ECE 445
Design Document
Fall 2019

Wearable Pediatric Eczema Tracker

Team 23
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1. Introduction

1.1 Objective

Eczema, also known as atopic dermatitis, is one of the most widespread skin conditions affecting nearly 20% of the world population and is more common and severe to young children and infants [1]. Its main symptoms are severe itching and skin cracking which eventually damages the skin. Until this day there is no known universal cure and what dermatologists suggest is to find the "triggers" which may involve consumed food, environmental exposures, or chemicals and to isolate the patient from it. The biggest problem is that it is nearly impossible to track down such triggers as symptoms of itchy skin rash may arise long after 24-48 hours from making contact, and since infants and children have limited means to convey their symptoms objectively for dermatologists to diagnose. There should be a viable alternative for such people in need.

With that said, our group aims to make a low cost wearable eczema tracking sensor specialized in pediatric population that helps dermatologists treat their patients using scratch monitor. It is equipped with bioimpedance tomography, accelerometer and temperature sensors for high detection accuracy. Patients will wear the sensor on the wrist of either arm with best comfort in a specific time of interest such as during sleep, where scratching events are detected directly through inference model in host PC and logged. Indication is given in green, yellow or red LED embedded in the device, depending on the severity of scratching through number and duration of scratches per timeframe so that guardians can notice right away. Users will also be able to log their daily information such as consumed foods, location and skincare appliances so when superimposing the scratch severity graph with these information, dermatologists can easily find pattern and track down which substance or environmental factor was the "trigger".

1.2 Background

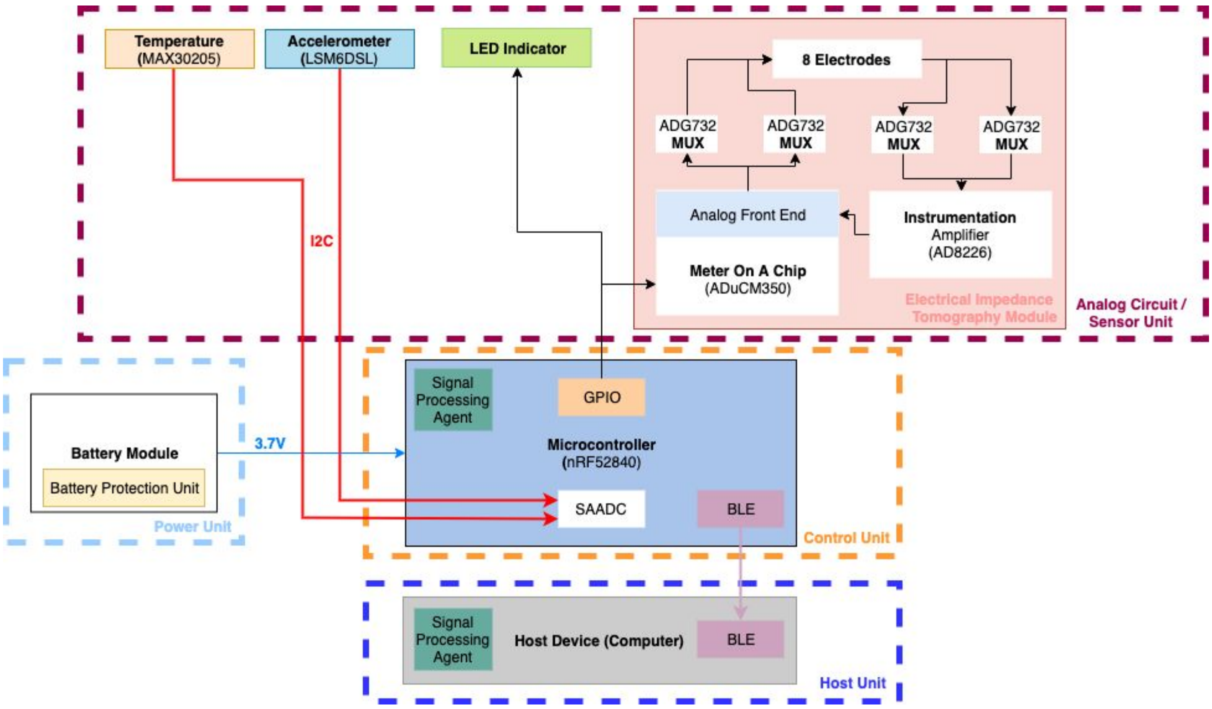
As of 2019 there are numerous solutions to bookkeep and track frequency of eczema flare-ups through smartphone applications [2, 3]. These applications provide daily tracking through manually logging score on the severity of the patient's pruritus. However there is still no known sensory-device based solution that provides objective metric of pruritus. Moreover this problem is pronounced for pediatric population as indicated by several literatures: "Because currently available tools to assess parental and patient reports of sleep disruption and itching correlate poorly with measures, objective studies are critical for the assessment of sleep disturbances in children with AD" [4, 5].

1.3 High-Level Requirements

- The device should stream data and be efficient enough to be used overnight (12H) using 850mAh or less battery.
- Sensory data is streamed through PC and tomographic figures are displayed in real-time. Frame rate of tomography should be higher than Nyquist rate of typical scratching, over 6Hz.
- Scratch detection classifier should perform better (0.90 sensitivity) than gold standard [10].

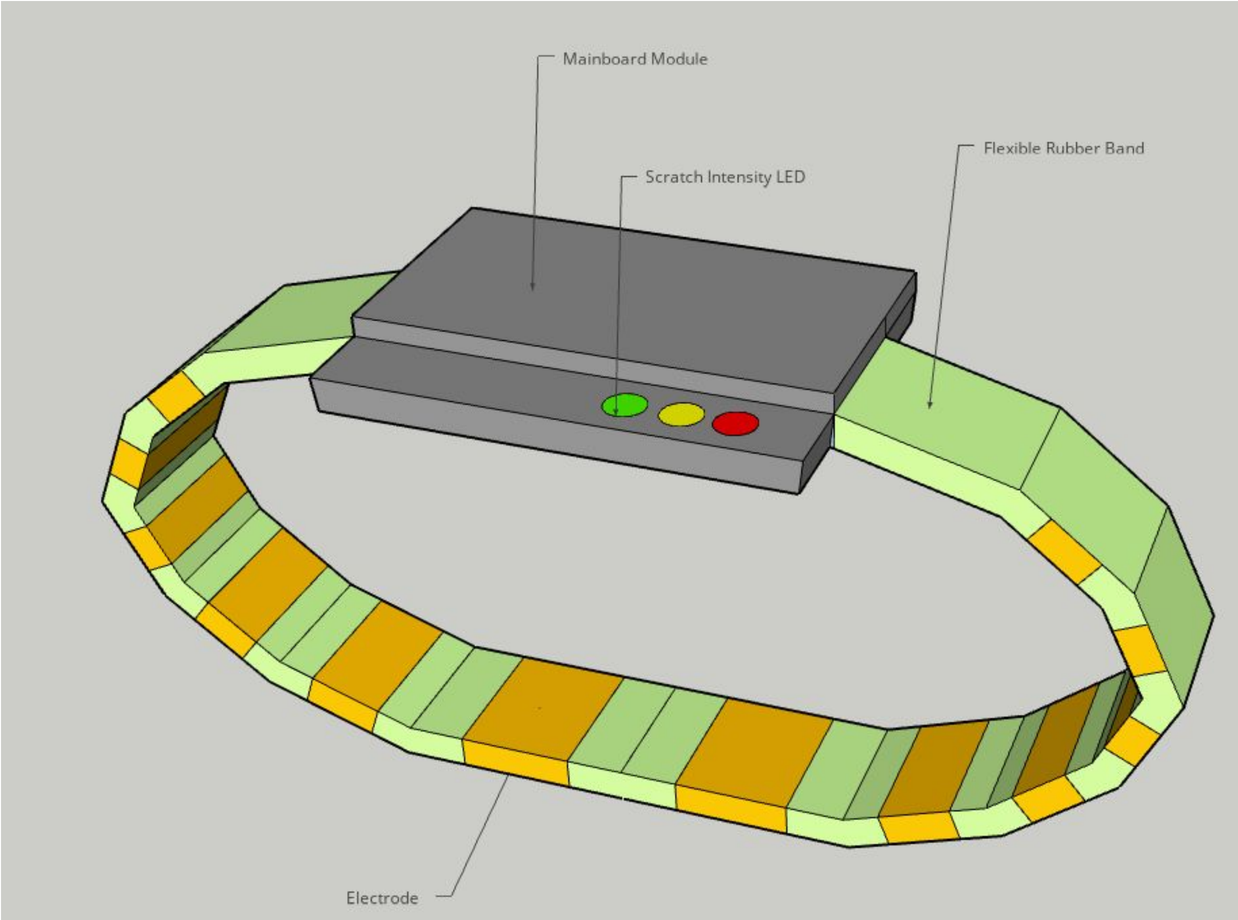
2. Design

2.1 Block Diagram

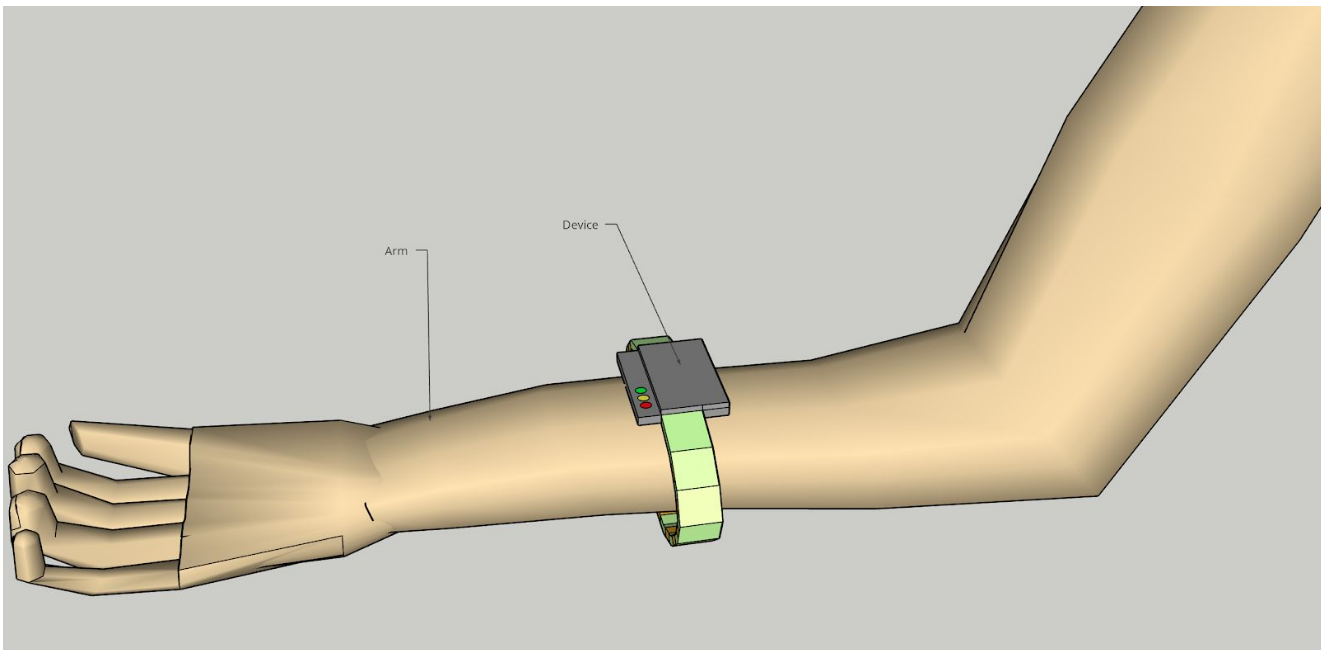


(Figure 1: Top Level Block Diagram for Wearable Pediatric Eczema Tracker)

2.2 Physical Design



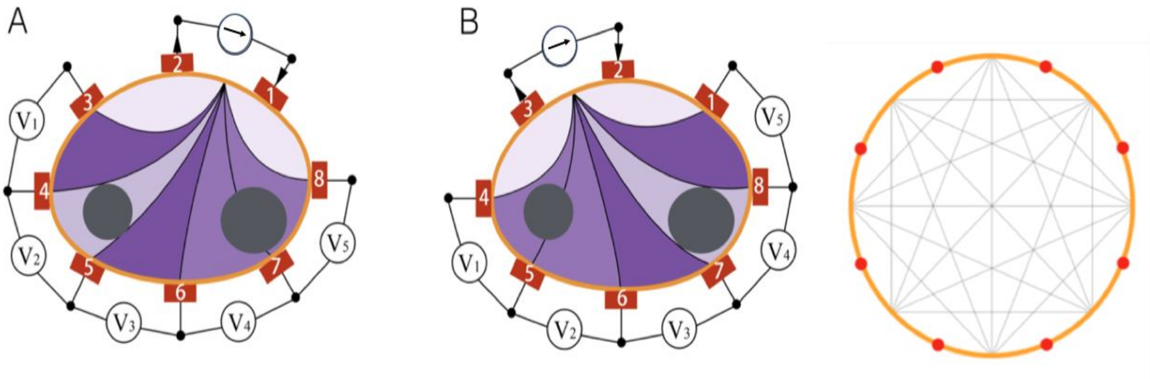
(Figure 2: Physical 3D Diagram for Wearable Pediatric Eczema Tracker)



(Figure 3: Actual Placement of the Sensor on the forearm)

2.3 EIT Module

By measuring multiple bio-impedance simultaneously using multiple electrodes, tomographic representation of the specific part of the body can be derived. Recently there has been attempts to detect hand gestures using EIT as it can track the movement and dynamics of muscles with high accuracy that EMG or accelerometer cannot deliver. It is also cost effective and consumes relatively low power compared to other tomography methods.



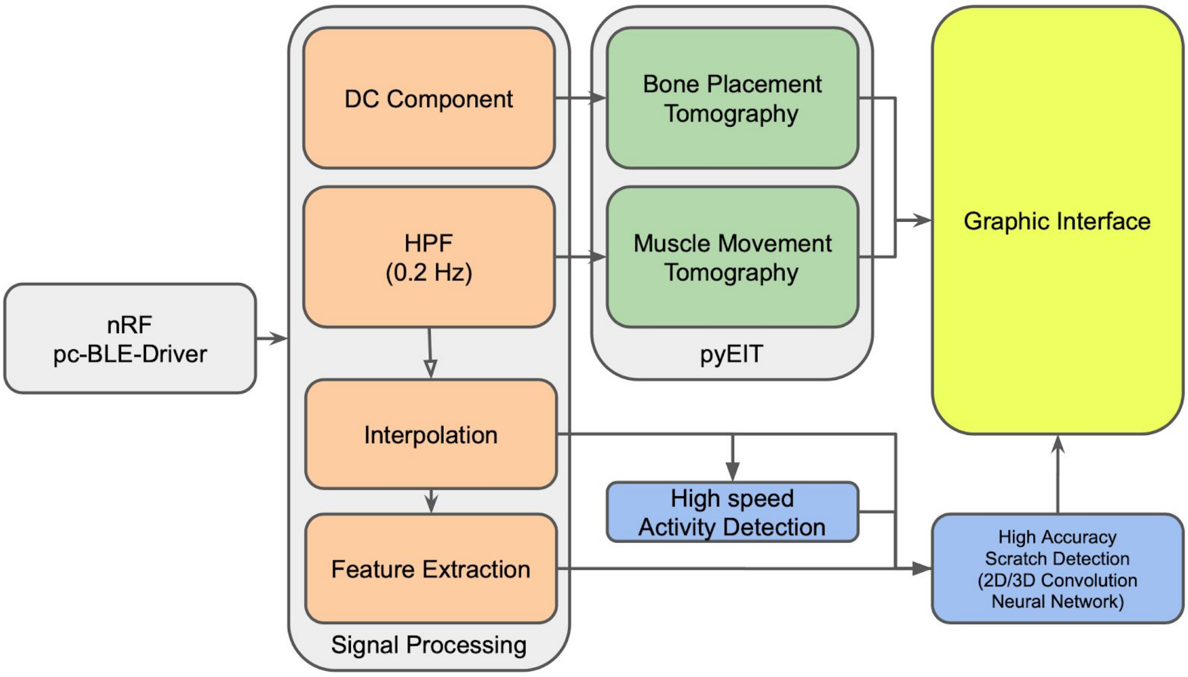
(Figure 5: Current injection and bioimpedance measurement in 4-pole scheme [9])

In order to measure bioimpedance, regulated AC current in fixed frequency is injected through one or a pair of electrodes depending on measurement method. Simultaneously, one or a pair of electrodes from other channels are used to measure the voltage for a short duration. For example, figure 5 shows how bioimpedance is measured from 4-pole scheme. Current is first injected through channel pair <1,2> and voltage is measured through <3,4>, <4,5>, <5,6>, <6,7>, <7,8> in order, each with brief time period for DC normalization. Therefore, with N electrodes, we can expect up to N-3 channels per single current injection, totaling up to N(N-3) channels.

We propose using 8 electrodes to maximize comfort and per electrode size as it is intended for pediatric use. Also, we plan on using a 4-pole sensing scheme as it is less affected by skin condition than technically more simple “two-pole” measurement scheme [9] and since we can achieve finer detail in tomography due to increased resolution given the same number of electrodes (40 channels for 4-pole, 28 channels for 2-pole with 8 electrodes). Using such technique requires using 4 multiplexers as described in Figure 2. Scratching involves applying periodic force where previous studies suggest that the frequency of such motion is no more than 3Hz [10], therefore we aim for refreshing rate of tomography image to be 10Hz, which would give us headroom for detecting scratching motion above the Nyquist rate (6Hz).

Requirements	Validation
1. Bioimpedance must be measured with minimum sampling rate of 6Hz for each channel	1. ADC in ADuCM350 is capable of pulling data at 160 kSPS. With <30kHz excitation AC current, therefore all the delays for measuring one sample of each channel must be summed and compared with the timing requirement (ex: 2.5ms for 40 channels with 10Hz sampling rate) A. Use an oscilloscope to measure the time delay for excited current to converge in steady state in <30kHz B. sum with minimum sampling number of ADC required for impedance calculation
2. Meets the IEC 60101-1 standards and current should not exceed 300μA rms [16]	2. A. Use additional instrumental amplifier (AD8226) for bio-isolated 4 pole scheme and prevent DC current bias B. Use R_limit in order to guarantee upper limit in current C. Using multimeter, test if electrodes meets the current limit standards

2.4 Software Module



(Figure 6: High level flowchart of software module)

2.4.1 Application for scratch logging and visualization, and Machine Learning Model

The application will have two main components- first, to log daily activity including which food the patient has consumed, places visited and skincare appliances used and second, give graphical information by superimposing these information with scratch severity graph for dermatologists to find patterns and track down which substance was the trigger. As scratch detection is done using time series data, we propose using two-pass method similar to continuous voice detection used in the industry [11]. First, the stream of data is processed and filtered so that only body movements to certain threshold are considered. Second, the filtered chunk of data is passed through main inference model to determine if such action is scratching or not. To minimize the data driven nature of certain inference models, we suggest performing preprocessing such as FFT, variational mode decomposition and autocorrelation to capture the periodicity, combined with other feature extraction and use linear SVM to lower the computation load.

Requirements	Validation
1. Robust tomographic image reconstruction, one figure with approximate with bone placement and second with muscle movement visualization	1. A. Prepare acrylic cylinder with embedded electrodes connected to EIT module B. Fill up 3-5cm of saline water with similar conductivity to that of human tissue C. Place EIT “phantoms (ex: wood, plastic object or vegetables)” with multiple placement D. Compare actual placement with reconstructed image
2. Scratch detection classifier has 90% detection sensitivity against other activities	2. A. Generate dataset with scratch, wave, walk activity on multiple subjects similar to gold standard B. Perform 5-fold cross validation on the dataset, performance on testing set is reported.

2.5 Analog Circuit Module

2.5.1 Temperature Module

Previous studies suggest that ambient temperature has high correlations with exacerbated eczema symptoms [5]. Therefore it is important to provide continuous temperature measured directly on the skin. The temperature sensor will regularly communicate with nRF52840 microcontroller through I2C protocol.

Requirements	Validation
Temperature sensor module has to collect accurate skin ambient temperature with precision of ±0.2°C with actual temperature within skin ambient temperature (25°C ~ 34°C) range [5].	1. Get a thermometer and measure the skin ambient temperature 2. Acquire temperature data using temperature sensor 3. Compare thermometer data with temperature sensor data to figure out the error range 4. Repeat several times to ensure precision

2.5.2 LED Indicator Module

For final demo purpose, the green LED will blink continuously every 5 seconds if infants do not scratch and perform normal activities. When the device predicts that an infant is scratching, through machine learning, the device will turn on the yellow LED when infant is scratching lightly or red LED indicating that the infant is scratching severely.

Requirements	Validation
Three LED indicators have to show user not scratching (Green LED blinking), mildly scratching (Yellow LED blinking), or severely scratching (Red LED blinking)	1. Acquire machine learning data and load each data of a person not scratching, mildly scratching, and severely scratching onto the microcontroller 2. Check for the LED change when loading different data

2.6 Power Circuit Module

2.6.1 Battery Module

Linear regulators are great choice for powering very low powered devices or applications where the difference between the input and output is small. Linear regulator resistance varies according to the load and results in a constant output voltage. However, switching regulators rapidly switch a series element on and off so that it can store the input energy temporarily and then release that energy to the output at a different voltage level. They can generate output voltages that are higher than the input voltage or of opposite polarity, so has more modes than linear regulators.

The device will have a form factor of arm band with part involving electrodes flexible in order to have them as adequately fit as possible and enhance signal quality. As the device is intended for everyday use, we will use battery system with switching regulator with single switch for use with minimal effort. In order to protect battery from severe draining, we will use battery protection chip from Texas Instruments BQ2970 which is a cost-effective voltage and current protection integrated circuit for single-cell Li-Ion and Li-Polymer batteries.

Requirements	Validation
The 3.7V battery with 850mAh has to provide fixed 3.7V in the tolerance of ±3% [19]	1. Use a multimeter to check constant 3.7V data without severe discharge 2. Using a multimeter, check to see if the battery provides fixed 3.7V in the tolerance range
Charged voltage after protection circuit should not exceed 4.2V(±0.1V) for inputs from 2.8V-4.2V the range [14].	1. Sweep voltage at the input connector from 2.8-4.2V using an oscilloscope when charging 2. Voltmeter at the output of the protection circuitry should not read more than 4.2V(±0.1V).

2.7 Control Unit

2.7.1 Bluetooth Low Energy (BLE):

The nRF52840 SoC [6] is equipped with 64MHz ARM® Cortex® M4 processor, 1MB flash storage and 256KB RAM and therefore is suitable for handling and streaming multi-sensor data. It is also embedded with a 2.4GHz RF transceiver and bluetooth 5.0 with up to 2Mbps data streaming in Bluetooth Low Energy (BLE) mode which has sufficient bandwidth for streaming tomographic data with relatively low energy use.

Required minimum data bandwidth calculation:

EIT Data - 400 Samples/s × 2 Bytes/Sample = 800B/s
Accl. Data - 10 Samples/s × 2 Bytes/Sample = 20B/s
Temp. Data - 1 Sample/s × 1 Byte/Sample = 1B/s

Total: 821 Bytes/s

Requirements	Validation
1. Supports minimum data transfer rate of 821B/s to host device.	1. A. Program two test boards with throughput test application provided on Nordic online documents. B. Setup one board as master and connect to an external terminal through UART/USB. Open a serial connection to COM port of the master board. C. Setup the other as slave. D. Start the application using onboard button and check the throughput displayed on the console.

2.7.2 Additional Information on NRF52840

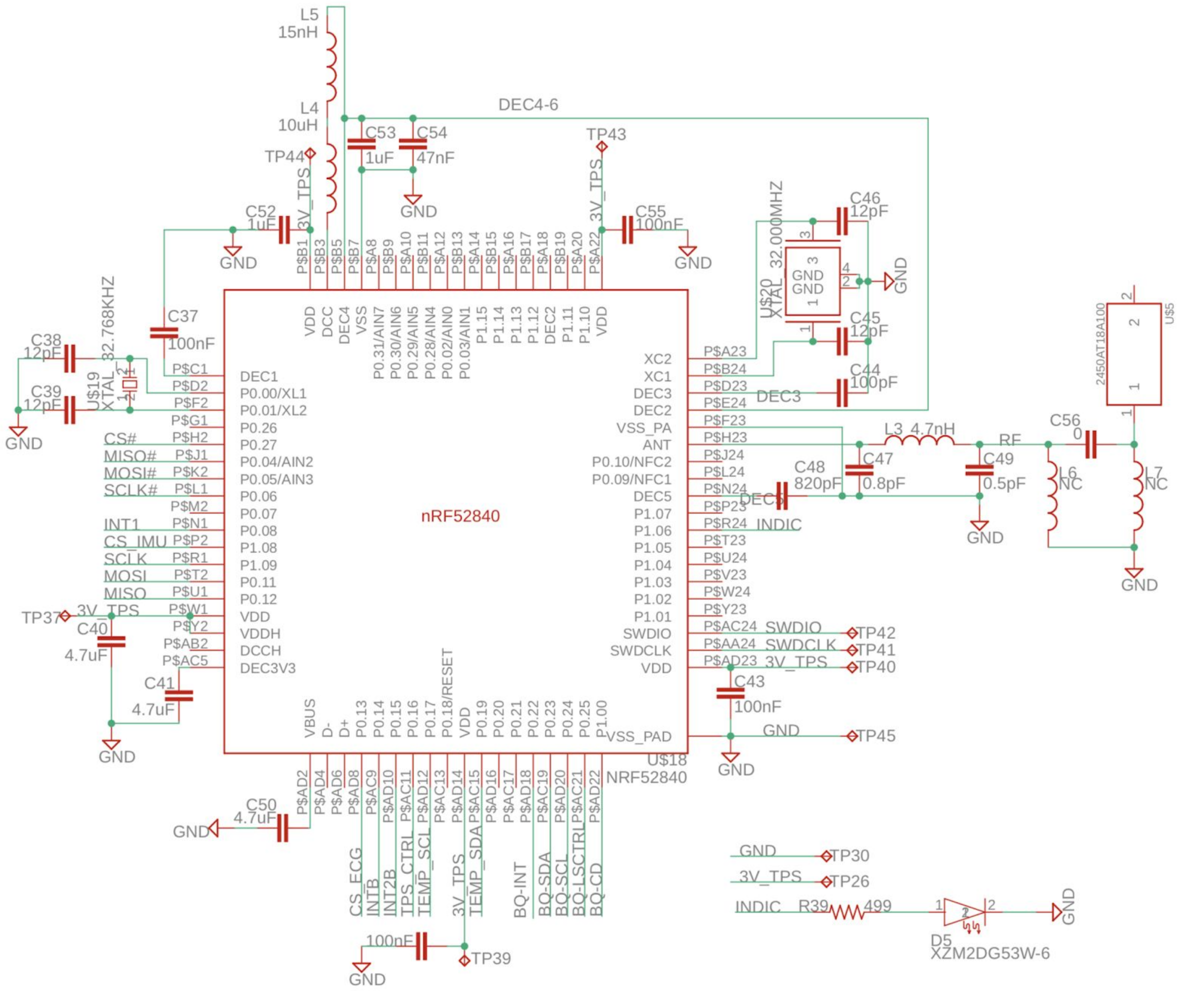
- **Memory :** nRF52840 has a 1 MB of flash and 256 kB of RAM that can be used for code and data storage. RAM AHB slave 0-7 is connected to 2x4 kB RAM sections each and RAM AHB slave 8 is connected to 6x32kB sections. The flash is divided into 256x4 kB pages that can be accessed by the CPU via both the ICODE and DCODE buses. This flash memory and RAM are enough to fetch data from the computer to real time track the data nRF chip collects.

- **SAADC :** Successive approximation register analog-to-digital converter can hold up to 8 different signals simultaneously and sample up to 100,000 samples per second, which is more than enough to handle our signals from the EIT module, accelerometer and temperature module from figure 1.

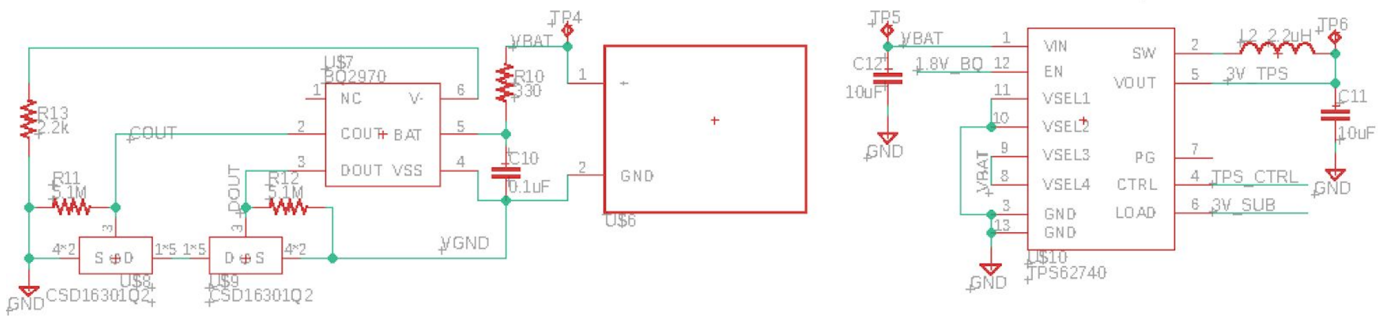
- **Timer :** nRF52840 has a timer module which the timer frequency = 16MHz / $2^{Prescaler}$. When the timer frequency is less than or equal to 1MHz, the timer will use PCLK1M instead of PCLK16M for reduced power consumption. However for our sensor, we will use typical 16MHz clock that is extremely precise for our real-time streaming for our eczema tracker.

- **GPIO :** nRF52840 chip's general purpose input/output will indicate LED status whether the infants are scratching or not and connect with ADuCM350 in the EIT module from figure 1 to provide current to the two electrodes to measure biological impedance of infants. Also battery level status can be seen from this GPIO port.

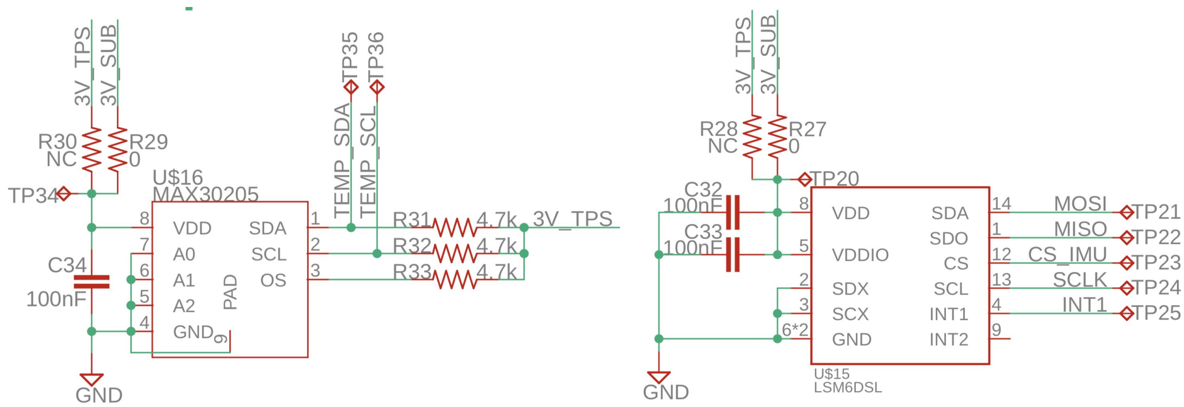
2.8 Schematics



(Figure 7: Schematic of NRF52840)



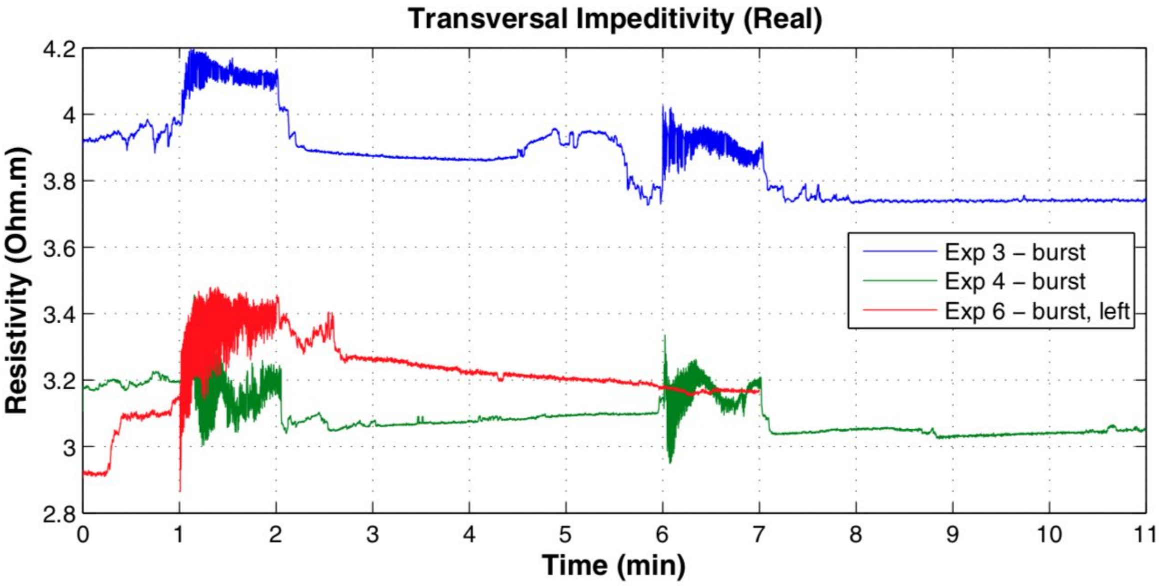
(Figure 8: Schematic of Battery Module)



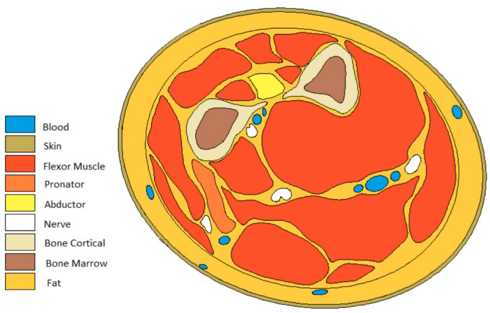
(Figure 9: Schematic of (Left) Temperature Module and (Right) Accelerometer)

2.9 Tolerance Analysis

The eczema tracking device requires precise bioimpedance measurement in order to meet the baseline functionality and for successful classification. The key is to have a high dynamic range so that while it can measure the absolute impedance value, it should also catch the impedance fluctuation from muscle contraction involved in scratching effort. To begin, we must address that the transversal muscle impedance difference when relaxed against when contracted or with stimulation, the resistivity difference is approximately 10% [6].



(Figure 11: Transversal impedance difference in swine muscle [7])



TISSUE	CONDUCTIVITY (S/m)	RELATIVE PERMITTIVITY
FAT	0.03	$5x10^6$
MUSCLE, TRANSVERSAL	0.09	$2x10^7$
MUSCLE, LONGITUDINAL	0.55	$3.3x10^6$
SKIN	0.1135	$6x10^5$
BONE, CORTICAL	0.03	$5.2x10^5$
BONE, MARROW	0.002	$45.5x10^3$
BLOOD	0.7	$3.0x10^3$
NERVE	0.028	$5.89x10^6$

(Figure 12:(Left) Ideal forearm model and (Right) impedance table [17, 18])

Combined with the ideal model (50mm radius cylinder consisting of different layers of 27.5mm muscle, 1.5mm skin, 8.5mm fat, 6 mm of bone and 6.5mm of bone marrow) and the impedance table of human arm [17, 18], we can assume that 50% of cross sectional impedance of arm to be muscle tissues from the sum of all portions including fat and skin. Then the total impedance difference that we should observe is 5% of the total value on the farthest electrodes when neglecting the dynamic effect of tissue differences. It should also be noted that most of the other 50% consists of bone, fat and skin which all have high impedance and as electric current flows to path with least resistivity, impedance difference of muscle plays most of the role. Therefore detecting impedance difference of 5% is the lower bound for the required dynamic range.

From previous studies (figure 13, [15]), we can expect absolute impedance of arm to be 1~1.8kΩ for adult male. To further expand the user population from pediatric to adults with thick arms, we can assume to have impedance boundary of 500Ω ~ 5kΩ, from which the minimum resolution required to detect muscle movement is 500 * 0.05 = 25Ω.

Then starting from provided formula to calculate impedance from measured voltage and current, we have:

$$Z(Magnitude) \;=\; (V_{Measured} \,/\, I_{Measured}) \,*\, (1.5/G_{AD8226}) \,*\, R_{TIA}\ [\Omega]$$

where R_{TIA} is the transimpedance amplifier resistance and G_{AD8226} is the gain from configurable resistor in AD8226 instrumental amplifier. We can first simplify to work with bit values as both voltage and current measurement are done on 16bit ADC on ADuCM350 and also expand this to approximate the maximum error due to the ADC as following:

$$Z(Error) \;=\left(\frac{(1+ADC_{V+DNL})}{(1-ADC_{I+DNL})} \;-\; \frac{(1-ADC_{V-DNL})}{(1+ADC_{I-DNL})}\right) *\ (1.5/G_{AD8226}) *\ R_{TIA}\ [\Omega]$$

and by applying setting provided in [16], DNL = 0.9*2 [LSB], R_{TIA} = $34.3k\Omega$, G_{AD8226} =1.494:

$$Z(Error) \;=\left(\frac{1+2^{-16+1.8}}{1-2^{-16+1.8}} \;-\; \frac{1-2^{-16+1.8}}{1+2^{-16+1.8}}\right) *\ (1.5/1.494) *\ 34.3k\Omega$$

$Z(Error) \;=\; 7.32\Omega$, which is well under 25Ω.

3. Cost and Schedule

3.1 Cost Analysis

3.1.1 Labor

From ECE Illinois website, the average starting salary for students graduating with a bachelor's degree in computer engineering is $96,518 (2016-17). Similarly, the average starting salary for students graduating with a bachelor's degree in electrical engineering is $71,166.

$$Electrical\ Engineering\ Hourly\ Wage = \frac{\$71,166}{yr} \times \frac{1yr}{52\ weeks} \times \frac{1\ week}{40\ hours} = 34.21\$/hr$$
$$Computer\ Engineering\ Hourly\ Wage = \frac{\$96,518}{yr} \times \frac{1yr}{52\ weeks} \times \frac{1\ week}{40\ hours} = 46.40\$/hr$$

We are averaging this semester as 16 weeks and averaging weekly hours we spend on this project to be 15 hours.

Team Member	Hourly Wage [$ / hr]	Weekly Hours	Number of Weeks	Multiplier	Cost per Member
Sung Hoon Lee	34.21	15	16	2.5	$20,526
Dong Hyun Kim	34.21	15	16	2.5	$20,526
Hyoungjo Hahm	46.40	15	16	2.5	$27,840
				Total Cost	**$68,892**

3.1.2 Parts

Part Name	Description	Manufacturer	Quantity	Unit Cost	Total Cost
LSM6DSLTR	Accelerometer	ST Microelectronics	1	$4.09	$4.09
MAX30205MTA+T	Temperature Sensor	Maxim Integrated	1	$3.64	$3.64
NRF52840	SoC Microcontroller	Nordic Semiconductor ASA	1	$6.38	$6.38
BQ29700DSER	Battery Protection Unit	Texas Instruments	1	$0.69	$0.69

CSD16301Q2	MOSFET	Texas Instruments	2	$0.54	$1.08
TPS62740DSSR	Bluetooth Voltage Regulator	Texas Instruments	1	$1.74	$1.74
ADUCM350BBCZ	16 bit Low Power Microcontroller	Analog Devices Inc.	1	$16.52	$16.52
ADG732BSUZ	32 Channel MUX	Analog Devices Inc.	4	$11.99	$47.96
AD8226BRMZ	Output Instrumentation Amplifier	Analog Devices Inc.	1	$5.06	$5.06
B0749KNFL3	3.7v 850mAh Battery	Three Stone	1	$4.75	$4.75
				Total Cost	**$91.91**

3.1.3 Grand Total

$68,892 (Labor) + $91.91 (Parts) = **$68983.91**

3.2 Schedule

Week #	Deadlines	Dong Hyun	Hyoungjo	Sung Hoon
Week 6 (9/30)	1. Design Document due 2. Design Review Sign-up	Prototype Embedded Programming with ADuCM350 Evaluation Board	Complete design document and polish up its structure	Finish design document and work on library update on parts used for the project
Week 7 (10/7)	Design Review	Complete 8-electrode setup with ADG732 MUX	Plan and complete BLE protocol between the device and the host	Complete library for the project and finish schematic on Eczema tracker
Week 8 (10/14)	1. Teamwork Evaluation I 2. Early Bird PCBway order 3. Soldering Assignment	Complete EIT module schematic implementation and soldering assignment	Complete schematic and embedded source codebase for BLE	Complete board file diagram for the Eczema tracker and soldering assignment
Week 9 (10/21)	1. First round PCBway order 2. Last week for Machine	Complete real-time image reconstruction in Python, report	Make sure that communication between the device and the host is	Write BOM files and Gerber files and revise design using machine shop

	shop revision	saline water test for validation	established without problem	
Week 10 (10/28)	Individual Progress Reports	Generate scratch detection dataset on three test subjects, train on two candidate classifier models	Record any progress while finalizing and debugging BLE component	Write Individual progress reports and work on debugging
Week 11 (11/4)	1. Final round PCBway order 2. Presentation Workshop	Complete signal processing pipeline with scratch classification model with best performance	Review the whole embedded codebase and amend or add extra features if needed	Work through embedded code on microcontroller specifics and timing issues for bluetooth
Week 12 (11/11)	Prepare for mock demo	Assemble device with electrodes placement, complete edge case on	Double check the current working model and work on any extra features is needed	Acquire more data for machine learning and finalize soldering
Week 13 (11/18)	Mock demo	Field Trial and validation	Prepare for the demo and conduct extra tests and debugging	Finalize the sensor for mock demo, and final demo, wrap up necessary debugging
Week 14 (11/25)	Fall Break	Final Demo Testing	Final Demo Testing	Final Demo Testing
Week 15 (12/2)	1. Final Demo 2. Mock Presentation	Final Paper Final Presentation	Final Paper Final Presentation	Final Paper Final Presentation
Week 16 (12/9)	1. Final Presentation 2. Final Paper 3. Lab Notebook 4. Lab Checkout 5. Teamwork Evaluation II	Final Paper Final Presentation	Final Paper Final Presentation	Final Paper Final Presentation

4. Safety and Ethics

According to IEEE Code of Ethics, technologies by all means must avoid causing human injury [6]. Since the product is a wearable technology that directly touches and wraps around a human body with electric circuitry, there are many possible safety concerns that must be handled in order to comply with the code. For example, the circuitry contains a battery, which might cause a skin burn when the electric flow is poorly designed or handled and result with heat up in the circuit. The electric current must be strictly controlled and cut off in necessary situations where any malfunctioning is detected.

As the device is intended for direct contact with human skin, the hardware must be equipped to comply with IEC 60101 standards. Therefore we must add additional bio-isolation circuitry to ensure the upper limit for current injection and prevent any DC voltage through additional instrumental amplifier (AD8226), capacitors for DC removal and current limit resistors with values according to the voltage output of AFE in ADuCM350.

From Battery module, we will be using a 3.7V LiPol battery as our power source, which has on average a capacity of 800mAh and electrical concerns such as discharge will be at a minimum. Other than electric hazards, the wrist band might also affect blood flow if worn too tightly. A way to properly adjust band should be provided to prevent adverse effect on the wearer's body while ensuring signal quality to be high enough for smooth processing.

The device is stretchable to some extent in order to fit patients' wrist and the electrodes should stick right on to the skin in order to minimize the noise. Depending on subject type, 8~32 electrodes are placed evenly around the device for even spatial resolution. Since we will be measuring and storing biological metrics which is sensitive and personal, it is necessary to come up with a reliable way to protect the privacy. For example, all stored data can be encrypted and the local raw data can be deleted right after the analysis. Also, we may obtain the user's consent to process his or her health data before conducting any measurements.

Lastly, in order to detect scratching, we use colored LED indicators: Green for normal activities, yellow for mild scratching and red for severe scratching. According to IEC 60601-1-8 standards [10], in the collateral standards, test and guidance for alarm systems in medical equipment is necessary using colors of indicator lights. Red indicates that immediate user intervention is required or used in dangerous situations. Yellow indicates that "prompt" user action or attention required or caution. Green indicates normal situation and equipment is ready to be used. We will be following IEC 60601-1-8 collateral alarm standard and implement alarm system into the wearable device.

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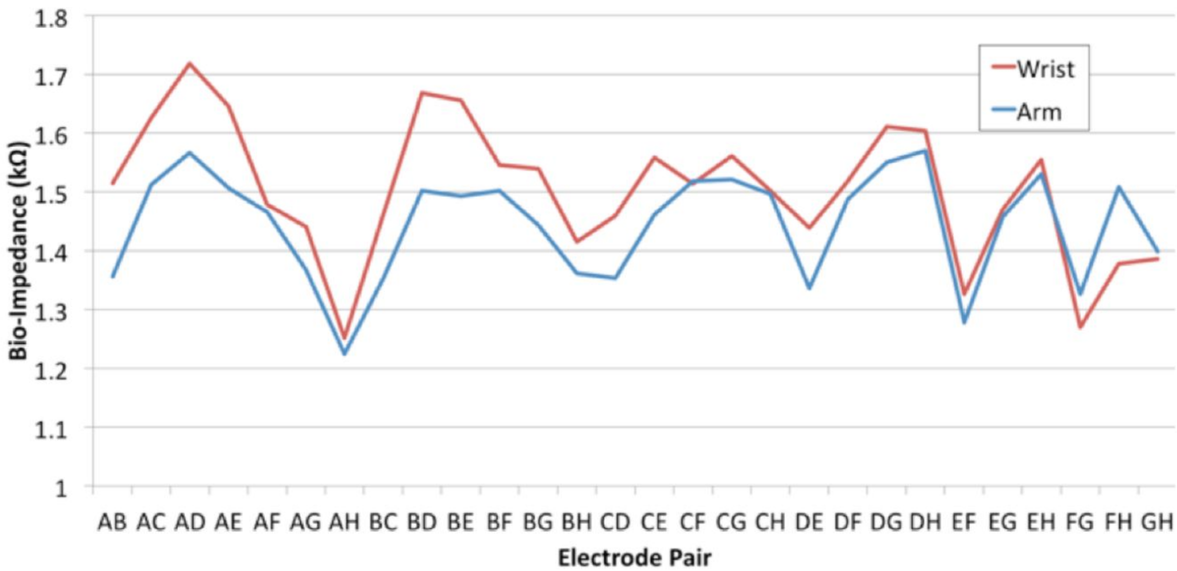
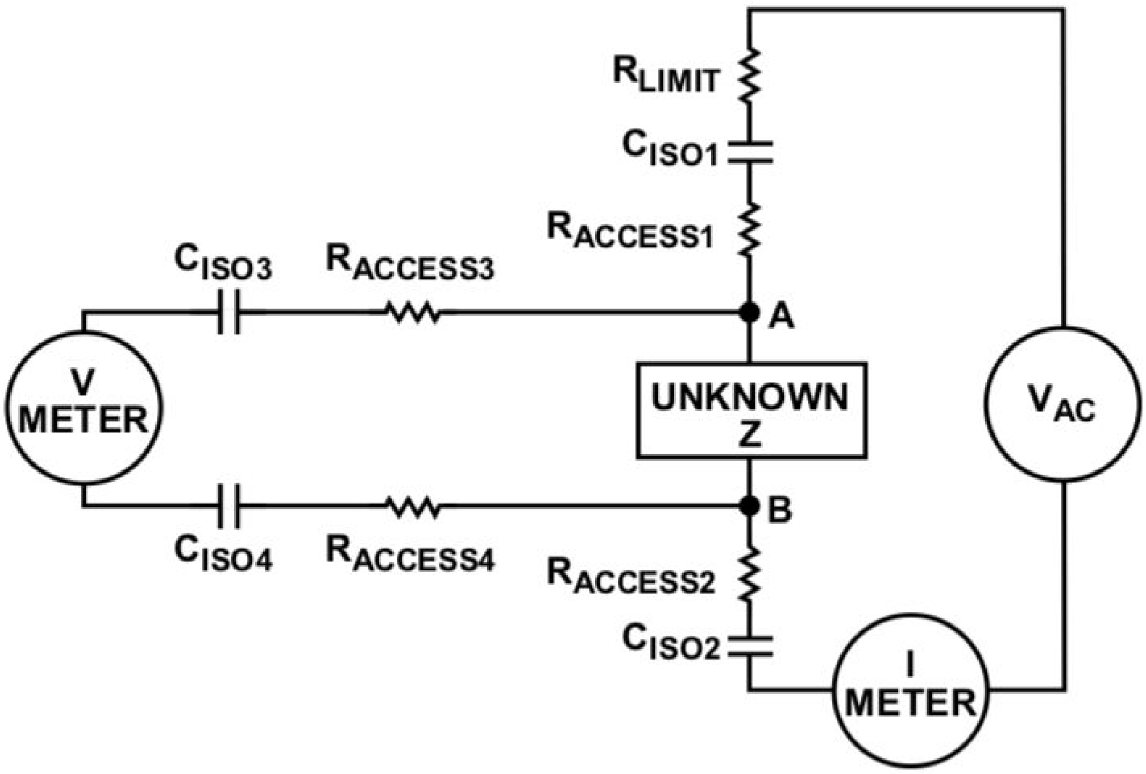
Appendix



(Figure 13: Bio-impedance of adult male arm on 28 channels [15])



(Figure 14: Bio-isolated impedance measurement scheme [16])