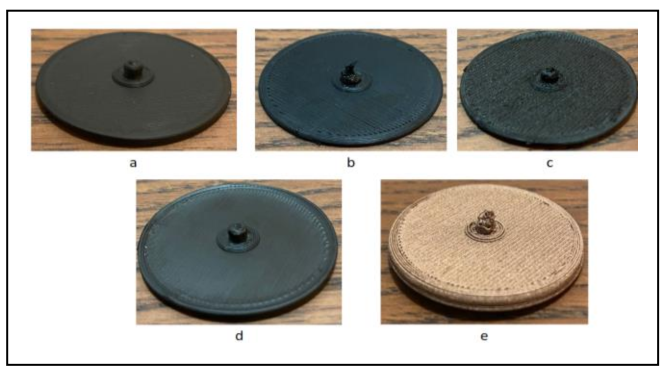

Figure 2. 3d printed electrodes: (a) Protopasta; (b) Palmiga; (c) Filaflex; (d) Sunlu; and (e) Multi3D.

TABLE III. SIGNAL QUALITY PROPERTIES FOR EACH SUCCESSFULLY PRINTED FILAMENT. DATA WAS COLLECTED FROM 1 SUBJECT AND A PORTION EQUALS TO 2 MINUTES WAS USED TO DO THESE CALCULATIONS. WET RAW ECG DATA WAS COLLECTED AT SAME CONDITIONS AND USED AS A REFERENCE DURING THESE CALCULATIONS

Filament	Properties			
	SNR	***PSNR***	***MSE***	***MAE***
Protopasta	20.87 dB	24.08 dB	977.22	19.4
Filaflex	20.97 dB	24.17 dB	956.94	18.76
Sunlu	19.94 dB	23.12 dB	1214.76	21.94

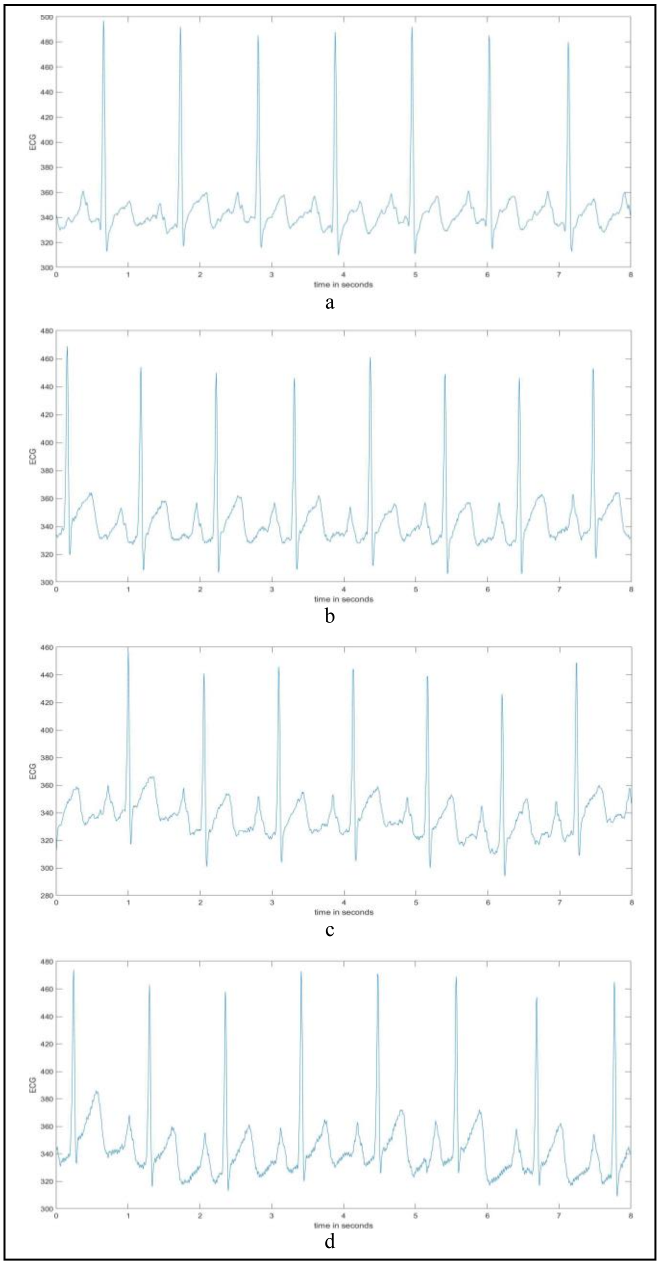

Figure 3. 8 seconds of raw ECG data for following electrodes: (a) Wet; (b) Protopasta; (c) Filaflex; (d) Sunlu.

Table IV demonstrates resistance values that were measured and calculated for each filament. Model dimensions presented in Fig. 1 were used to calculate resistance values. Electrode base has a diameter equals to 4 cm and cross sectional area of 12.56 cm^2. Knop area was calculated by dividing the knop to 2 sections; knop base and the knop. Knop base has a diameter equals to 0.9 cm which leads to cross sectional area equals to 0.64 cm^2 and the knop has a diameter equals to 0.466 cm resulted in cross sectional area equals to 0.17 cm^2. On the other hand, cross sectional areas in x/y direction were assumed to be 0.4 cm^2 (4 cm*0.2cm/2) for electrode base, 0.02 cm^2 (0.9 cm*0.05cm/2) for knop base, and 0.07 cm^2 (0.466 cm*0.3cm/2) for the knop.

IV. DISCUSSION

This experiment finds observable differences when compares the shape of printed electrodes (see Fig. 2). Protopasta and Sunlu filaments produced the most accurate electrodes in shape. Filaflex electrodes were efficiently accurate and have the advantage of being flexible. Palmiga and Multi3D electrodes were not printed successfully in the knop section and unfortunately, data could not be collected as a result of their melted knops. These melted knops were observed for all sets of electrodes printed using these two filaments (at least three electrodes were printed from each filament). Moreover, there were some mechanical difficulties which occurred during the process of printing these filaments. Palmiga filament caused noticeable stringing and oozing covering the nozzle during the printing process and Multi3D electrodes were very adhesive and it was a hard process removing these electrodes from printer bed.

TABLE IV. MEASURED AND CALCULATED RESITANCES.

FILAMENT	Resistance				
	Measured	***Calculated***			
		Electrode Base	***Knop Base***	***The Knop***	***Total***
Protopasta	~ 900 Ω	(x/y) = 30 Ω.cm * 4 cm / 0.4 cm^2 = 300Ω (z) = 115 Ω.cm * 0.2 cm / 12.566 cm^2 = 1.83 Ω	(x/y) = 30 Ω.cm * 0.9 cm / 0.02 cm^2 = 40 Ω (z) = 115 Ω.cm * 0.05 cm / 0.636 cm^2 = 9.04 Ω	(x/y) = 30 Ω.cm * 0.466 cm / 0.07 cm^2 = 6.67 Ω (z) = 115 Ω.cm * 0.3 cm / 0.171 cm^2 = 202.28 Ω	559.82 Ω
Filaflex	~ 400 Ω	3.9 Ω.cm * 0.2 cm / 12.566 cm^2 = 0.06 Ω	3.9 Ω.cm * 0.05 cm / 0.636 cm^2 = 0.31 Ω	3.9 Ω.cm * 0.3 cm / 0.171 cm^2 = 6.86 Ω	7.23 Ω
Palmiga	~ 2 kΩ	800 Ω.cm * 0.2 cm / 12.566 cm^2 = 12.73 Ω	800 Ω.cm * 0.05 cm / 0.636 cm^2 = 62.88 Ω	800 Ω.cm * 0.3 cm / 0.171 cm^2 = 1407.18 Ω	1.48 kΩ
Multi3D Electrifi	~ 10 Ω	0.006 Ω.cm * 0.2 cm / 12.566 cm^2 = 0.1 mΩ	0.006 Ω.cm * 0.05 cm / 0.636 cm^2 = 0.47 mΩ	0.006 Ω.cm * 0.3 cm / 0.171 cm^2 = 0.01 Ω	0.01 Ω
Sunlu	~ 50 kΩ	10^4 Ω.cm * 0.2 cm / 12.566 cm^2 = 159.16 Ω	10^4 Ω.cm * 0.05 cm / 0.636 cm^2 = 785.95 Ω	10^4 Ω.cm * 0.3 cm / 0.171 cm^2 = 17.59 kΩ	18.53 kΩ

Signal quality metrics were satisfactory for all successfully printed electrodes as shown in Table III. Also, looking at the collected raw ECG data in Fig. 3, these electrodes produced ECG with visible features. Table IV listed measured and calculated electrical resistance values. In general, measured resistances were relatively closed in values with calculated resistances except with Filaflex and Multi3D. Multi3D mentioned in their website that their filament will likely see a higher resistance as a result of the contact resistance between the probes and the filament.

V. CONCLUSION

This paper designed and printed a 100% 3d printed dry bio-potential electrodes successfully. The quality of the ECG signal acquired by these electrodes was very promising. Therefore, such electrodes could be used in the future as a standalone device or incorporated in a multiple parameters monitoring system. Also, these electrodes could be printed and incorporated with 3d printed assistive devices.

This was a primary study and further testing and validation are required. Future studies could focus on experimenting with signal quality during body movement, using EMG and EEG acquisition systems, using acquisition system with better performance and higher sampling frequency, using different sizes and shapes of the 3d model, using more accurate techniques to measure and calculated resistance values, and exploring various printers and printing settings.

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