Lab 2. Physiological Signal Processing – ECG, EMG, PPG

1. Objective

- Understand the procedure to process biosignals
- Learn ECG analysis: Peak detection, waveform averaging, heart rate variability
- Learn EMG analysis: EMG power analysis

2. Background

2.1. Analog-to-digital conversion

To analyze biosignals using a computer, biosignals should be converted into digital format. This process consists of converting the continuous ('analog') signal into a discrete signal. When the conversion from analog to digital involves two procedures, sampling and quantization. Sampling is the process of recording an analog signal at regular discrete moments. The sampling rate *fs* is the number of samples per second. The time interval between samples is called the sampling interval *Ts*=1/*fs*. Quantization is the process of mapping each sample value to a discrete level (represented by a sequence of bits). In a *B*-bit quantizer, each quantization level is represented with *B* bits, so that the number of levels equals 2^B. These procedures are done by an analog-to-digital converter (ADC). An ADC samples a value at every sampling interval t so that a continuous-time signal (x(t)) becomes a discrete-time signal (x[n]). The sampled value is expressed in finite digits (e.g. 8 bit, 12 bit, 16 bit, etc.) so that continuous-valued signals become discrete-valued signals. To reproduce the original x(t) from x[n], the sampling frequency (fs = 1/Ts) should follow Nyquist criterion.

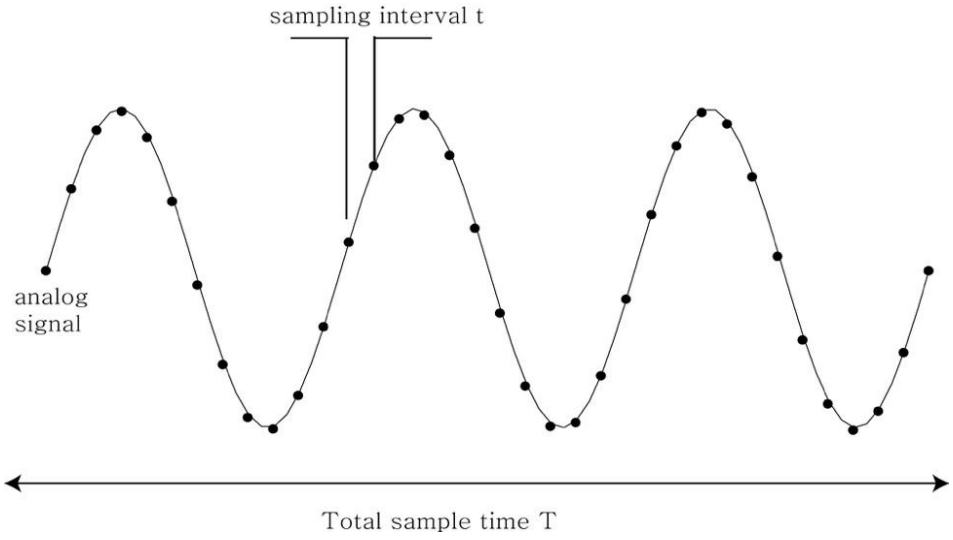


Figure 1. Sampling

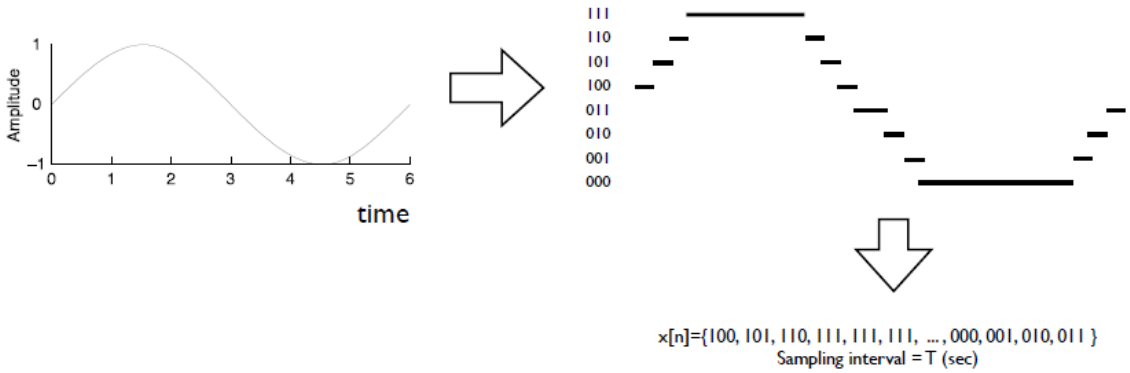


Figure 2. Quantization

2.2. MATLAB basics

① Documentation

In MATLAB, it is important to know the shapes of input and output of the function since they are directly related to the usage of given function. There are a number of functions that MATLAB supports so that in most case you face the function for the first time. Fortunately, MATLAB provides documentation which kindly tells us such information we need.

There are two ways of accessing to the documentation: in the MATLAB running or website.

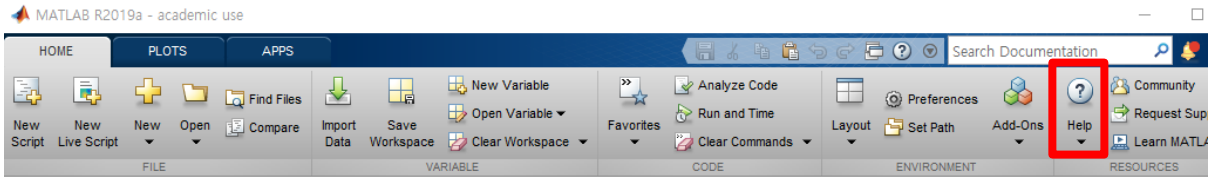


Figure 3. Accessing the documentation in MATLAB running

Pushing the 'help' menu with the question mark icon (indicated by a box in the Figure 3), you can access to the documentation. Also, you can access to the same page in web environment.

As an example, here is the documentation page describing linspace(.) function.

In the first 'Syntax' section, you can see the syntax, which means in what form input/output should be. In case of linspace(.), its input is 2 or 3 scalar number and output is in form of row vector. In the 'Description' section, how those input and output are related is explained. If you don't get any sense of how linspace(.) works even after reading those sections, that's not a big problem. There is an 'Example' section, which provides most practical information. You can see the actual implementation of given function and corresponding results in this section.

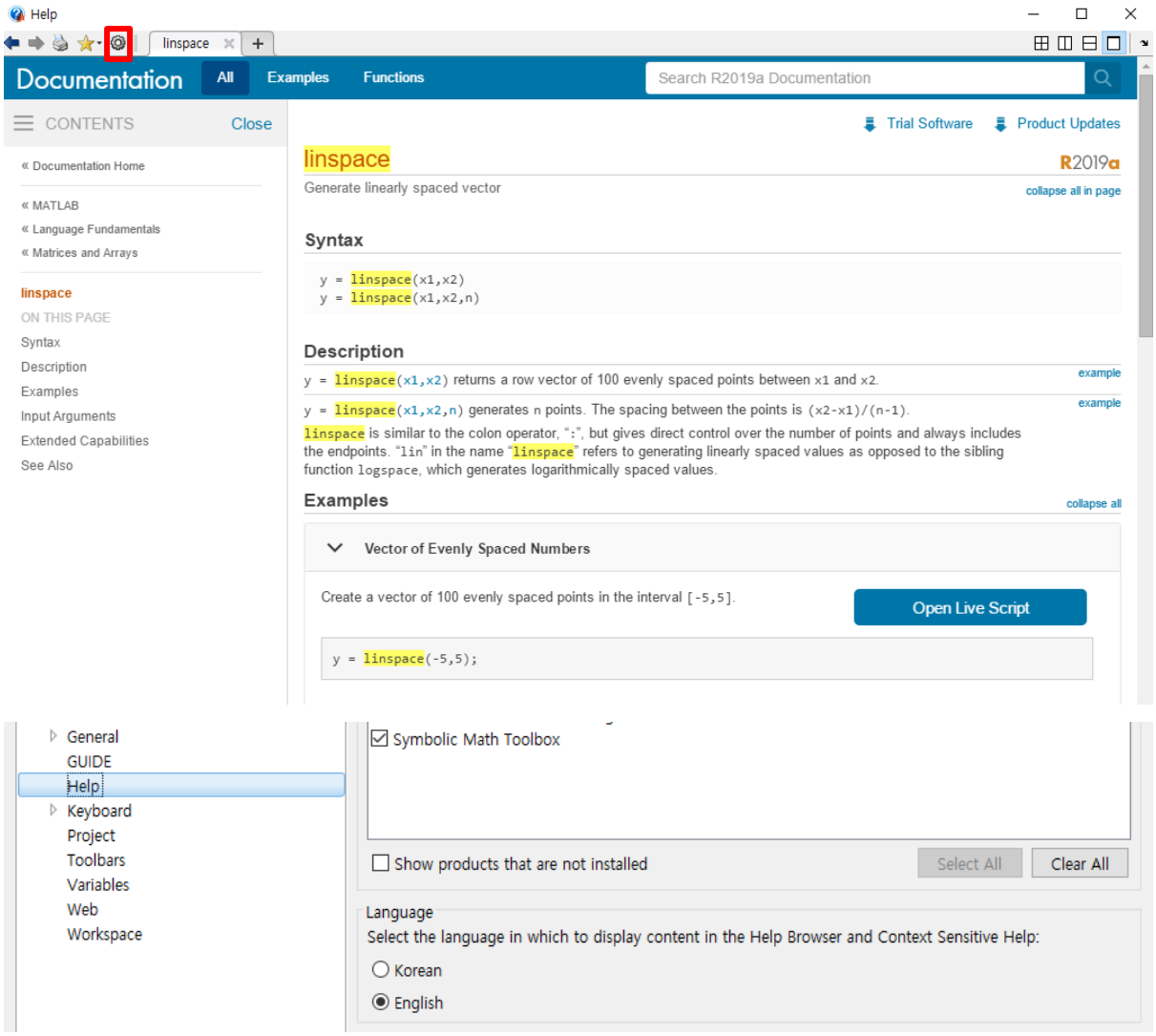


Figure 4. linspace(.) documentation and each section

If you have some trouble regarding language while reading those documentations, you can change the language setting in preference>Help>Langauge menu by clicking gear-shaped icon (indicated by a box in figure 4).

② Vectors and Matrices

In MATLAB, most data are dealt with in form of vector or matrix. Technically, all MATLAB variables are multidimensional 'arrays', no matter what type of data. In case of the number, one-dimensional array is called vectors and two-dimensional is a matrix.

There are some ways of creating vector

Example	**Result**	**Remark**
a = [1 2 3 4]	[1 2 3 4]	Implement each element directly.
a = (0:2:6)	[0 2 4 6]	Useful when you need a certain interval.
a = linspace(1,7,4)	[1 3 5 7]	Useful when you need a certain length.

a = zeros(1,4)	[0 0 0 0]	If you want certain size of other vector, use size(.) function.
a = ones(1,4)	[1 1 1 1]	Frequently use in forms of k*ones(1,4)

To make matrices, you can use similar implementation with semicolons. You can simply regard semicolon as a 'line-break'. Matrices can be created not only by directly implementing, but also by concatenating existing vectors as indicated in the below example. Some examples are in Figure 5.

```
>> a = ones(3,3)
a =
     1     1     1
     1     1     1
     1     1     1
```

```
>> a = [1 2 3; 4 5 6; 7 8 9]
a =
     1     2     3
     4     5     6
     7     8     9
```

```
>> a = [1 2 3 4];
b = [2 4 6 8];
c = [a; b]
c =
     1     2     3     4
     2     4     6     8
```

Figure 5. Several examples of matrix creating

To get further information, read the document in Ref 4.

③ Array indexing

To extract or edit certain elements of given vector, it is important to know the index expression. Different from the other programming language, all index number starts with 1, not 0, in MATLAB environment.

Below table shows some examples of vector indexing (a = [11 12 13 14 15 16 17 18 19 20])

Example	**Result**	**Remark**
b = a(3)	13	Index '3' extracts third element.
b = a([2 4 6])	[12 14 16]	Index can be used in form of vector.
b = a(1:3)	[11 12 13]	
b = a(8:end)	[18 19 20]	Useful when the length of vector is uncertain.
b = a(end-1)	19	'end-1' means one index before the end.
b = a(:)	[11 12 … 20]	Using colon only means whole index range.
b = a(a>16)	[17 18 19 20]	Logical condition can be applied.

It is similar to the matrix indexing except it needs two indices (row and column number).

To get further information, read the document in Ref. 5.

If you are totally new to MATLAB so that get in trouble while reading previous articles, it might be helpful to watch following videos. They are video tutorials for MATLAB basics.

2.3. ECG analysis

① Physiological nature of ECG

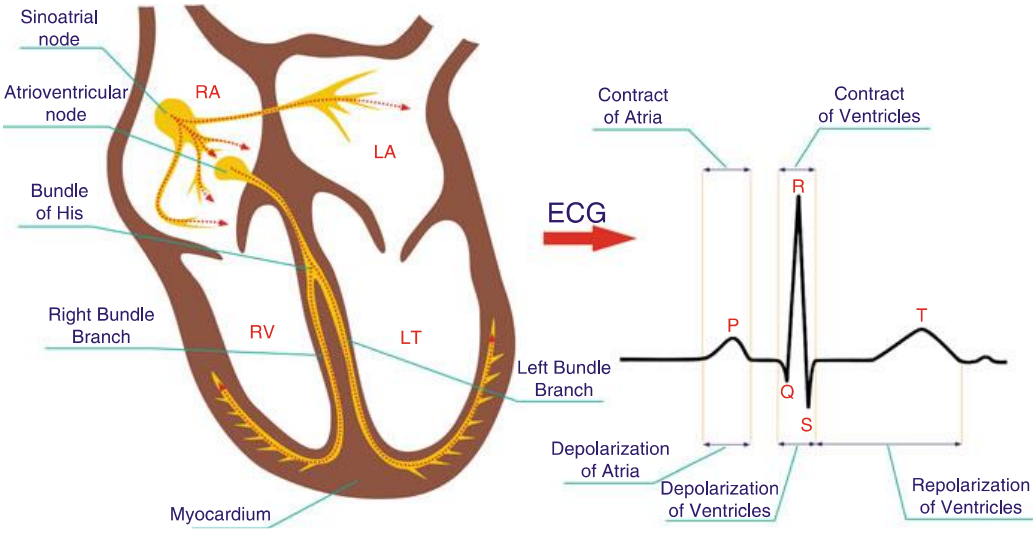


Figure 6. Propagation of the depolarization wave in the heart muscle (Source: Ref 1)

ECG signals are reflective of an electric activity of heart as indicated in Figure 6. The ECG signal is some kind of an electric provocation spread in the heart muscle cells. The propagation of electric provocation in the heart muscle forms a depolarization wave of the bioelectric potentials of the neighboring heart cells. After moving of the depolarization wave, the heart muscle cells return to their rest state recovering before starting resting negative potential.

The depolarization and repolarization phenomena of the heart muscle cells are caused by the movement of ions. This is the essence of the heart electric activity. Movement of ions in the heart muscle cells is the electric current, which generates the electromagnetic field around the heart. Those magnetic field arranges the distribution of ions in the body. Using the electrode which transforms ion flow into electron flow, that heart electric activity can be measured in electronic signals.

② Features of ECG

In ECG, three features represent cardiac cycles in a regular sequence: P wave, QRS complex, and T wave (Figure 7). P wave represents atrial depolarization, QRS complex represents ventricular depolarization, and T wave represents ventricular repolarization. The R peak is the dominant feature in QRS complex and it is used for determining the heart rate even in the presence of noises due to its high amplitude. The current heart rate can be determined by calculating the time period between two consecutive R peaks (R-R interval).

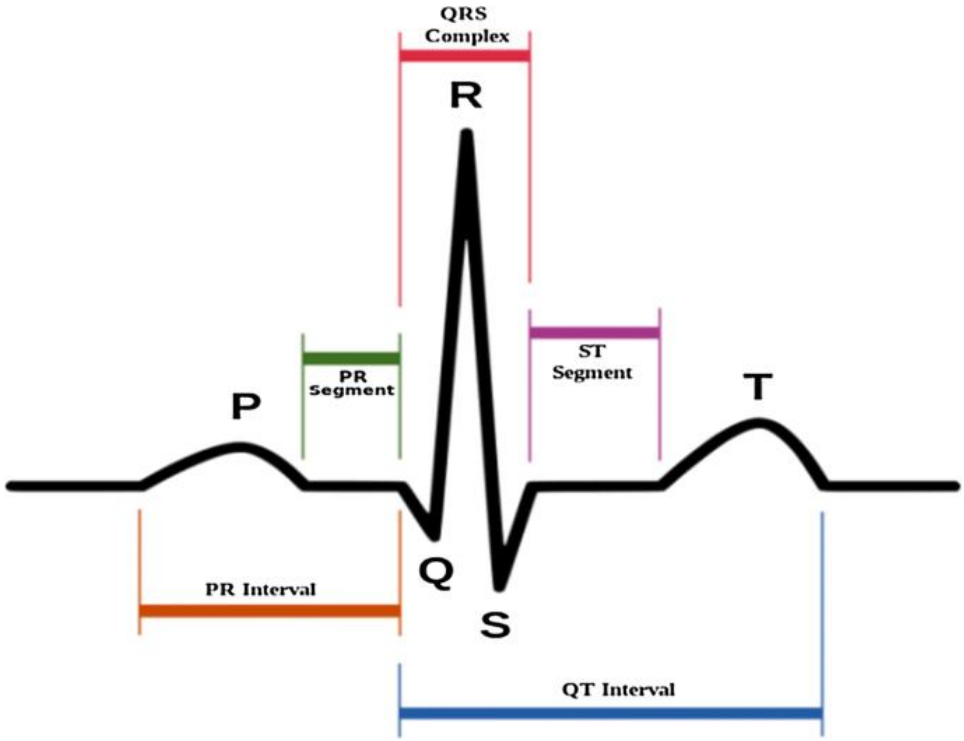


Figure 7. Features of typical ECG waveform

③ P-QRS-T complex, R point

A characteristic feature of ECG signal comes with a cyclic occurrence of its components consisting of the P-QRS-T complex. The ECG signal in this region is reflective of performance of the conduction system of the heart that pertains to a single heart evolution involving contraction of atria and ventricles. This part of the ECG signal forms a region of interest (ROI) as it contains the most essential diagnostic information. Therefore, during ECG signal processing and analysis, an important task is to detect each section containing the P-QRS-T complex.

A detection of the part of the signal containing the O-QRS-T complex is realized through a detection of the most characteristic basis point, which is the location of the R point in time. The overall P-QRS-T complex is taken as the part of the ECG signal present in some time interval that is formed by taking nb samples and nf samples of the signal located before and after the location of the R point.

The simplest methods of detection of the R point involve finding a sample of the signal of the highest amplitude at the point where the first derivative crosses zero or the signal exceeds a certain predetermined threshold level.

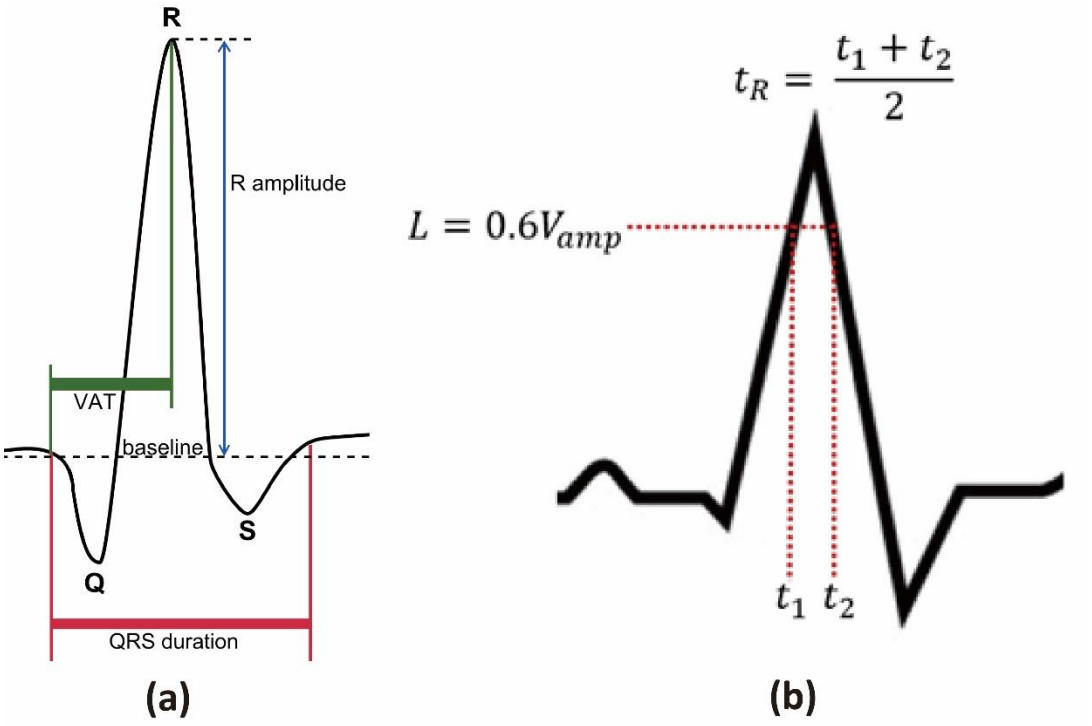


Figure 8. (a) Baseline of ECG signal and (b) double level method

The PR segment serves as the baseline of the ECG curve. The amplitude of any deflection/wave is measured by using the PR segment as the baseline. Refer to Figure 8 (a).

In “double level method”, the R point is measured as an average of two points t1 and t2 that correspond to the crossing points of the rising and falling slope of the signal determined for some threshold level L as shown in Figure 8 (b). Typically, the level L is determined as 0.6 times of signal amplitude, which is maximum level of ECG from baseline.

2.4. EMG analysis [2]

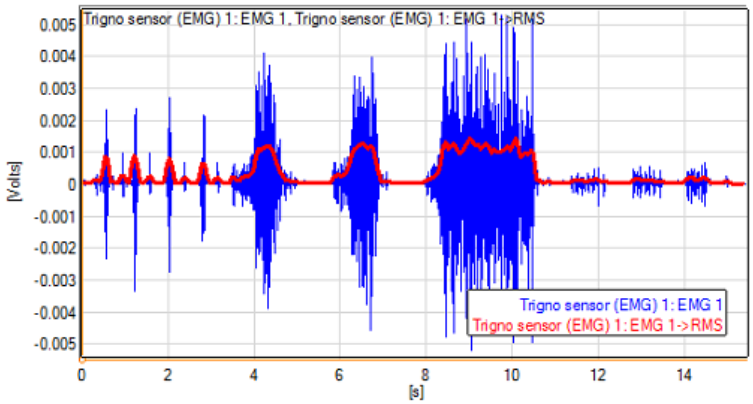


Figure 9. Surface EMG signal amplitude analysis

EMG measures the electrical potentials from muscle cells. EMG signals are composed of superimposed motor unit action potentials from several motor units. Surface EMG is non-invasive and convenient

method to assess muscle function by recording muscle activity on the skin. The EMG signal is a time and force dependent signal whose amplitude varies in a random nature above and below the zero value. There are several techniques that are used to analyze EMG signals.

① Rectification

Rectification is rendering only positive deflections of the signals. Eliminating the negative values [Half wave rectification] or inverting the negative values [Full-wave rectification]. Full-wave rectification can maintain all the energy of the signal.

② Averages or Means of Rectified Signals

This method is taking the average of the randomly varying value of a signal g. By taking the average of randomly varying values of a signal, the larger fluctuations are removed, thus achieving the same results as the analog smoothing operation. To obtain the time-varying average of a complete record of a signal, it is necessary to move the time window T duration along with the record.

$$|\mathrm{V}_{mean}| = \frac{1}{T}\int_{t}^{t+T}|v(t)|dt$$

③ Integration

Integration applies to a calculation that obtains the area under a signal or a curve. The units of this parameter are volt seconds (Vs) value of the EMG signal. concept of integration may be applied only to the rectified value of the EMG signal

$$\mathrm{V}_{int} = \int_{t}^{t+T}|v(t)|dt$$

④ Root-Mean-Square (rms) Value

RMS value provides more a more rigorous measure of the information content of the signal because it measures the energy of the signal.

$$\mathrm{V}_{rms} = \sqrt{\frac{1}{T}\int_{t}^{t+T} v^2(t)dt}$$

⑤ Zero Crossings and Turns Counting

Zero Crossings is a point where the sign of a mathematical function changes. Turns counting is counting the number of times per unit time that the amplitude of the signal contains either a peak or crosses a zero value of the signal. This technique is popular among clinicians. But not recommended for measuring the behavior of the signal as a function of force or as a function of time during a sustained contraction

⑥ Frequency Domain Analysis

Frequency Domain Analysis is analysis of the EMG signal in the frequency domain involves measurements and parameters that describe specific aspects of the frequency spectrum of the signal. Three parameters of the power density spectrum may be conveniently used to provide

useful measures of the spectrum. They are the median frequency, the mean frequency, and the bandwidth of the spectrum.

3. Prelab activities

3.1. Analog-to-digital conversion

① Explain the time sampling by showing that the following operation is the equivalent to the sampling of x(t): $x[n]=x(nT_s)$, where T_s: sampling interval, n: positive integer.

② Explain the Nyquist sampling theorem.

③ Typically, ADC specification is given by a sampling frequency f_s (unit: Hz or samples/sec). Can you derive the mathematical relationship between f_s and T_s?

④ Draw a sampled analog sine signal (amplitude: 1, frequency: 10 Hz) on the time axis according to Nyquist sampling theory.

⑤ Draw a quantized ④′s signal by 3-bit ADC (8 possible output values)

3.2.MATLAB functions

Before you do the task below, you should read the documentation explaining find(.), findpeaks(.)and histogram(.) unless you already get used to how to implement them.

① Write a code that perform the following task

i.	Generate vector t = [0 : 0.01 : 5]
ii.	Generate vector y = cos (2*pi*t)
iii.	Plot t vs. y using plot (.)
iv.	Find zero-crossing points, that is, find t when y = 0. If there is not t (t is empty), explain why you get no points. Use find (.) function.
v.	Find the range of t (time points) for | y | < 0.01.
vi.	Mark the points from (v) with marker ‘o’ on the plot from (iii) (use plot (.), hold on)
vii.	Find local maxima (peaks) in y using findpeaks(.)
viii.	Mark the peaks with markers on the plot from (vi)
ix.	Generate matrix y2 = [cos(2*pi*t); sin(2*pi*t)]
x.	Check the size(dimension) of y2, and explain what is stored in column and row vectors
xi.	Plot t vs y2

xii.	Find the range of t (time points) for | y2| < 0.01. Use find (.) function. You need to check the output of find (.) when the input is matrix instead of a single column vector
xiii.	Mark the points from (x) with marker 'o' on the plot from (ix) (use plot (.), hold on)
xiv.	Generate a histogram with the edge [-1:0.1:1] for sin(2*pi*t). Use y2 matrix from (vii).

3.3. ECG signal processing [1]

① ECG signals are essentially the electric activity of heart muscle cells. Explain how can we measure ECG signals on the skin, without directly touching the heart.
(Hint: our body is conductive thanks to the ions in our body fluids)

② Draw a typical ECG waveform and identify the features including P wave, QRS complex, T wave, PR interval, QRS interval, QT interval, RR interval. Make sure to label x-, y- axis. Time scale, magnitude scale.

③ Suppose your colleague determine R point simply by finding the point whose first derivative is zero. Estimate whether it is plausible method or not referring to the typical ECG waveform.

④ Explain the double level method (method to determine the R point) referred in the background. Drawing the ECG waveform, show how the double level method can specifically detect R point.

3.4. EMG signals [2]

① Choose three different analytical techniques and explain advantages and disadvantages of each. Give the examples where each analysis can be applied and why you thought so.

4. Experimental procedure (Please show the red marked part as a plot on the report)

- Import data to MATLAB environment and plot data
- ECG analysis
- EMG analysis

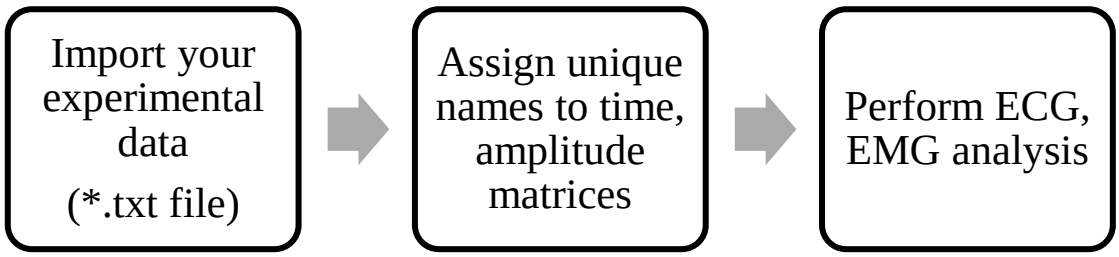


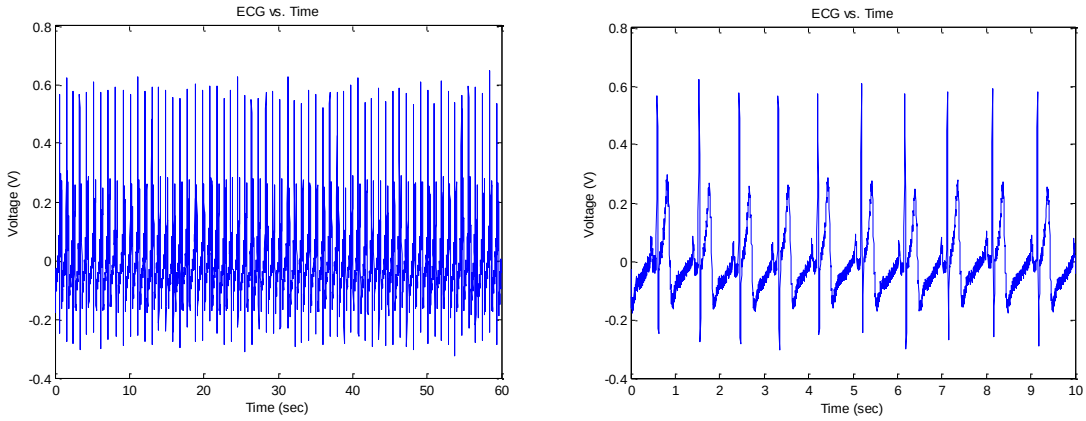
Figure 10. Experimental procedures for ECG, EMG signal analysis

4.1.Import data to MATLAB environment and plot data

① Write command "importdata('file directory')" on your MATLAB command window.
e.g.) my_data = importdata('C:\Users\username\Desktop\my_data_file.txt');

② Assign unique names for data parameters you need

③ Plot ECG vs. time [MATLAB command: plot(), title(), xlabel(), ylabel(), xlim(), ylim()]

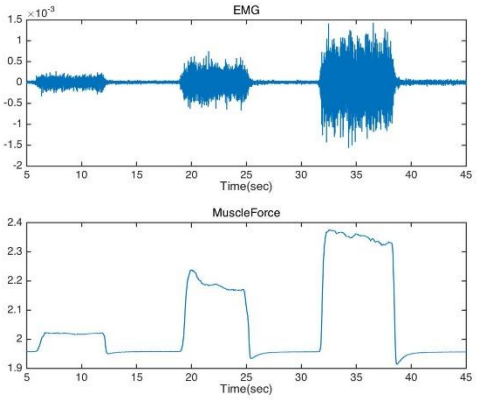


Q1. Can you identify P wave, QRS complex, T wave, U wave, PR interval, QRS interval, QT interval, RR interval, PR segment, ST segment in the plot?

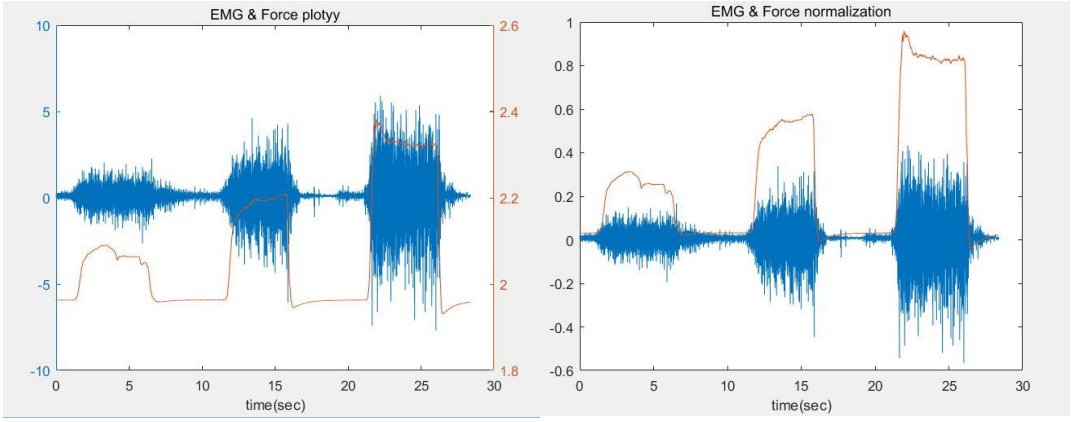
④ Plot EMG vs. time

⑤ Plot force vs. time

⑥ Dual plots (EMG and Force) [MATLAB command: subplot()]



⑦ Overlay plots [MATLAB command: hold on, plotyy(), legend()]



Q2. How can we normalize two data with different units?

4.2. ECG analysis

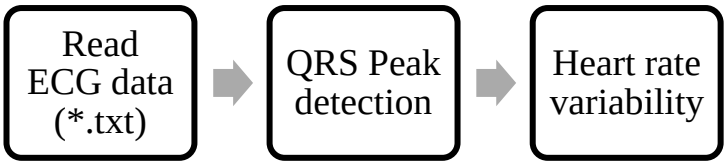
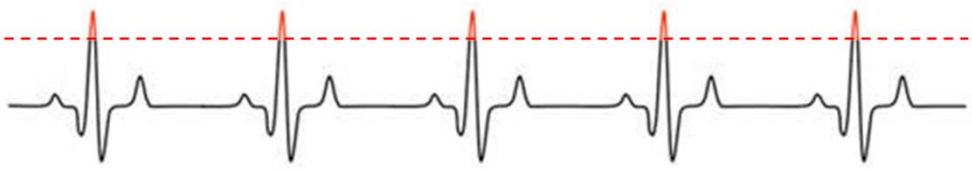
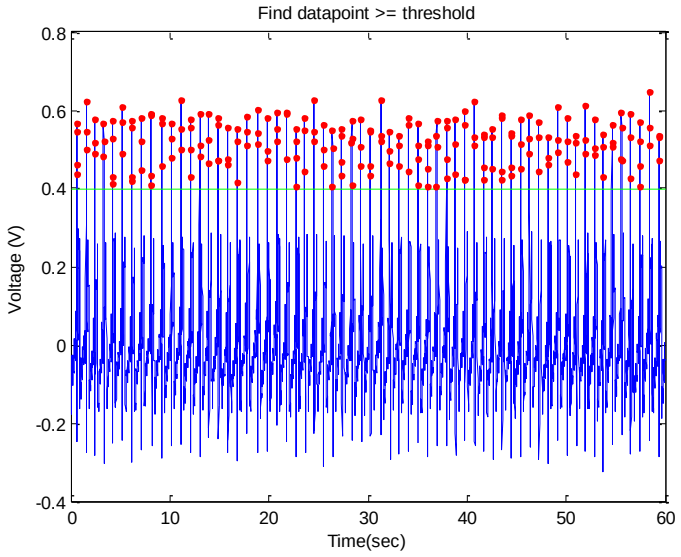


Figure 11. Experimental procedures for ECG analysis

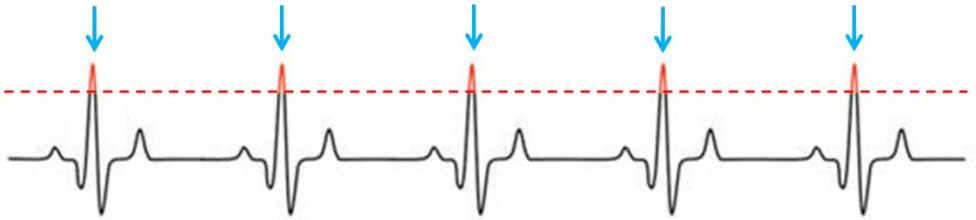
① Use threshold method to localize QRS complexes

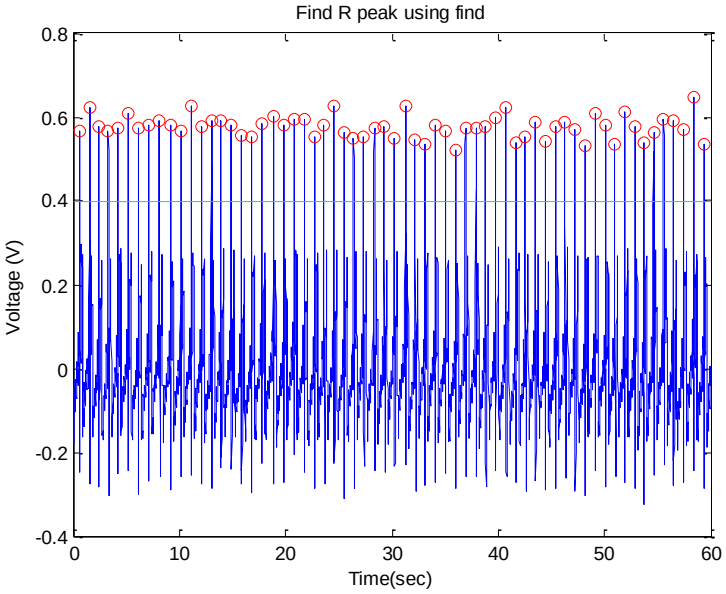
[MATLAB command: findpeaks(~,minpeakheight', 'minpeakdistance'),find()]





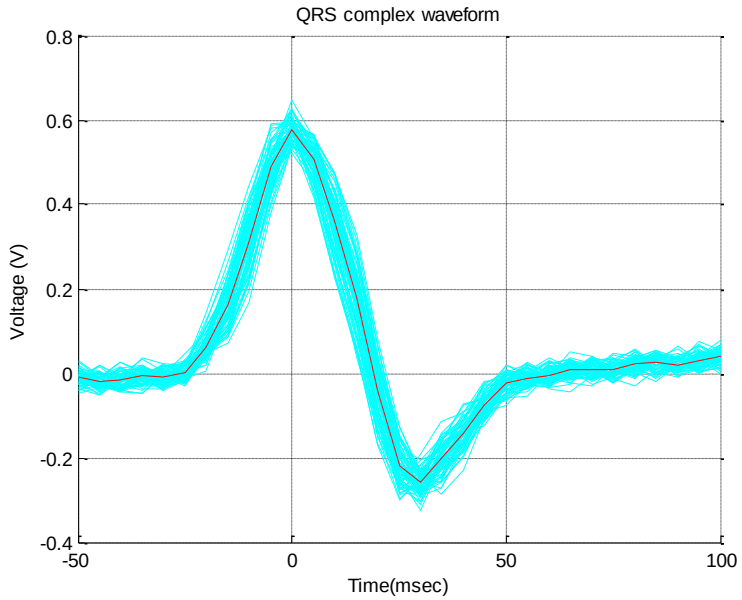
② Find R peak timing [MATLAB command: for, if, max()]





③ Separate QRS complex waveforms (R peak - 50 ms ~ R peak + 100 ms)

④ Find an average QRS waveform [MATLAB command: mean(), grid on()]



Q1. Why you using averaged data instead of raw data?

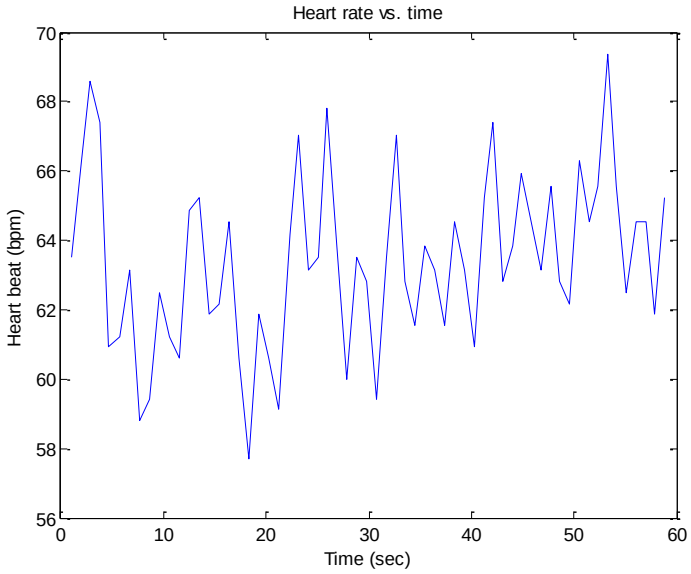
Q2. Explain three noise sources of ECG signals

(low frequency noise, muscle noise, electromagnetic noise)

⑤ Calculate R-R interval

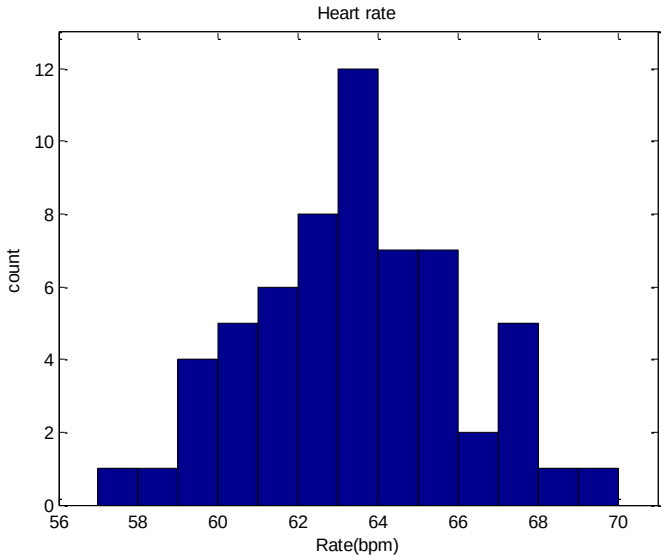
Q3. What is the difference between commands 'a/b' and 'a./b'?

⑥ Plot Heart rate vs. time (using 1-minute data)



⑦ Plot heart rate histogram (using 1-minute data)

[MATLAB command: histogram()]



Q4. What is heat rate variability (HRV)? How is it used in diagnosis?

4.3. EMG analysis

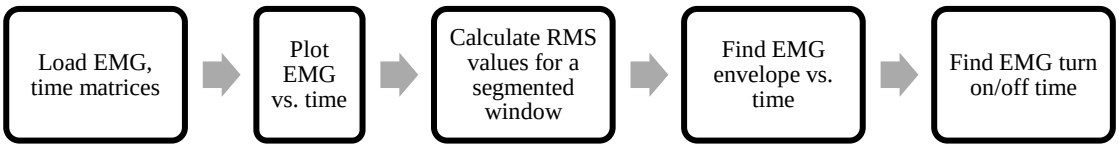
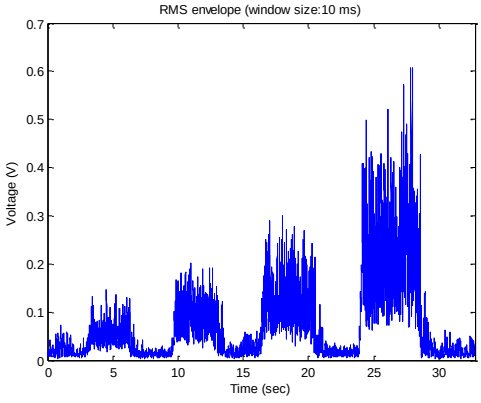
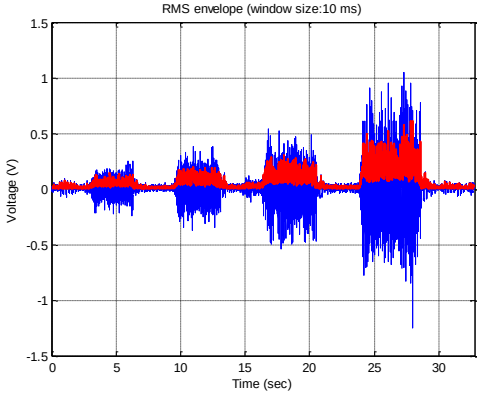


Figure 9. Experimental procedures for EMG signal analysis

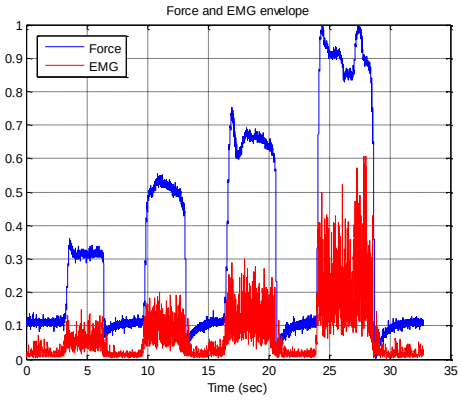
① Find the EMG envelope using RMS (root mean square) values by calculate RMS values for different window sizes: 10 ms, 100 ms, 1 sec. [MATLAB command: rms()]

② Plot EMG envelope vs. time (overlaid with original EMG)
[MATLAB command: plot(~, 'linewidth')]





③ Plot force vs. EMG envelope



5. References

[1] Adam Gacek Introduction to ECG Signal Processing Analysis. ECG Signal Processing, Classification and Interpretation, (Adam Gacek, Witold Pedrycz, Ed.) Spinger, 21 – 46, 2012

[2] De Luca, C. J. Electromyography. Encyclopedia of Medical Devices and Instrumentation, (John G. Webster, Ed.) John Wiley Publisher, 98 – 109, 2006.

[3] https://www.mathworks.com/help/matlab/learn_matlab/matrices-and-arrays.html

[4] https://www.mathworks.com/help/matlab/math/array-indexing.html