EMI Evaluation and Immunity Testing Method for Wearable Devices

Jianqing WANG

Nagoya Institute of Technology
Japan

2016.09.06

About Wearable Devices

- A wearable device usually consists of a sensor and a transceiver. It is worn on the body, either as an accessory or as part of material used in clothing.
- The sensor is used to acquire various data such as vital signs in daily life, and the transceiver enables data to be exchanged between a network and the device.
- Body area network (BAN), a short range communication and networking technique in the vicinity of, or inside, a human body, is essential for a wearable device.

✓Categorization of Applications

Medical and healthcare application	Assistance to people with disabilities	Consumer electronics and user identification
Medical check-up Medical diagnosis and treatment Physical rehabilitation Physiological monitoring	Blind person Speech disability Artificial hands and legs Accident prevention for elder people	Wireless headphone Audio/video streaming share User identification Automatic payment

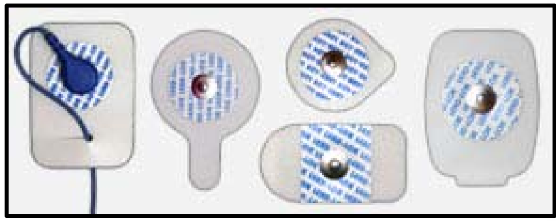
Typical Examples of Wearable Devices and Representative Detection Methods

Watch Type

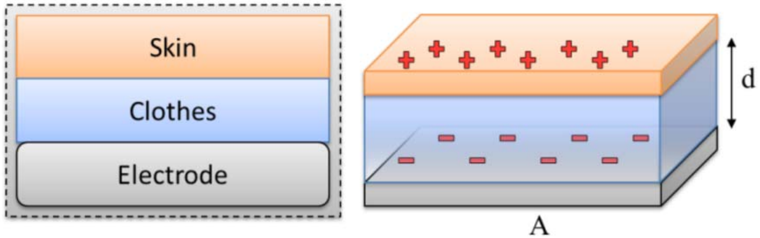
http://biz.chosun.com/site/data/html_dir/2014/09/18/2014091802812.html

Glasses Type

- Conducting electrodes
  - •Conductors directly touching skin
  - •Ex) ECG, heartbeat, EMG

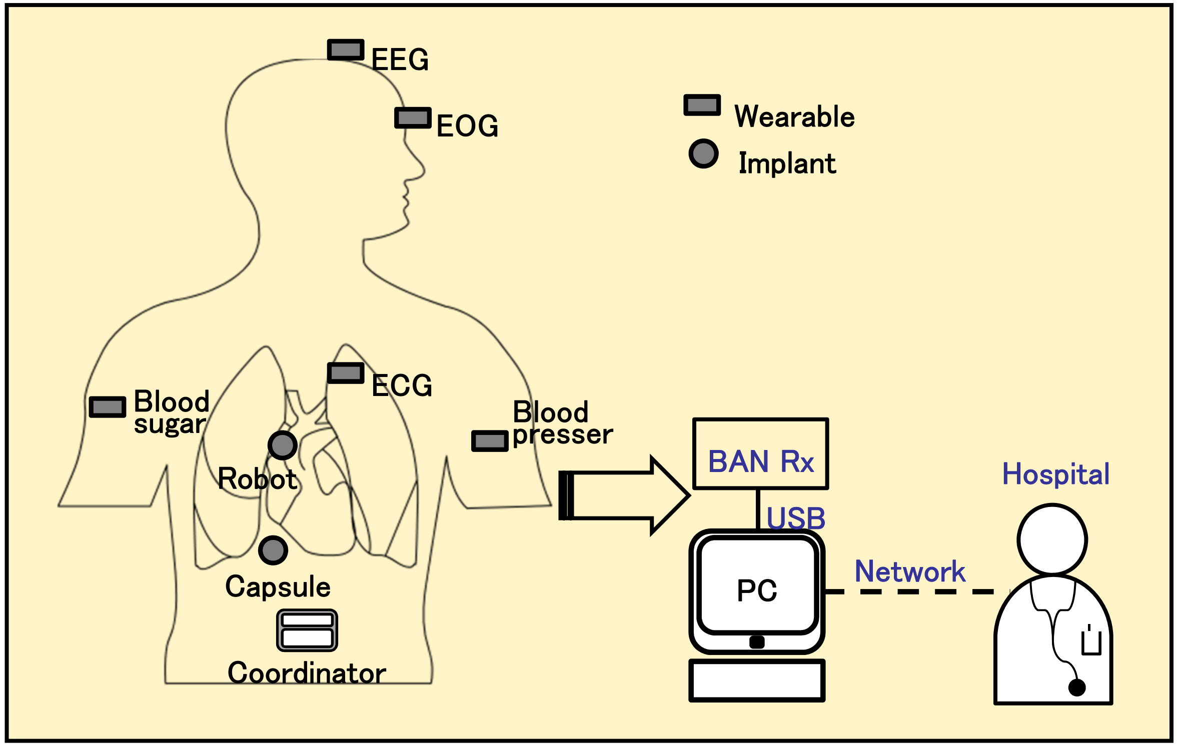


- Capacitive coupling electrodes
  - •Non-contact & a few mm detection
  - •Bed, chair, and wearable application



Healthcare and Medical BAN Developed in NITech
at Extremely Weak Radio Band 10-60 MHz

J. Wang, T. Fujiwara, T. Kato, and D. Anzai, "Wearable ECG based on impulse radio type human body communication", IEEE Trans. Biomed. Eng., vol.63, no.9, pp.1887-1894, Sept. 2016



- ✓ Each sensor with a transceiver is used to collect vital data and send them to an on-body coordinator
- ✓ Wireless link to the on-body coordinator employs human body communication (HBC)
- ✓ Data transmission to a hospital or medical centre employs cellular systems or LANs

- Increasing aging population is leading to a wide-scale demand in healthcare and medical applications. This makes various wearable devices with vital signal sensing and communication functions be developed and put into the market in a high speed.

- However, EMI evaluation and immunity testing method for these wearable devices have not been well established because of their too rapid advances.

Contents of This Talk

This talk consists of two parts:

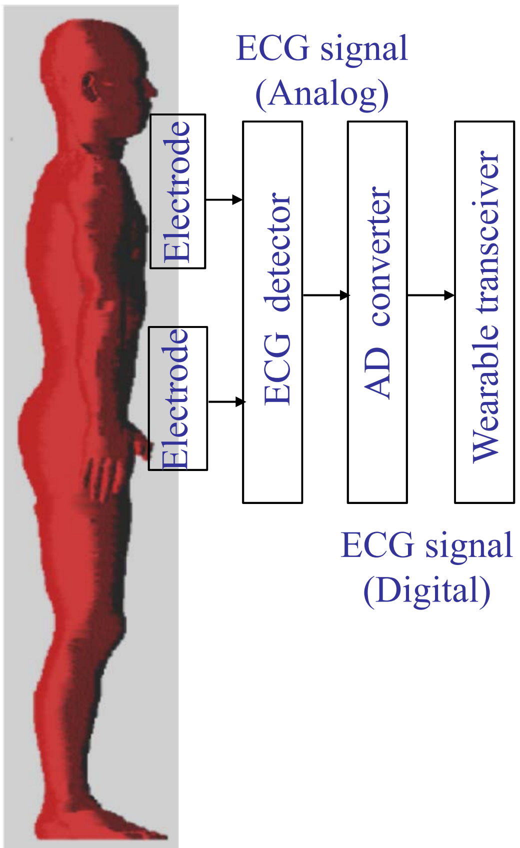
1. We show a two-step approach to quantitatively evaluate the EMI for a wearable device in the design stage. The approach combines electromagnetic field analysis and electronic circuit analysis, and clarifies the main EMI mechanism in wearable devices.

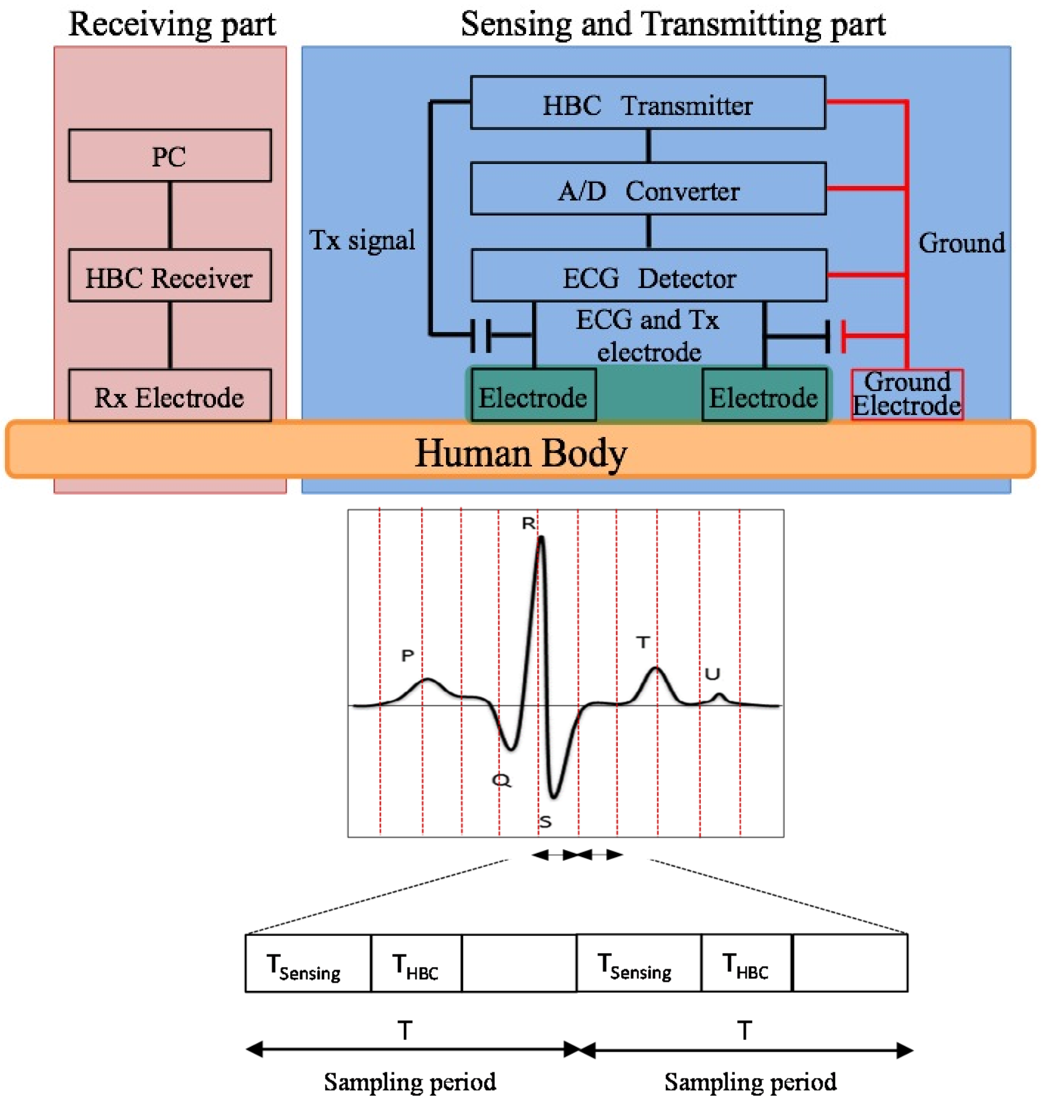
2. We show an immunity testing system which consists of a pseudo vital signal generator and a biological-equivalent phantom. By applying this testing system to a myoelectric artificial hand in an electrostatic discharge (ESD) test, we demonstrate its usefulness for immunity testing of wearable devices.

(1) EMI Evaluation of Wearable Devices

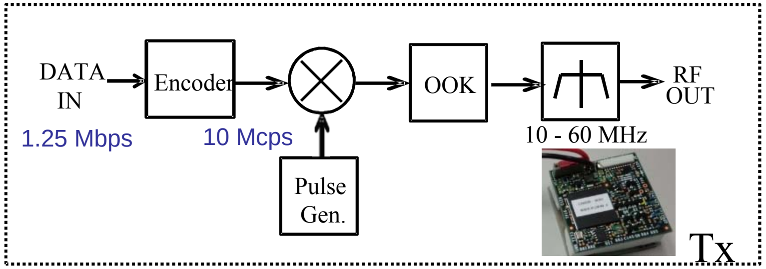
Human Body Communication – Based Wearable ECG

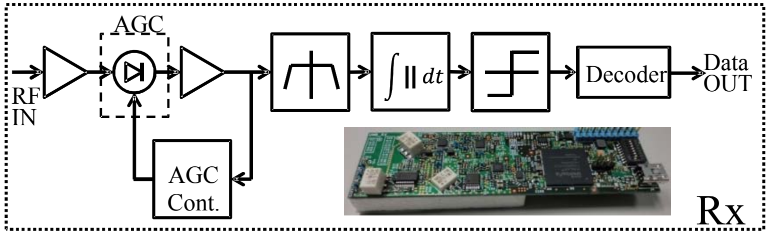
J. Wang, T. Fujiwara, T. Kato, and D. Anzai, “Wearable ECG based on impulse radio type human body communication”, IEEE Trans. Biomed. Eng., vol.63, no.9, pp.1887-1894, Sept. 2016





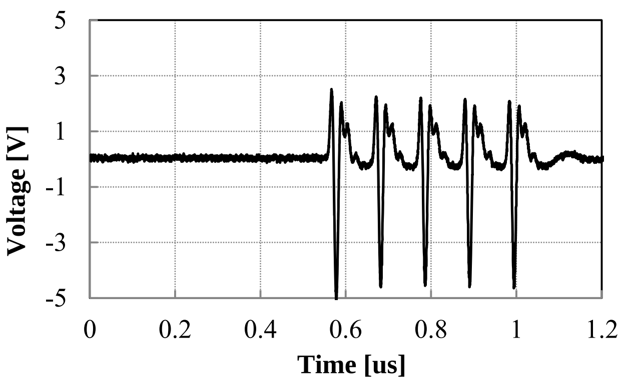
HBC Transceiver



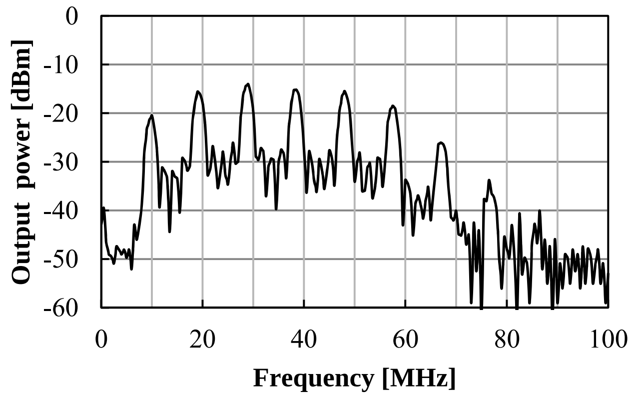


Function	Specification
Pulse width	10 ns
Pulse number per bit	8
Frequency band	10 – 60 MHz
Modulation	IR-MPPM
Data rate	1.25 Mbps
Maximum output	-15 dBm
Demodulation	Envelope detection
Tx consumption power	4.8 mW

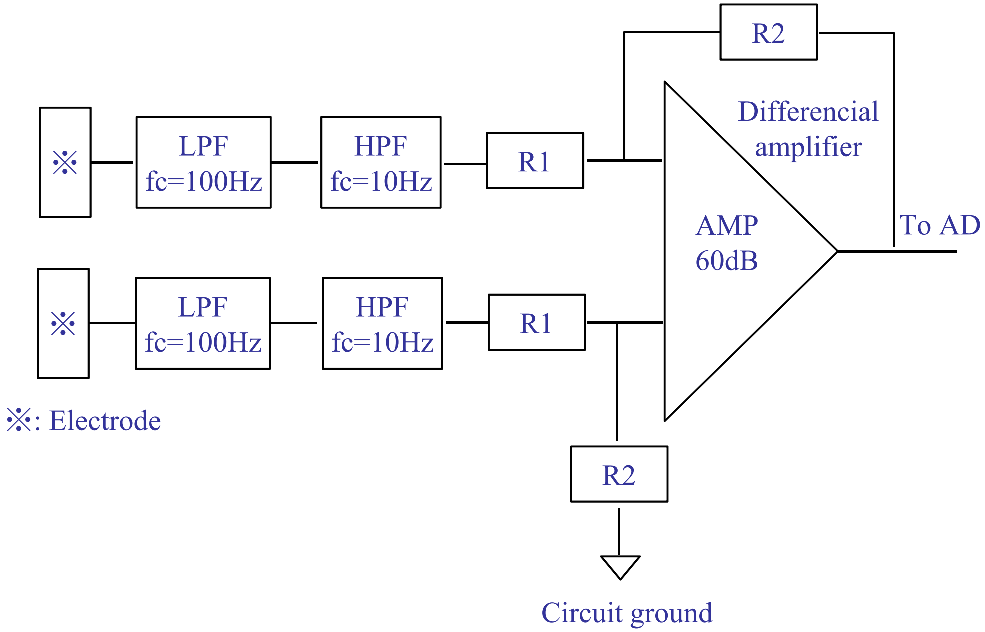
- Example of Tx time waveform

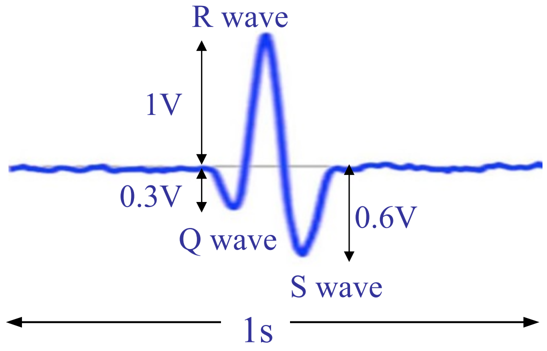


- Spectrum of Tx signal



ECG Detection Circuit



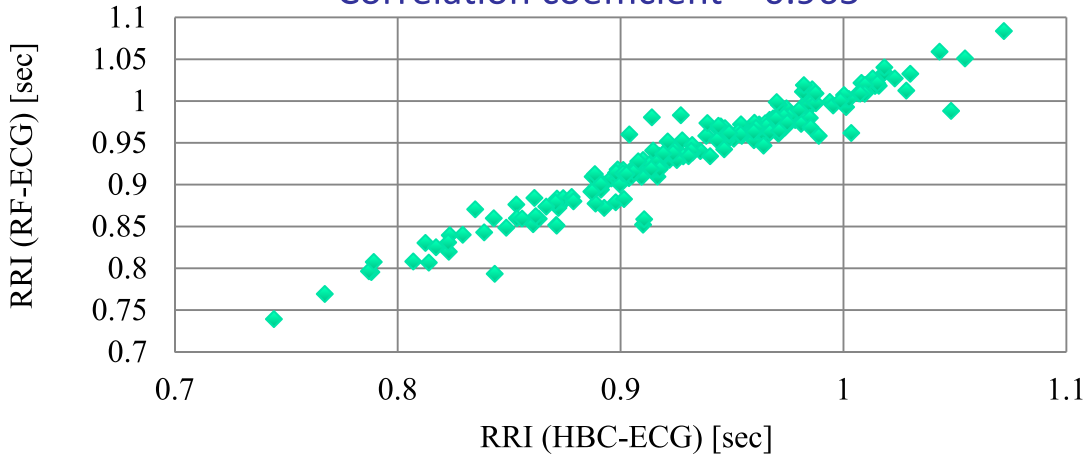


- ECG signals acquired from the two sensing electrodes are filtered and differentially amplified with an operational amplifier.
- LPF and HPF are used respectively to remove DC component, drift noises, and high frequency interference noises.

Wearable ECG Performance Verification (1)

- Time domain parameters

Correlation coefficient = 0.965



RF-ECG

Function	Specification
Company	Micro Medical Device, Inc.
Frequency	2.4 GHz
Transmit power	1 mW (0dbm)
Data rate	1 Mbps
Communication distance	15 m
Sampling rate	204 Hz

Comparison for RR50 [Sample/min]

Subject	A	B	C	D	E	F	Average
HBC-ECG	12	16	12	15	13	11	13.2
RF-ECG	15	13	14	14	14	11	13.5
Relative diff. (%)	20.0	23.1	14.3	7.1	7.1	0.0	11.9

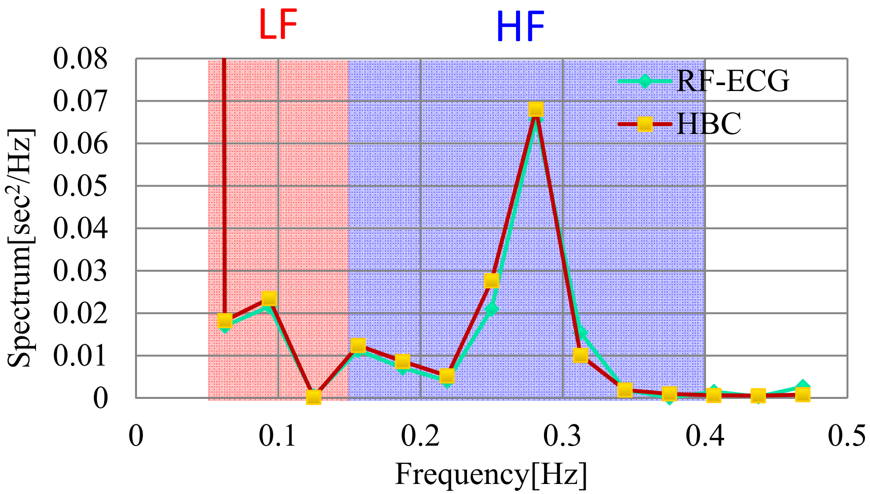
Comparison for SDNN [Sec]

Subject	A	B	C	D	E	F	Average
HBC-ECG	0.069	0.051	0.069	0.053	0.066	0.041	0.0582
RF-ECG	0.066	0.043	0.069	0.049	0.067	0.039	0.0555
Relative diff. (%)	4.3	15.7	0.0	7.5	1.5	4.9	5.65

Relative difference ～ 10%

Wearable ECG Performance Verification (2)

- Frequency domain parameters

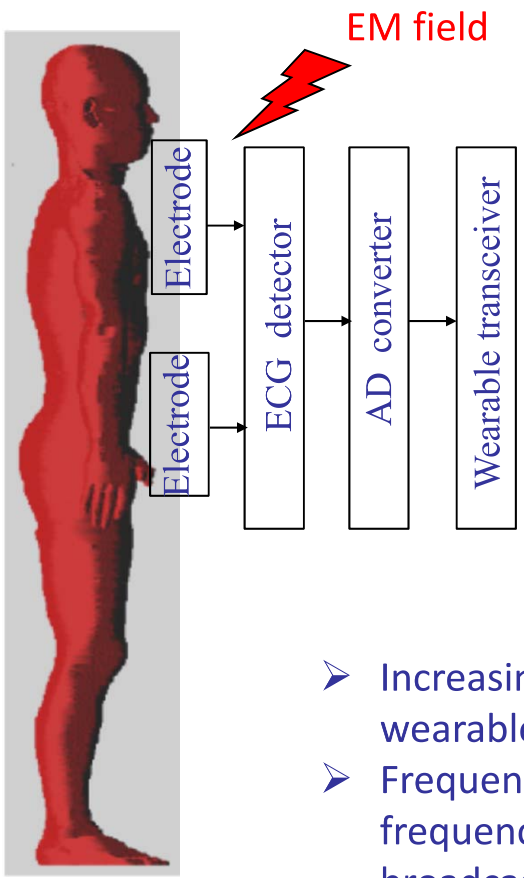


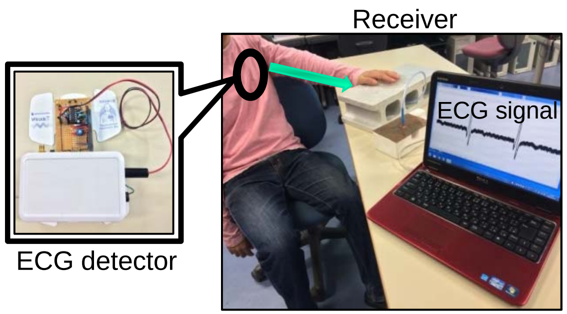
Comparison for LF/HF

Subject	A	B	C	D	E	F	Average
HBC-ECG	5.53	0.31	1.86	0.51	2.29	0.39	1.82
RF-ECG	5.42	0.31	1.37	0.40	2.14	0.46	1.68
Relative error (%)	2.0	0.0	26.3	21.6	6.6	17.9	12.4

The same performance as commercial RF-ECG

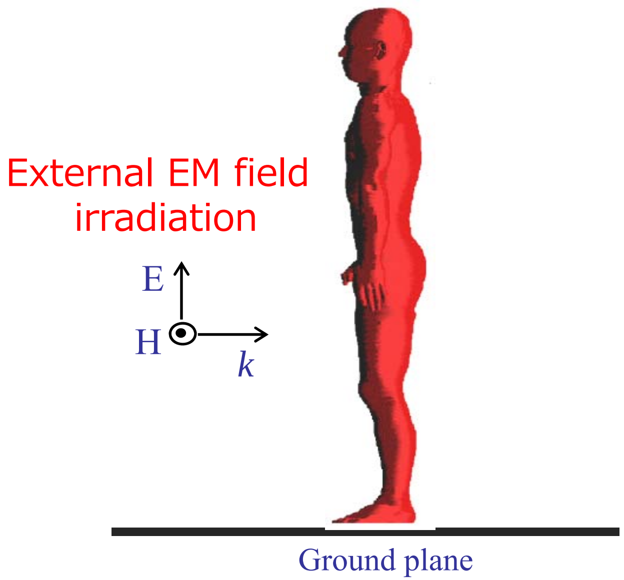
EMI to the Wearable ECG by Radiated EM Field

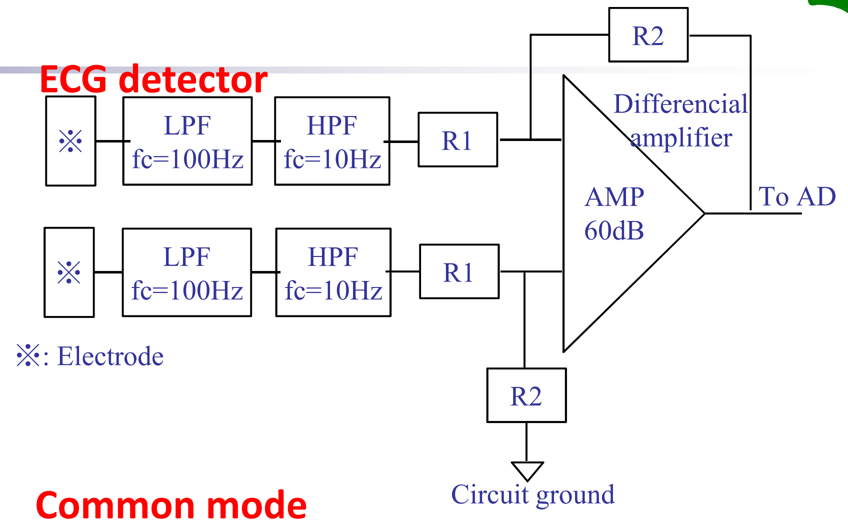




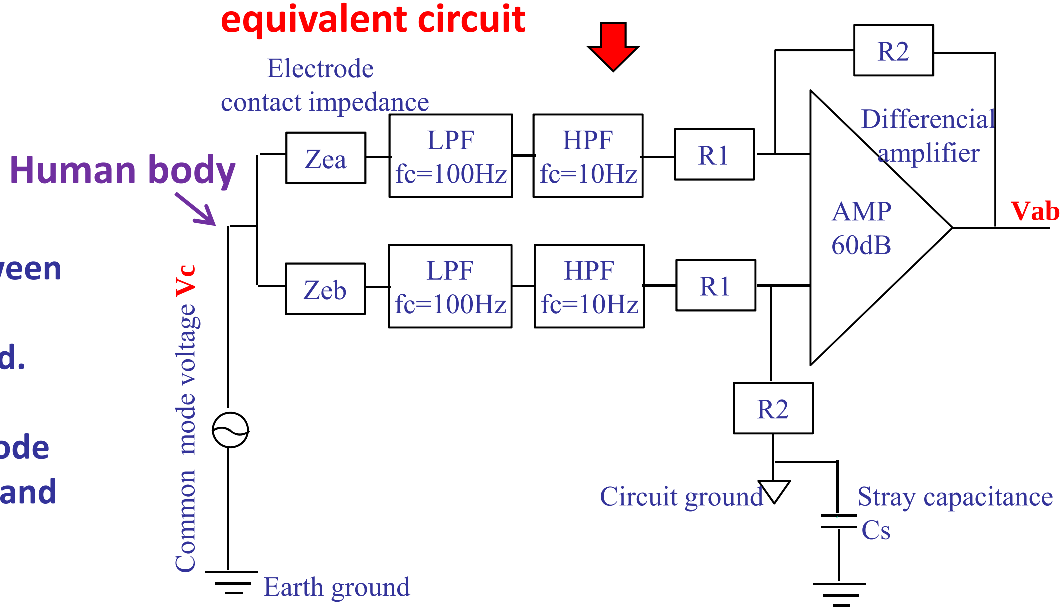
- Increasing EM wave applications imply a potential EMI problem with a wearable device.
- Frequencies below several MHz, which are especially near the ECG signal frequencies, are being used not only for commercial power supply and broadcast but also for rising wireless power transfer and in-car.

Common Mode Equivalent Circuit





Common mode equivalent circuit

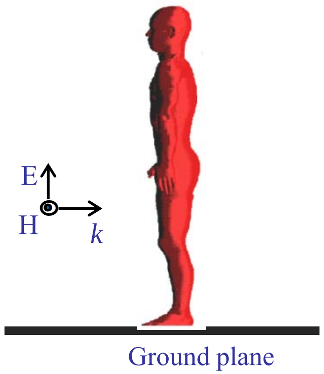


- **An interference voltage Vc is induced between the human body and the ground plane, here we denotes which as the earth ground.**
- **Between the human body and each electrode there is a contact impedances such as Zea and Zeb.**
- **Vab is the differential output of the ECG detector with respect to the circuit ground.**

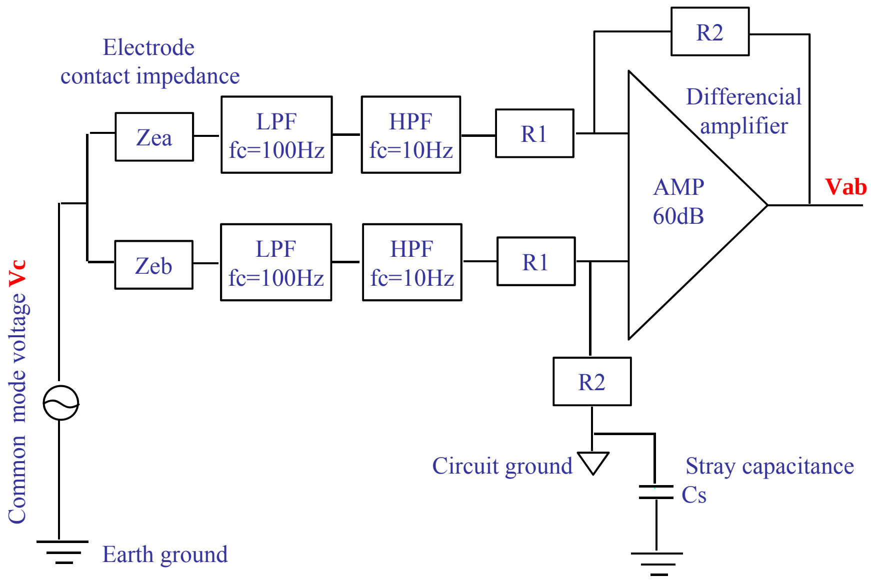
Two Step Approach

- Derive the EMI voltage induced between the human body and the ground as a common mode voltage Vc by EM field simulation or measurement

- Evaluate the differential mode interference voltage Vab at the ECG detector output by a circuit analysis or simulation



$$V_{ab}=\frac{R_2(Z_{ea}-Z_{eb})}{(Z_{ea}+Z_{eb}+2R_1)Z_{cs}+(Z_{ea}+R_1)(Z_{eb}+R_1+R_2)}V_c$$

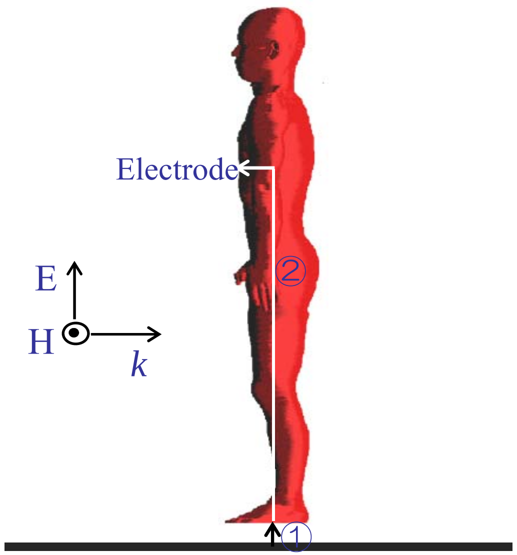


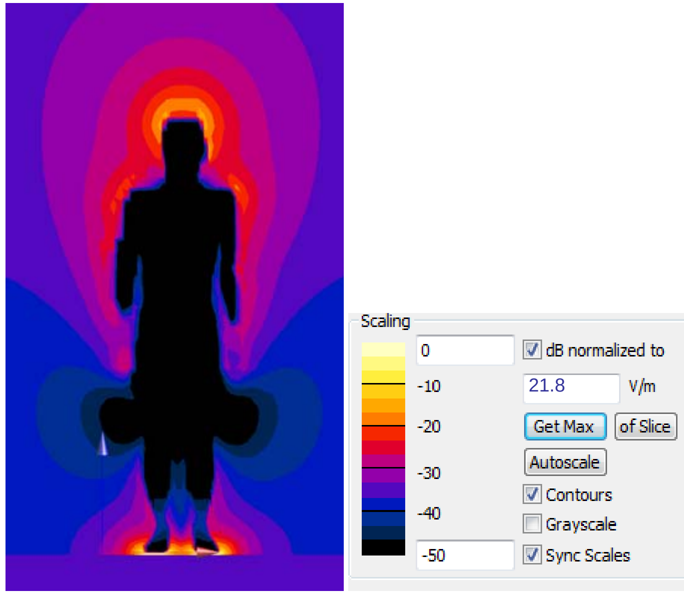
- **The external EM field induces a common mode voltage Vc between the human body and the earth ground.**
- **The two contact impedances (either contact resistance or coupling capacitance) are usually imbalanced due to their different contact conditions, i.e., Zea ≠ Zeb, which results in a differential output at the differential amplifier.**
- **This imbalance in the contact impedance is the main reason to change the common mode input voltage Vc into a differential mode interference voltage Vab at the output of the differential amplifier.**

EMI mechanism : Zea ≠ Zeb

Step I : Calculate the Common Mode Voltage Vc

- Running EM simulator to obtain E-field at interested frequency
- Integrating E-field along route① and ② to obtain the common mode voltage Vc

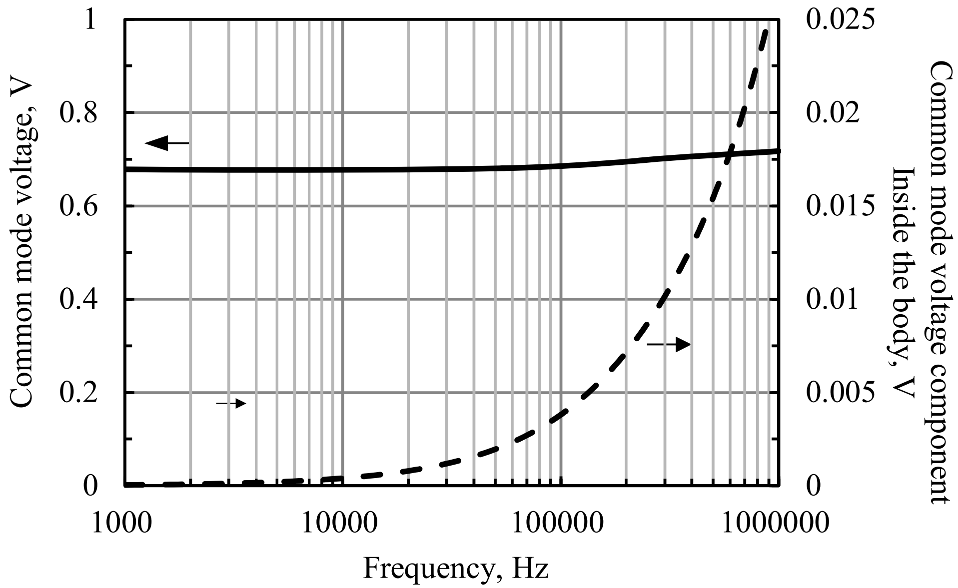




FDTD-simulated electric field distribution at 10 MHz

Calculated Common Mode Voltage Vc

Plane-wave incident electric field ：1V/m



- The component inside the human body is very small and increases with frequency.
- The total component is mainly due to the outside electric field between the human body and the ground, and is almost flat with respect to frequency at below several MHz.

Step II: Calculate Differential Mode Voltage Vab

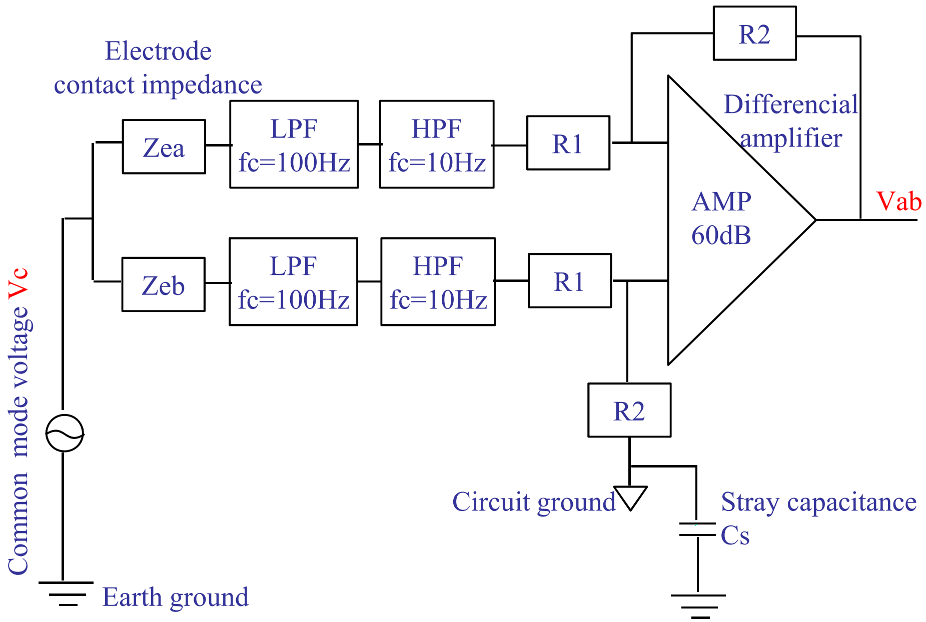


Table 1 Circuit parameters

R_e, average of R_{ea} and R_{eb}	10 kΩ - 100 kΩ
C_e, average of C_{ea} and C_{eb}	30 pF - 300 pF
Z_{in}, input impedance	100 MΩ
R_1	5 kΩ
R_2	5 MΩ
Differential amplifier gain	60 dB
C_s	20 pF - 200 pF
LPF cutoff freq.	100 Hz
HPF cutoff freq.	10 Hz
Attenuation outside pass band	60 dB

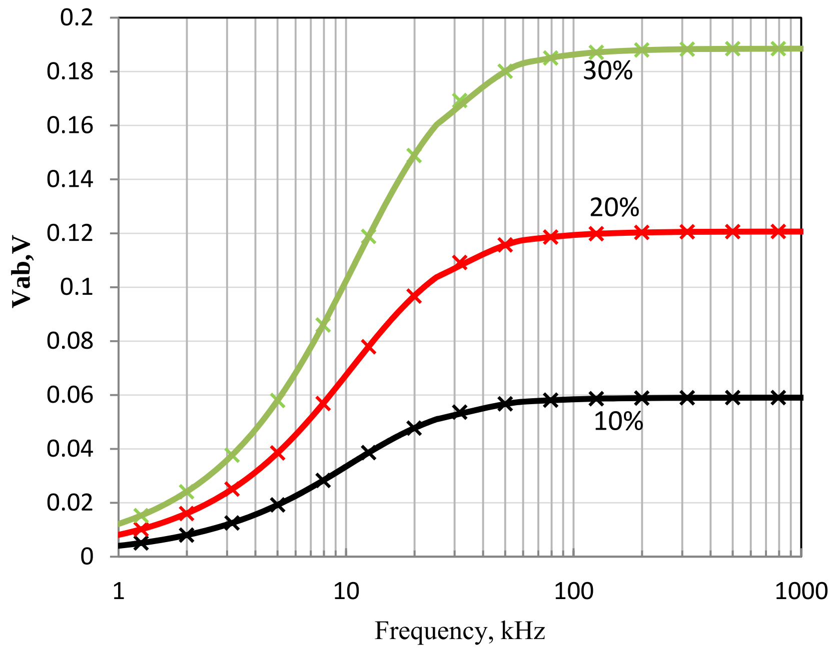
$$V_{ab} = \frac{R_2(Z_{ea} - Z_{eb})}{(Z_{ea} + Z_{eb} + 2R_1)Z_{cs} + (Z_{ea} + R_1)(Z_{eb} + R_1 + R_2)} V_c$$

Interference Voltage vs. Frequency

for Different Imbalance of Contact Resistances

Plane-wave incident electric field strength：10V/m

$$V_{ab}=\frac{R_2(Z_{ea}-Z_{eb})}{(Z_{ea}+Z_{eb}+2R_1)Z_{cs}+(Z_{ea}+R_1)(Z_{eb}+R_1+R_2)}V_c$$



Average Ze=100kΩ

Symbol: SPICE
Line: Theory

The differential interference voltage V_{ab} is induced by the common mode voltage Vc due to the imbalance of the contact resistances

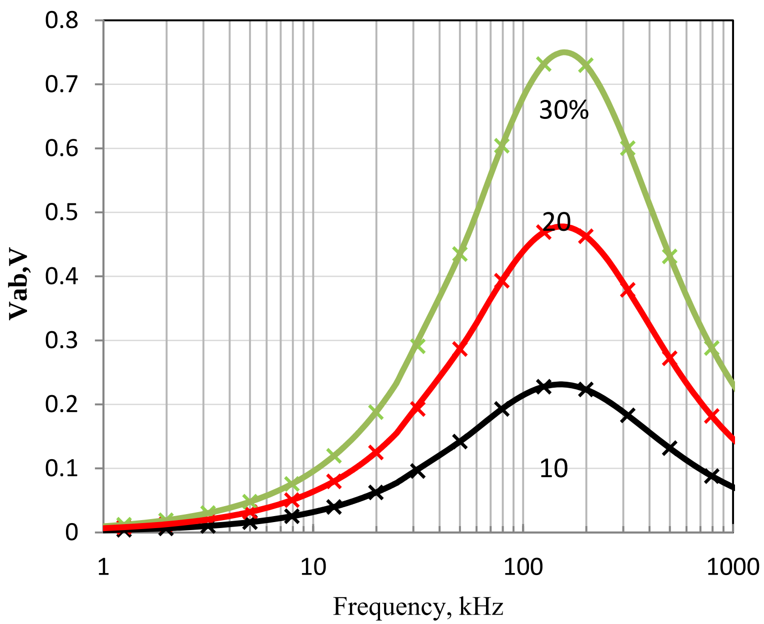
- increases with frequency between 1 kHz and 100 kHz, and keeps constant after 100 kHz.
  → HPF characteristic
- may achieve nearly 0.2 V above100 kHz when the imbalance is 30%.

Interference Voltage vs. Frequency

for Different Imbalance of Coupling Capacitances

Plane-wave incident electric field strength：10V/m

$$V_{ab} = \frac{R_2(Z_{ea} - Z_{eb})}{(Z_{ea} + Z_{eb} + 2R_1)Z_{cs} + (Z_{ea} + R_1)(Z_{eb} + R_1 + R_2)} V_c$$



Average Ce=300pF

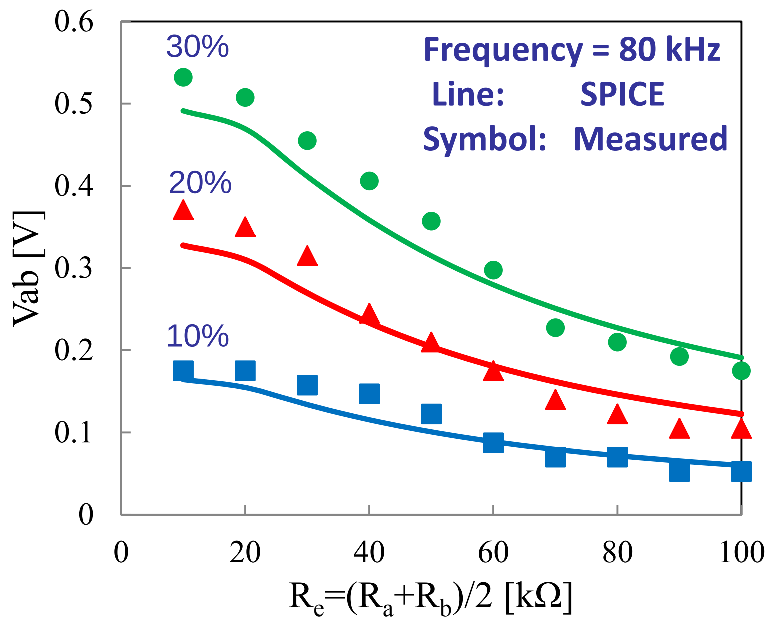
Symbol: SPICE
Line: Theory

The differential interference voltage V_{ab} is induced by the common mode voltage Vc due to the imbalance of the coupling capacitance

- increases with frequency between 1 kHz and 150 kHz, and then decreases after 150 kHz.
  → BPF characteristic
- may achieve nearly 0.8 V at 150 kHz when the imbalance is 30%.
  → completely mask the ECG signal

Experimental Validation

Plane-wave incident electric field strength：10V/m

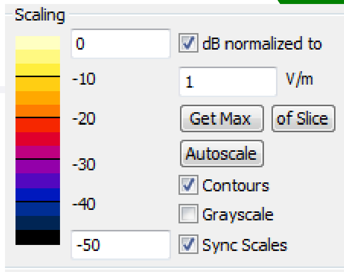


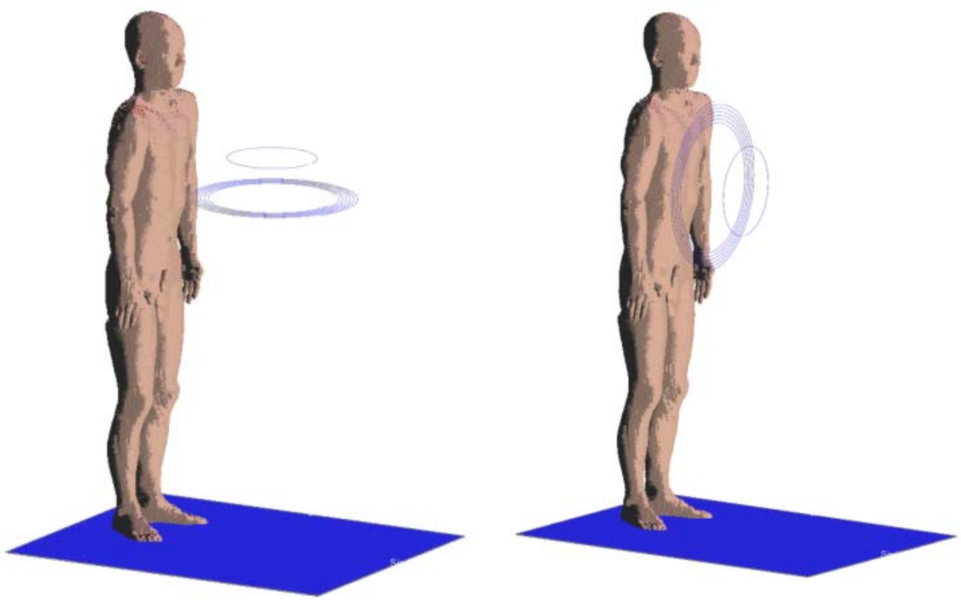
Fair agreement

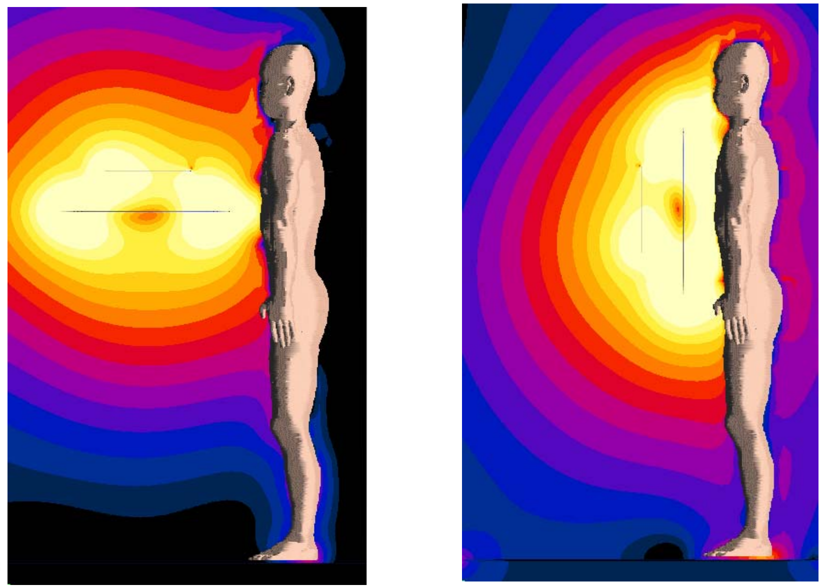
- Vab vs. average contact resistance was measured for validation.
- Fair agreement between SPICE-simulated and measured ones
  → confirmed the validity of the proposed approach.
- The interference voltage Vab was found to increase with the decrease of the average contact resistance.
  → more sensitive to small contact impedance

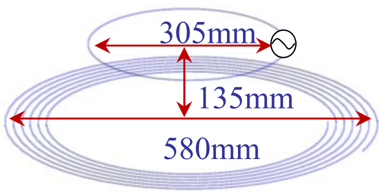
EMI Evaluation for a Wireless Power Transfer System at 6.8 MHz

Wireless power transfer system at 6.8 MHz
for consumer electric devices









Drive loop and transmit coil

Produced common mode voltage

Arrangement	d = 1 cm	d = 10 cm
Horizontal	0.50 V	0.39 V
Vertical	1.36 V	1.24 V

Transmit coil current = 1 A_{rms}

SPICE Simulation Parameters in the Common Mode Equivalent Circuit

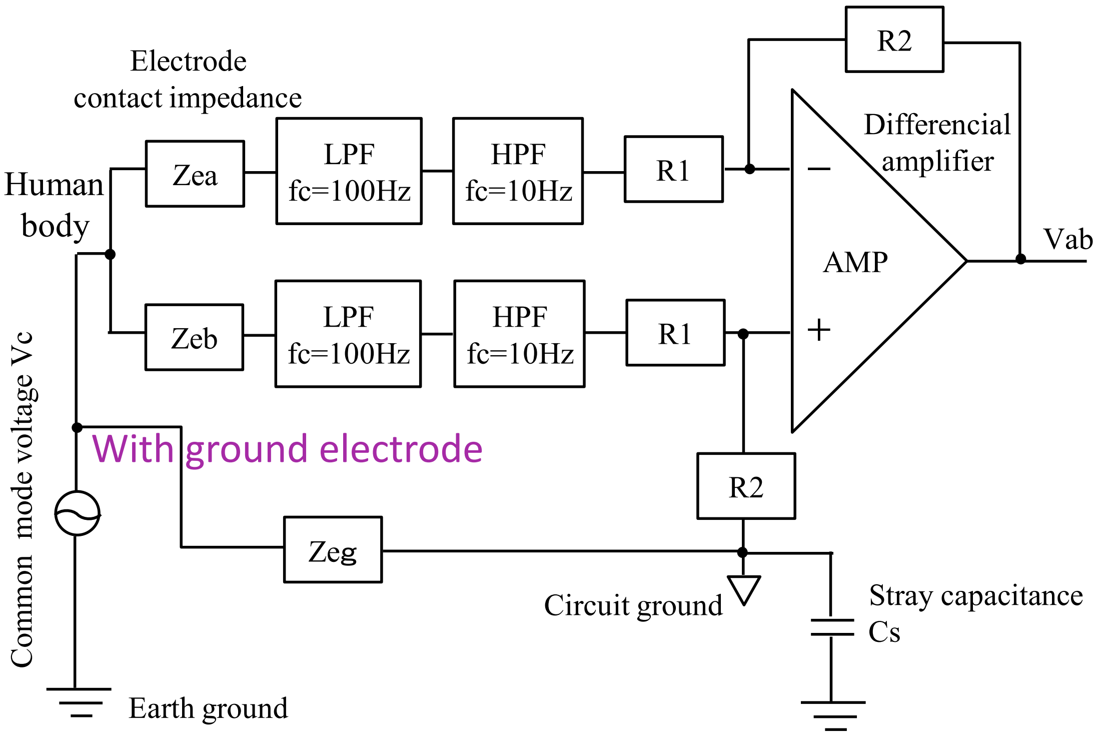


Table 2. Circuit parameters for simulation

R_e, average of R_{ea} and R_{eb}	10 kΩ - 100 kΩ
C_e, average of C_{ea} and C_{eb}	30 pF - 300 pF
R_1	10 kΩ
R_2	316 kΩ
Stray capacitance C_s	200 pF

$$V_{ab} = \frac{j\omega C_s R_2 Z_{eg}(Z_{ea} - Z_{eb})}{(Z_{ea} + Z_{eb} + 2R_1)Z_{eg} + (Z_{ea} + R_1)(Z_{eb} + R_1 + R_2) + j\omega C_s (Z_{ea} + R_1)(Z_{eb} + R_1 + R_2)Z_{eg}} V_c$$

Relationship between Impedance Imbalance and EMI Voltage

Table 3. Differential mode interference voltage V_{ab} [mV] under direct contact condition for 1 A_{rms} transmit coil current

Contact electrodes
Resistive

	d = 1 cm		d = 10 cm	
Imbalance	Horizontal	Vertical	Horizontal	Vertical
10%	63.3	172.2	49.4	157.0
30%	171.0	465.1	133.4	424.1
50%	262.7	714.4	204.9	651.4

The average R_e of R_{ea} and R_{eb} = 100 kΩ, and R_{eg} = 100 kΩ

Table 4. Differential mode interference voltage V_{ab} [mV] under non-direct contact condition for 1 A_{rms} transmit coil current

Non-contact electrodes
Capacitive

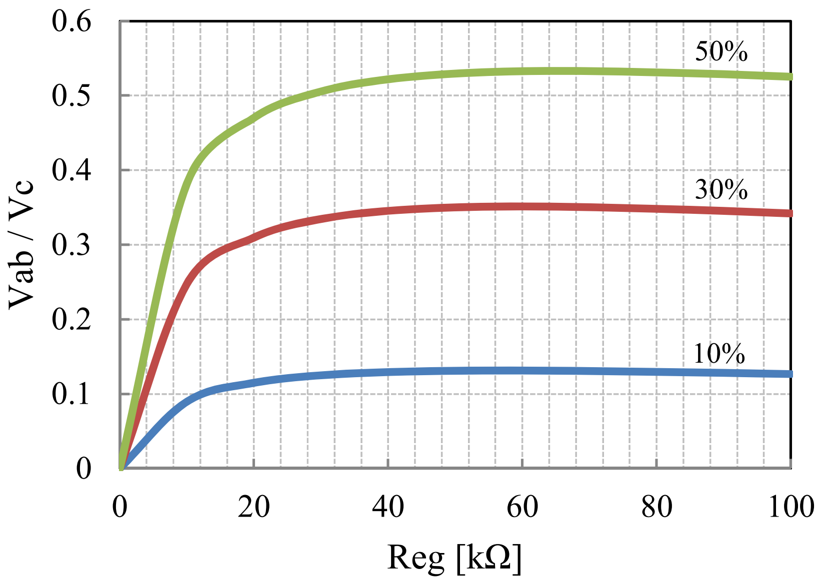
	d = 1 cm		d = 10 cm	
Imbalance	Horizontal	Vertical	Horizontal	Vertical
10%	6.7	18.1	5.2	16.5
30%	21.7	58.9	16.9	53.7
50%	43.8	119.1	34.2	108.6

The average C_e of C_{ea} and C_{eb} = 30 pF, and C_{eg} = 30 pF

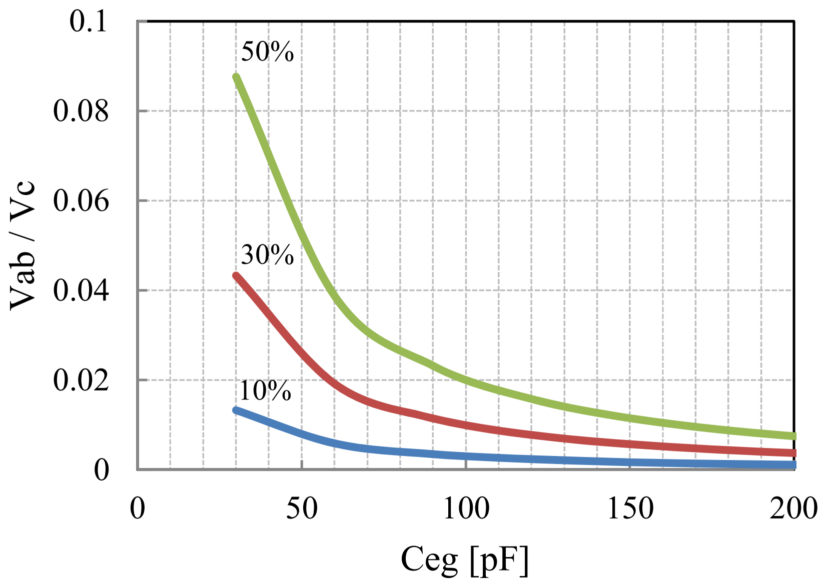
- EMI voltage V_{ab} increases with the imbalance of electrode impedances
- A 50% imbalance produces an EMI voltage of 0.6V, which may mask the ECG signal

Influence of Ground Electrode's Contact States

Contact ground electrode



Non-contact ground electrode



- Good contact state of ground electrode is effective to reduce EMI voltage

- $R \to 0$ or $C \to \infty$: Vab =0

Summary for EMI Evaluation of Wearable Device

- For EMI evaluation of wearable devices, we need a two-step approach, the 1st step is an EM field analysis or measurement , and the 2nd step is an electric circuit analysis or measurement
  -> This approach is especially useful in the design stage

- The two-step approach has been applied to our developed wearable ECG to demonstrate its validity and find some basic design guidelines

  - For a 6.8 MHz wireless power transfer system, the 1 A transmit coil current may produce an interference voltage of 0.6 V at an impedance imbalance of 50%
    -> which may mask ECG signal

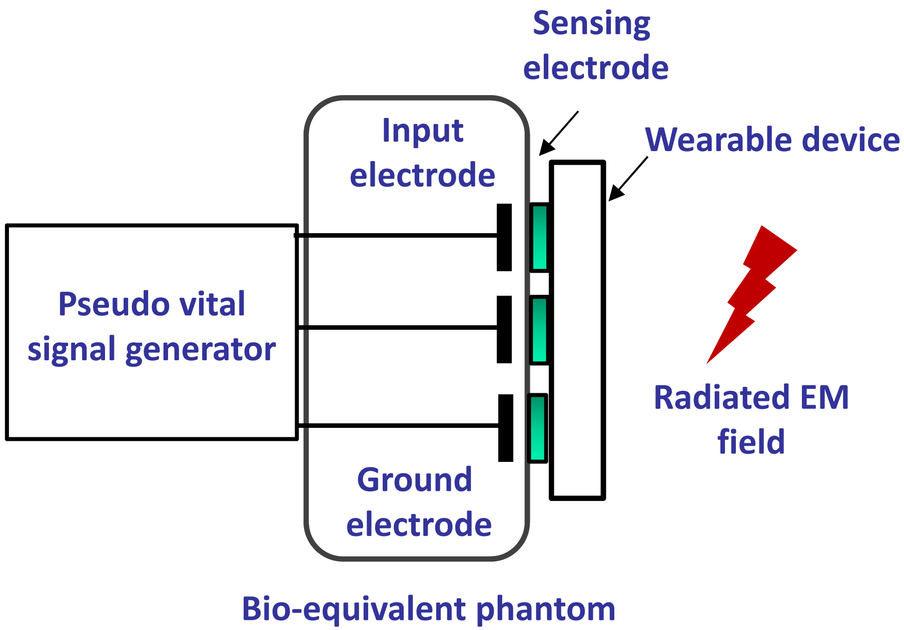
- In a wearable device, the main reason for changing the common mode interference voltage into a differential mode voltage is due to an imbalance between the contact impedances of the sensing electrodes.

  - to suppress such interferences , the imbalance between the two contact impedances should be reduced as much as possible -> an automatic cancelling circuit is effective
  - a good ground electrode is also effective

(2) Immunity Testing Method for Wearable Devices

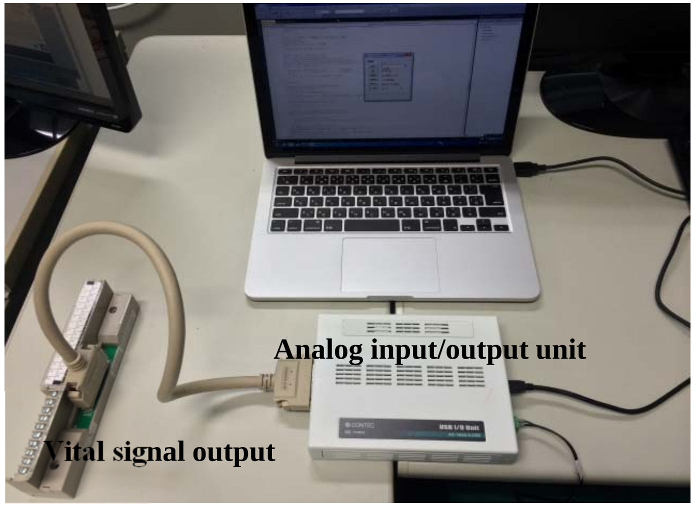
Immunity Test System for Wearable Devices

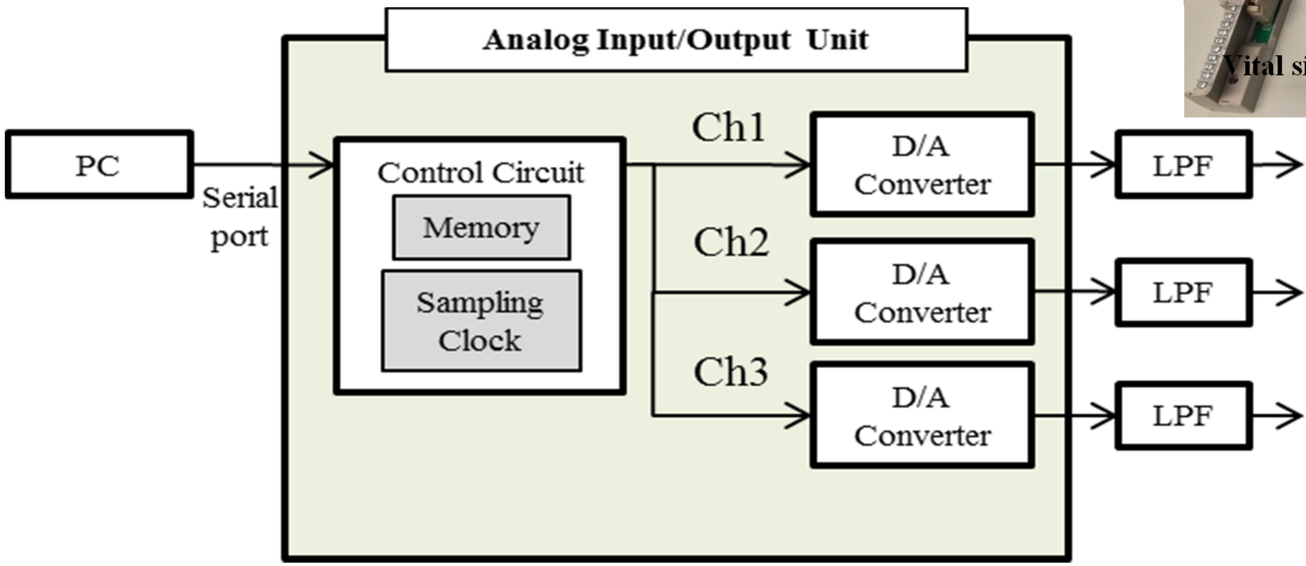
- The wearable device has some sensing electrodes attached on human body for detecting the vital signals.
- A test system with human body is unreal from the consideration of human safety and reproducibility.
- In place of human body, we employ a bio-equivalent phantom.
- In order to produce the vital signals inside the phantom for detecting by the wearable devices, we need a pseudo vital signal generator.



Pseudo Vital Signal Generator

- Vitals signals acquired from human body in advance are stored in PC in digital format.
- PC sends these data to control circuit, and the control circuit divide them to different channels.
- In each channel, after DA and filtering the vitals signals are output as an analog signal.

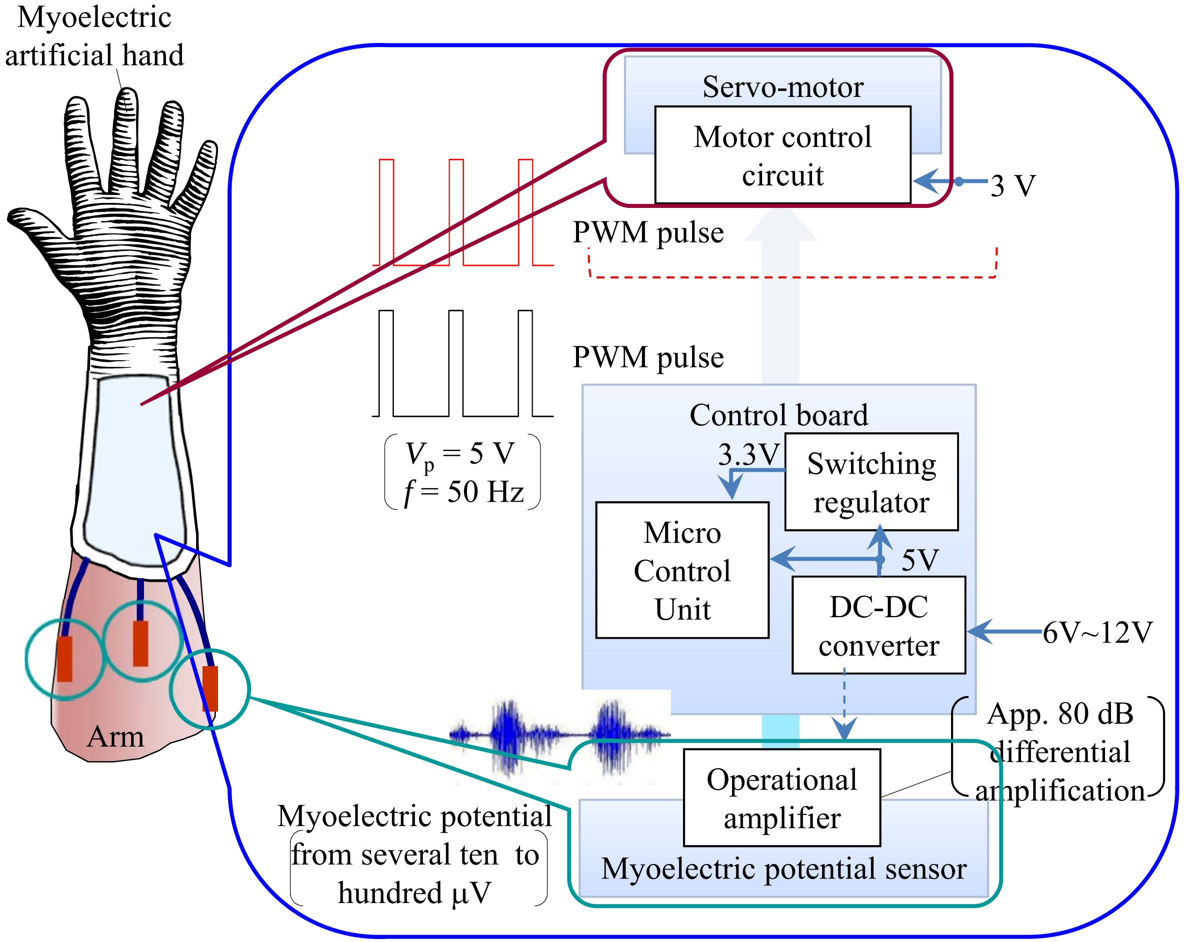




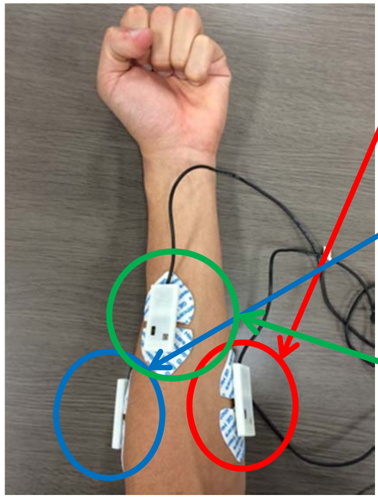
Sampling frequency	2 kHz
Quantization level	8 bits
Number of output channels	4
Maximum output voltage	±5V

Structure of Myoelectric Artificial Hand

- Three sensing electrodes are use to acquire the myoelectric signals.
- The myoelectric signals are sent to the control circuit and changed to PWM pulses.
- The PWM pulses are sent to the motor controller to move the motor and then hand.



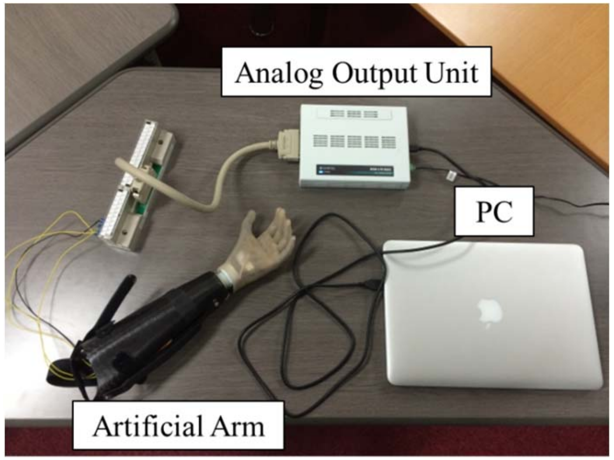
Generated Pseudo Myoelectric Signals



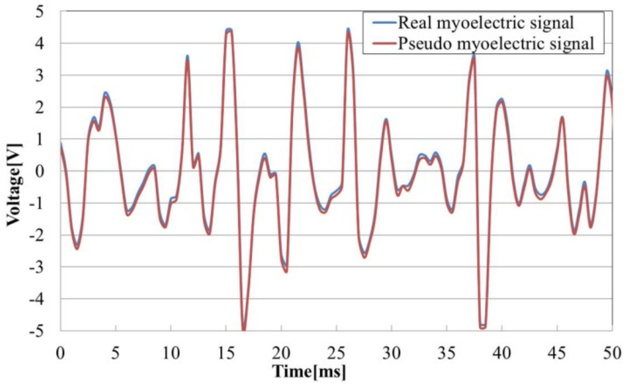
(1) Superficial flexor muscle of fingers

(2) Musculus extensor digitorum communis

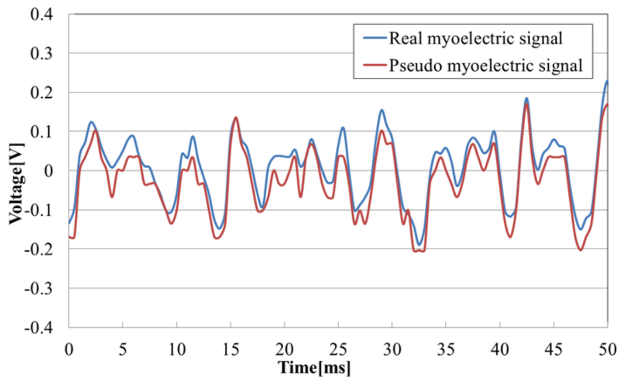
(3) Chief thumb extensor



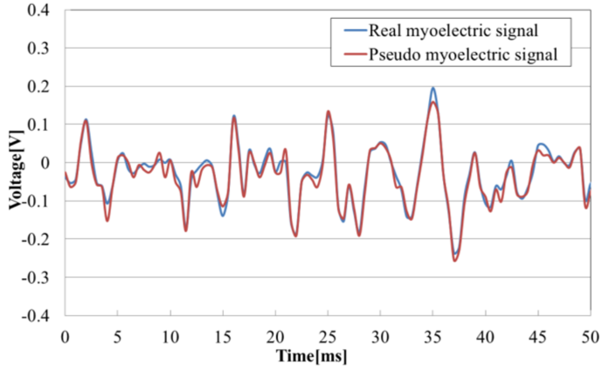
Correlation coefficient : 0.999



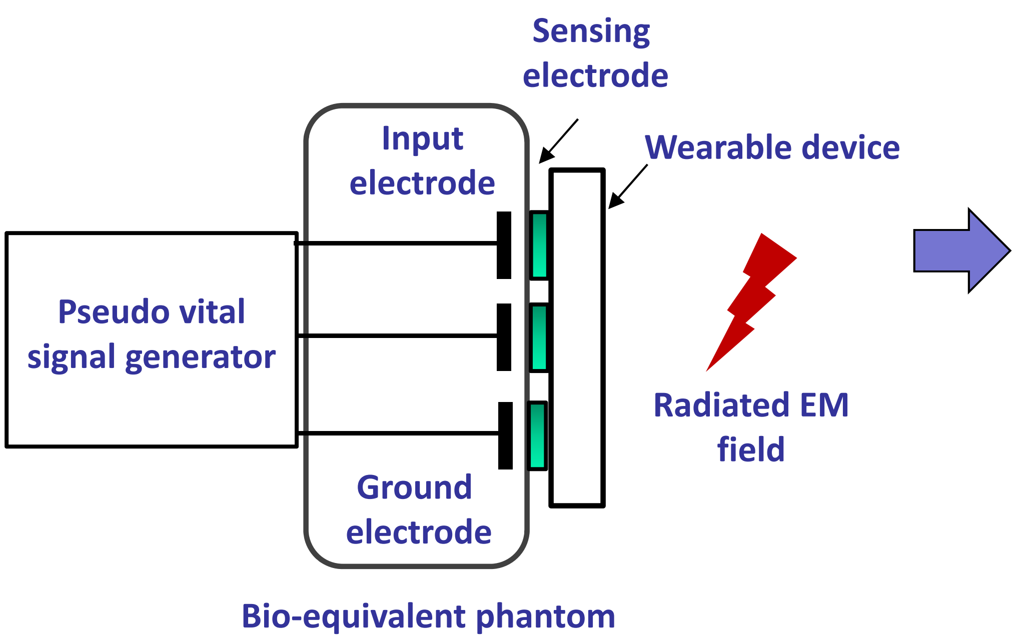
0.981

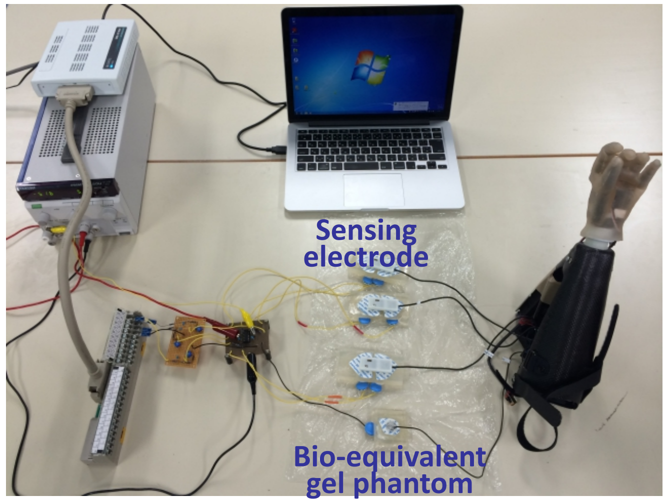


0.988



Apply to Myoelectric Artificial Hand





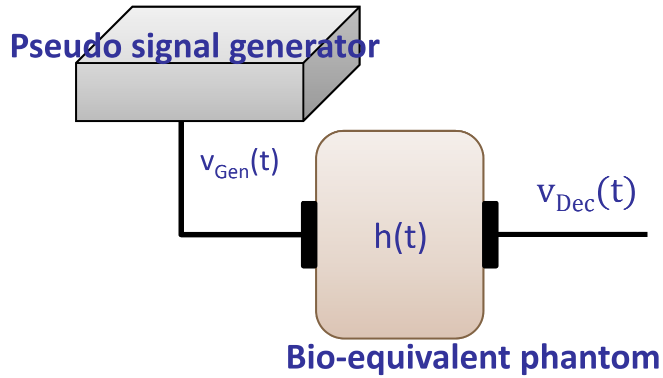
The spacing between the input electrode and sensing electrode is 1 cm

Detected signal at the phantom surface differs from the output of pseudo signal generator because the human body is a frequency-dependent dielectric object which results in a distortion when the signal propagates through it.

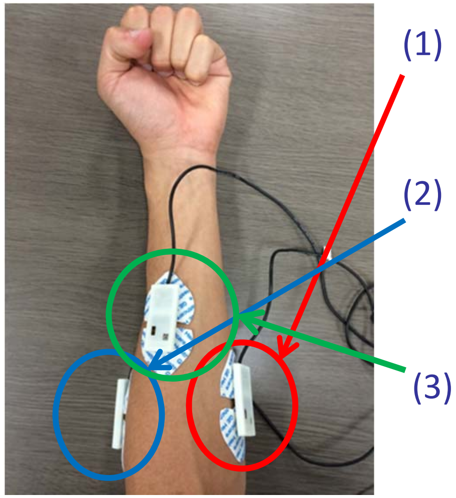
Signal Correction based on Transfer Function

- Desired myoelectric signal at the phantom surface is V_{Dec}
- Output of the pseudo signal generator is V_{Gen}
- Using the transfer function of bio-equivalent phantom H(f), we produce the pseudo signal as follows

$$V_{Gen}(f) = \frac{V_{Dec}(f)}{H(f)}$$



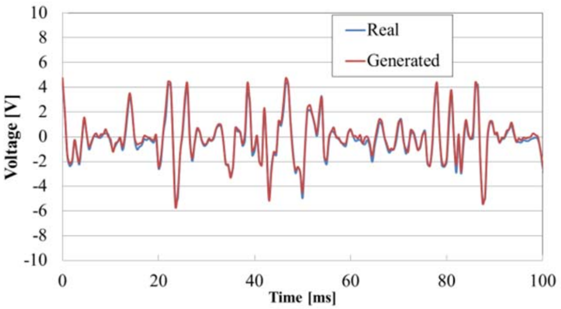
Corrected Myoelectric Signals



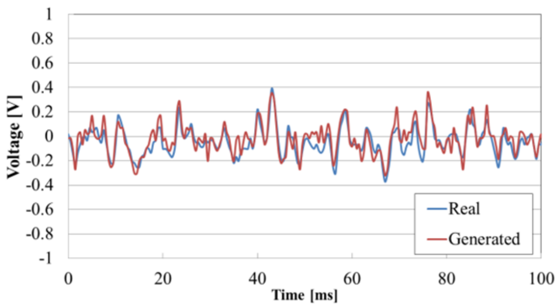
Correlation coefficients

	Before correction	After correction
(1)	0.69	0.99
(2)	0.72	0.85
(3)	0.67	0.78

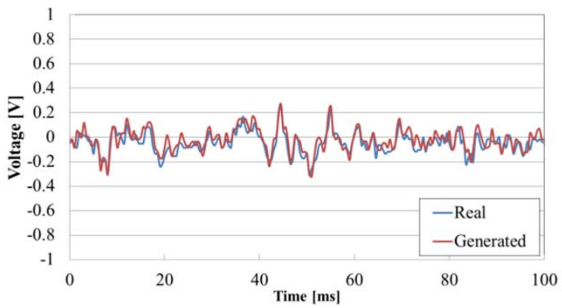
(1)



(2)



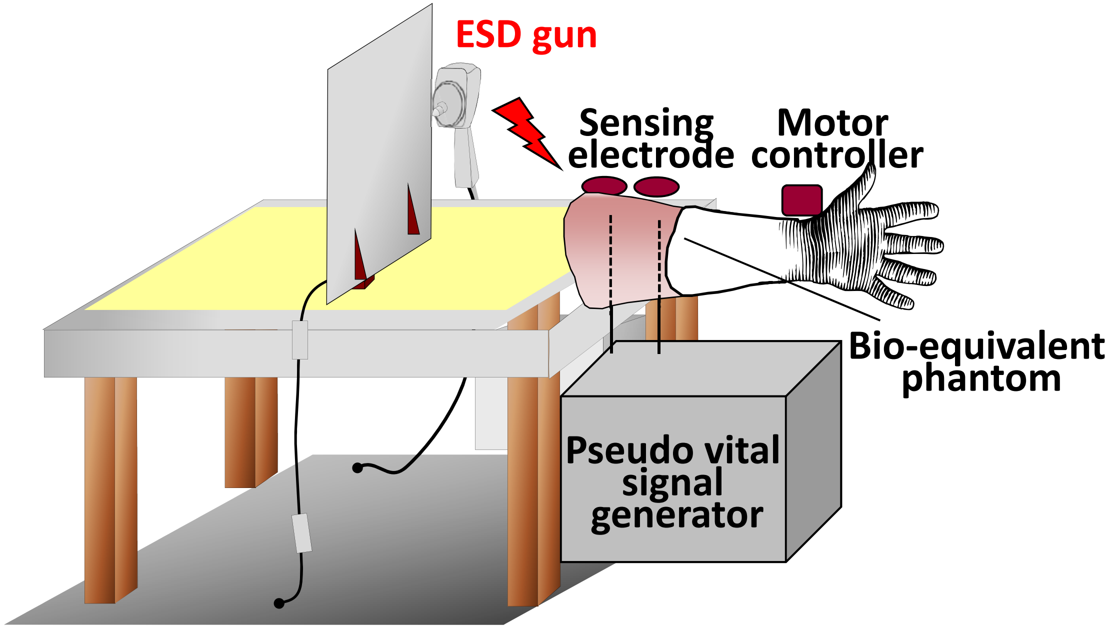
(3)



Blue lines: Original myoelectric signals

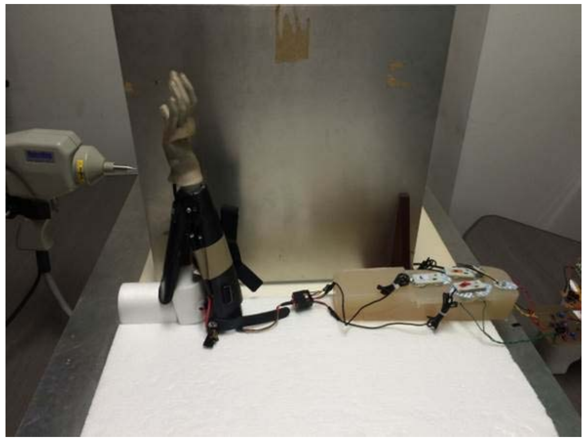
Red lines: Corrected signals detected by the sensing electrodes of wearable device

Demonstration of ESD Immunity Test



Human body

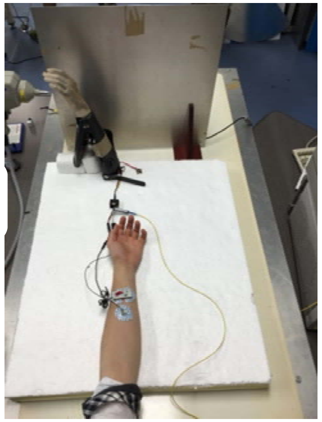
Proposed system

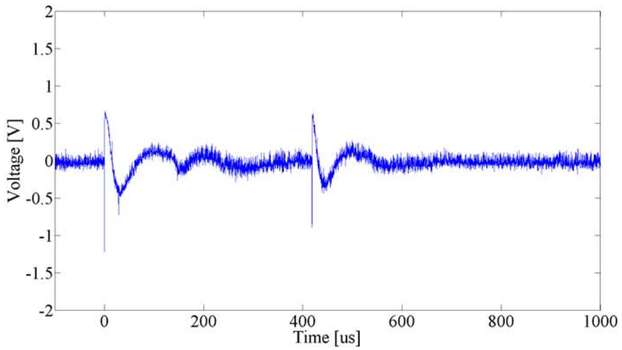


Validation of Immunity Test System

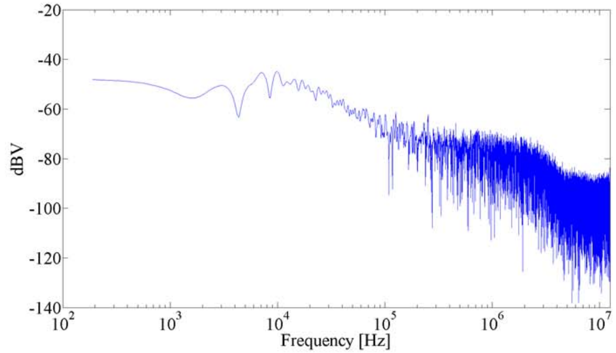
Observed ESD noises at the input of driving circuit of artificial hand by using an optical E-field probe

Actual arm



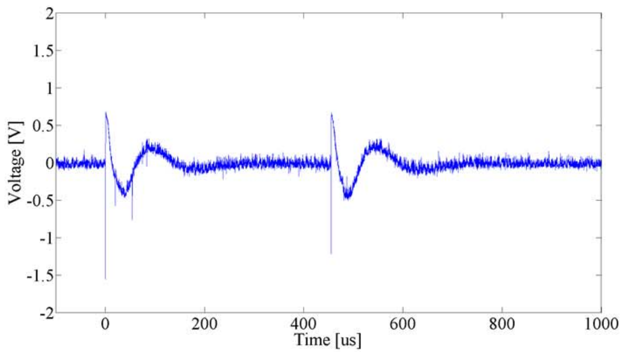


Time waveform

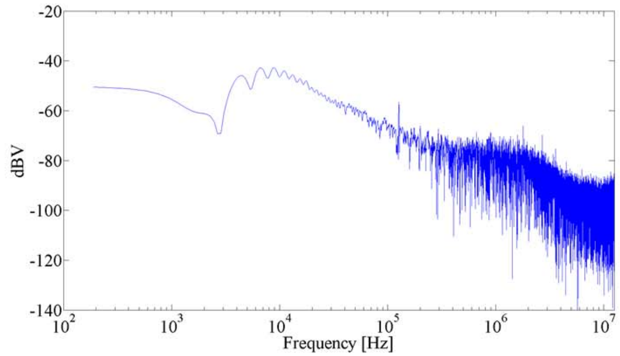


Frequency spectrum

Proposed immunity system



Time waveform

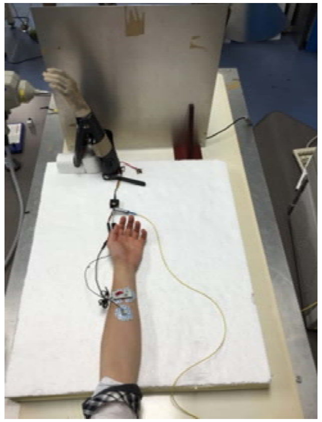


Frequency spectrum

Very similar noise characteristics

Comparison of ESD Testing Results

Human arm



Voltage	Positive	Negative
0kV	1	1
2kV	2	2
4kV	2	2
6kV	2	3
8kV	3	3

Pseudo immunity system

Voltage	Positive	Negative
0kV	1	1
2kV	2	1
4kV	2	2
6kV	2	2
8kV	3	2

1: Normal 2: Partial work 3: Not work

Summary for Immunity Test System

- A pseudo vital signal generator has been developed to produce various signals in wearable devices such as ECG, EMG, EEG, EOG, etc.

- An immunity test system for wearable devices, with the pseudo vital signal generator and bio-equivalent phantom, has also been developed

- Applying it to ESD immunity test for a myoelectric artificial hand has demonstrated its usefulness

---> Further improvement and standardization