Acquisition and Analysis of Biosignals DTEK0042

Biosignal analysis II

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Introduction

So far, we learned:

- ❑ Objectives of biomedical signal analysis
- ❑ Correlation techniques (e.g., EEG)
- ❑ Waveform analysis and feature extraction in biosignals (e.g., ECG)

In this session, we will learn:

- ❑ Frequency domain analysis
- ❑ Analysis of PPG
- ❑ Waveform analysis of EMG and PCG

Biosignal analysis

- Biomedical signals carry signatures of physiological events
- The objective is to use **different time-domain and frequency domain techniques** to analyze these events
  - Differentiate normal events from abnormal events
- The features are selected with respect to the biosignals and applications

Frequency domain analysis

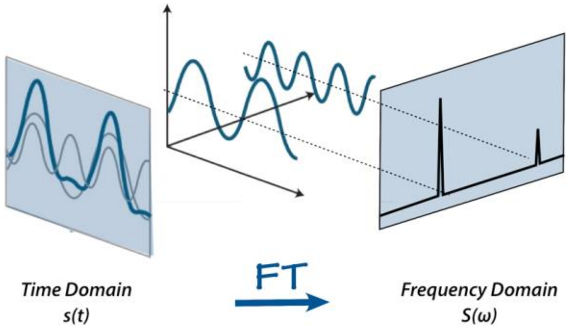
Frequency domain features

- Many biomedical systems exhibit rhythms that are more readily expressed in terms of frequency than temporal measures
  - E.g., Heart cycle
  - E.g., EEG rhythms
- Features are extracted from the amplitude or energy of the signal as a function of frequency

Fourier Transform

- **Fourier Transform**: decomposes a function of time (a *signal*) into its frequencies

$$X(\omega) = \int_{-\infty}^{\infty} x(t)e^{-i\omega t}\,dt$$



http://mriquestions.com/fourier-transform-ft.html

- **Discrete-time Fourier Transform**:

$$X(\omega) = \sum_{n=-\infty}^{\infty} x(n)e^{-i\omega n}$$

- **Inverse FT/ Inverse DTFT**: transform a continuous or discrete spectrum into a function for the amplitude with the given spectrum
- **Fast Fourier Transform** is an efficient algorithm for computing the Discrete Fourier Transform.

Energy / power of the signal

- Let's consider the signal as $x(t)$
- The **energy distribution** or **density function** is defined as $x^2(t)$ where $0 \leq t \leq \mathrm{T}$
- The total energy of the signal is:

$$E_x = \int_0^T x^2(t)dt$$

$$E_x = \sum_{n=0}^{K} x^2(n)$$

- Power is the energy of a signal divided by the signal length

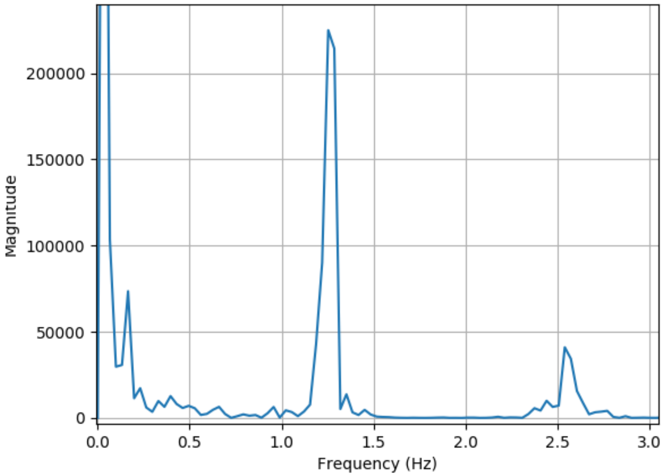
Power Spectral Density (PSD)

- Power Spectral Density (PSD)
  - shows the signal's power content as a function of frequency
  - Fourier transform of the auto-correlation
- PSD can be calculated using Welch's method[1]:
  1. The time signal is divided into successive blocks,
  2. Computing the discrete Fourier transform of each block and then computing the squared magnitude of the result
  3. Averaging

$$S_{xx} = \frac{1}{M}\sum_{m=0}^{M-1} |DFT(x_m)|^2 \triangleq \{|X_m(\omega_k)|^2\}_m$$

[1] Welch, P., 1967. The use of fast Fourier transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms. IEEE Transactions on audio and electroacoustics, 15(2), pp.70-73.

PSD analysis



- ❑ We may study the shape of the spectrum graphically and observe its general characteristics

- ❑ Since the PSD is a nonnegative function, we may readily treat it as a PDF, and compute statistics using moments.
  - Moments of PSDs may be useful in characterizing the general trends in the distribution of the power of a signal over its bandwidth
  - The higher-order moments are sensitive to noise in the PSD estimate and may not be reliable measures if the PSD pattern is not simple
- ❑ We may also detect peaks corresponding to resonance, measure their bandwidth, and derive measures of concentration of power in specific frequency bands of interest.

Moments of PSD – Mean (1)

- Mean frequency is a useful measure of the concentration of signal power

Sampling frequency

PSD of x(n)

$$\overline{f_{Hz}} = \frac{f_s}{N} \frac{2\sum_{k=0}^{N/2} kS_{xx}(k)}{E_x}$$

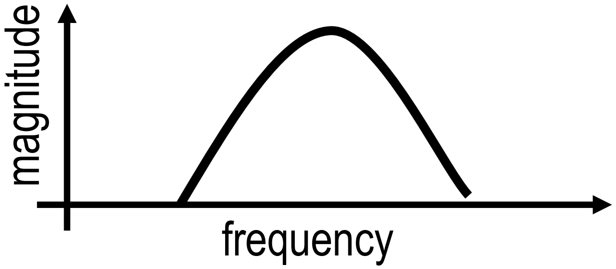
Number of samples in the DFT-based representation of the PSD

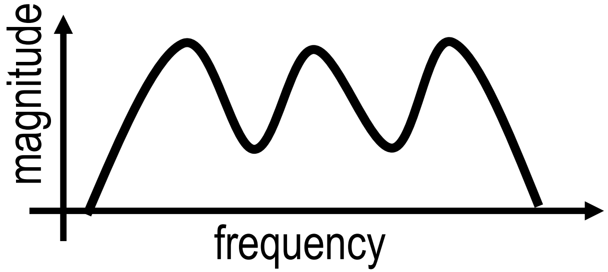
Total power of the signal

$$\frac{1}{N}\sum_{k=0}^{N-1}|X(k)|^2$$

Moments of PSD – Mean (2)

- Mean frequency:
  - Indicates the resonance frequency in the case of unimodal distributions.
  - Not useful when PSD is uniform
  - Not useful when there are multiple resonance frequencies (Multimodal PSD)





Moments of PSD - Median

- Median frequency is the frequency which splits the PSD in half:
- Median frequency:

$$f_{med} = \frac{m}{N} f_s$$

With the largest m that:

$$\frac{2}{E_x} \sum_{k=0}^{m} S_{xx}(k) < \frac{1}{2}; \qquad 0 \leq m \leq \frac{N}{2}$$

Moments of PSD - Variance

- Variance:

Frequency sampling index corresponding to the mean frequency

$$f_{m2} = \left(\frac{f_s}{N}\right)^2 \frac{2\sum_{k=0}^{N/2}(k-\bar{k})^2 S_{xx}(k)}{E_x}$$

$$\bar{\boldsymbol{k}} = \boldsymbol{N}\frac{\bar{\boldsymbol{f}}_{\boldsymbol{Hz}}}{\boldsymbol{f}_{\boldsymbol{s}}}$$

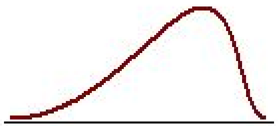
- Standard deviation (root of variance) provides a measure of spectral spread

Moments of PSD - Skewness

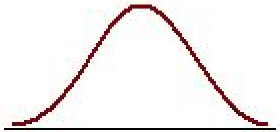
- ❑ Skewness is a measure of the asymmetry
- ❑ Skewness is zero if the density function is symmetric about the mean frequency

$$Skewness = \frac{f_{m3}}{\left(f_{m2}\right)^{3/2}}$$

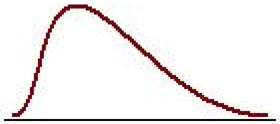
$$f_{m3} = \left(\frac{f_s}{N}\right)^3 \frac{2\sum_{k=0}^{N/2}\left(k-\bar{k}\right)^3 S_{xx}(k)}{E_x}$$



Skewness < 0



Skewness = 0



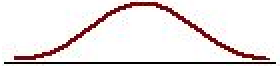
Skewness > 0

Moments of PSD - Kurtosis

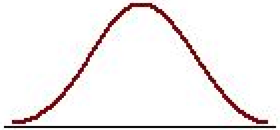
- Kurtosis indicates if the PSD is a long-tailed function

$$Kurtosis = \frac{f_{m4}}{(f_{m2})^2}$$

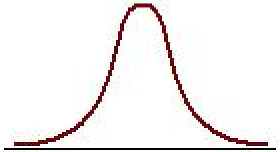
$$f_{m4} = \left(\frac{f_s}{N}\right)^4 \frac{2\sum_{k=0}^{N/2}\left(k-\bar{k}\right)^4 S_{xx}(k)}{E_x}$$



Kurtosis < 0

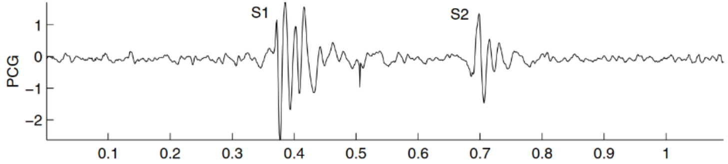


Kurtosis = 0

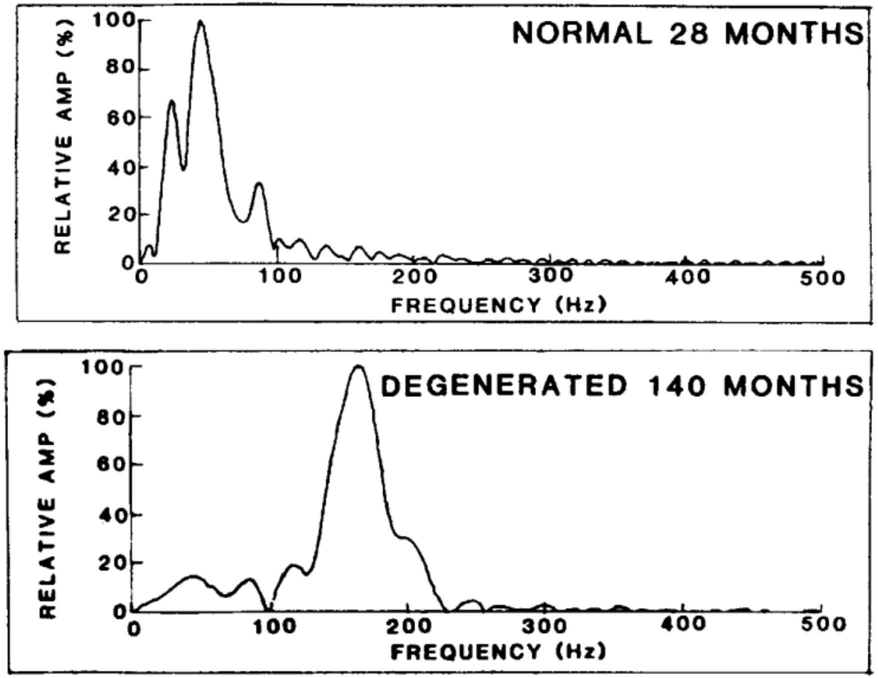


Kurtosis > 0

Example – PSD of PCG



- Power spectra of S1 in the case of normal and degenerated porcine (pig) bioprosthetic valves implanted in the mitral position
- The increased stiffness is expected to lead to higher-frequency components in the opening or closing sounds of the valve



Durand, L.G., et al., 1990. Comparison of pattern recognition methods for computer-assisted classification of spectra of heart sounds in patients with a porcine bioprosthetic valve implanted in the mitral position. IEEE Transactions on Biomedical Engineering, 37(12), pp.1121-1129.

Note

- ❑ Such statistical analysis can be used for time-domain analysis
  - Waveform analysis

- ❑ Examples:
  - PPG
  - EEG
  - Acceleration data

Power band

- The power of the signal in a given frequency band [f_1,f_2] can be computed as

$$\frac{2}{E_x}\int_{f=f_1}^{f_2} |X(f)|^2 df$$

Or

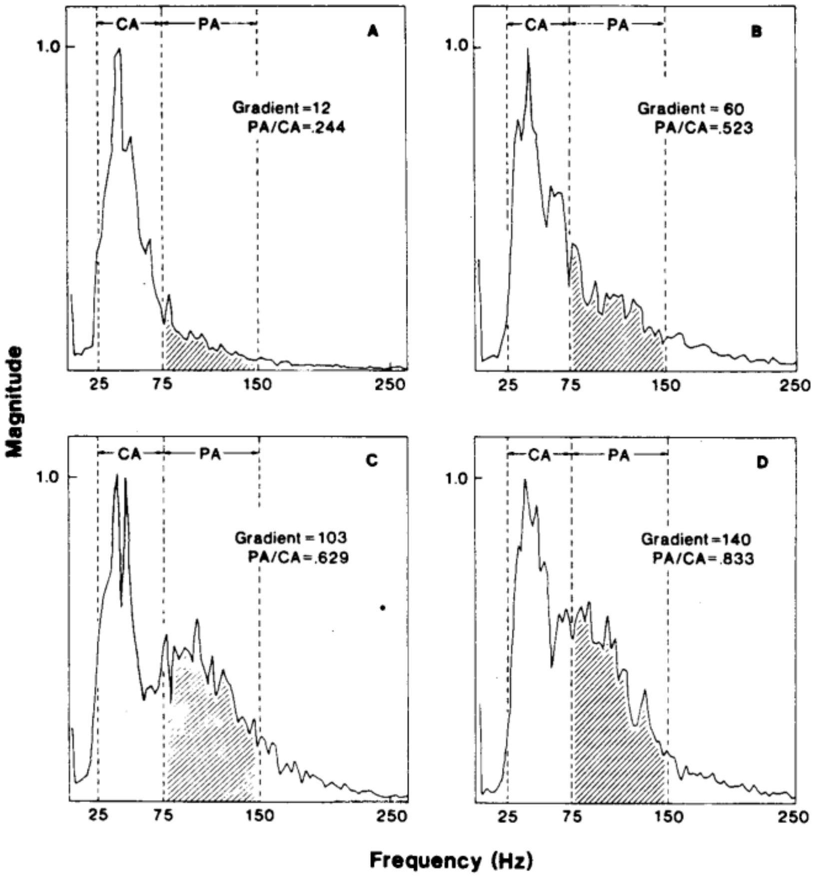
$$\frac{2}{NE_x}\sum_{k=k_1}^{k_2} |X(k)|^2$$

k_1 and k_2 are the DFT indices corresponding to f_1 and f_2

- Spectral power ratios also provide information
  - E.g., diagnostic purposes

Example – PSD of PCG

- Synchronized averaging of the PSDs of PCG signals over several cardiac cycles
- PSDs of four patients with aortic stenosis of different levels of severity
- Constant Area (CA) is related to normal sounds and Predictive Area (PA) is related to murmurs
- The ratio correlates well with the severity of aortic stenosis



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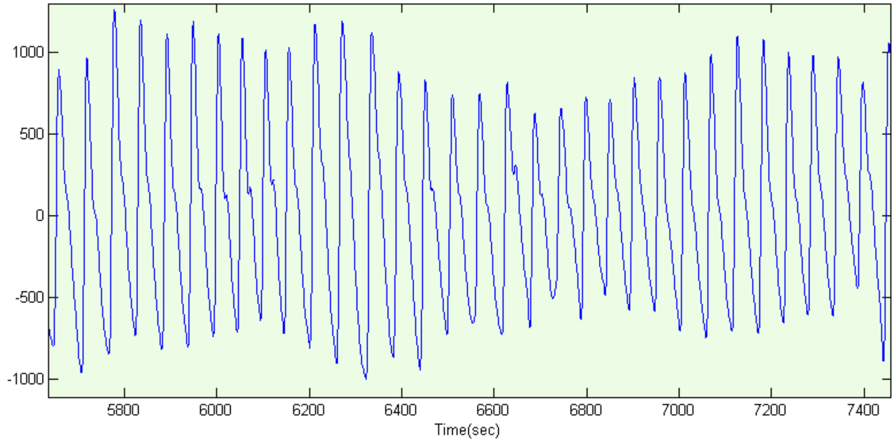
Analysis of PPG

PPG signal

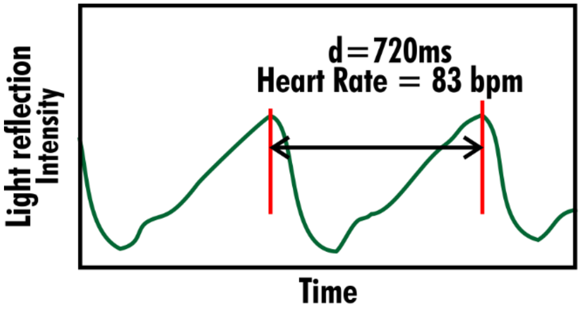
- PPG is the signal which indicates blood volumetric changes in the tissue
- PPG includes various health information:
  - Extract vital signs

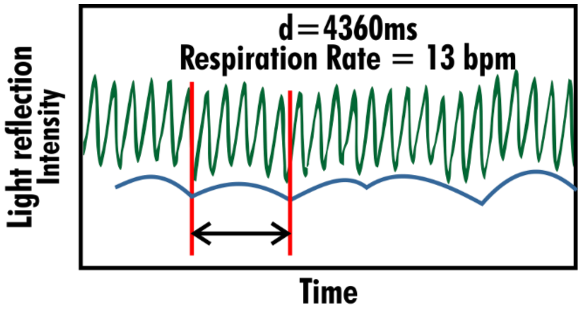


https://en.wikipedia.org/wiki/File:PPG.PNG

PPG – heart rate and respiration rate

- The PPG variations[1,2] are related to:
  - Heart cycles
  - Respiration cycles => slowly varying baseline or low frequency components





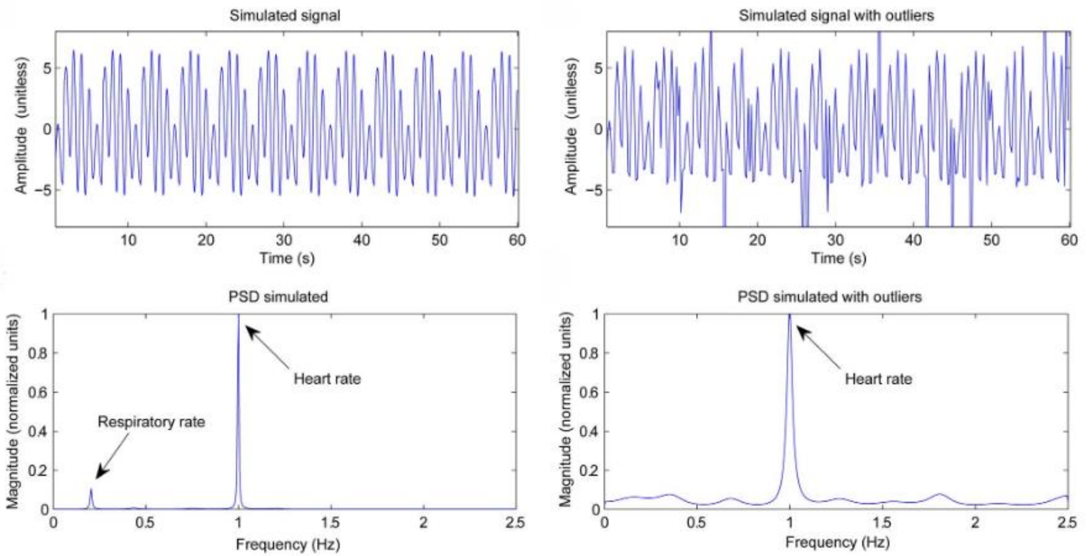
- The oscillations can be investigated by spectral analysis of the signal
  - Calculating the DFT or PSD of the signal

[1] Allen, J. (2007). Photoplethysmography and its application in clinical physiological measurement. Physiological measurement, 28(3), R1.
[2] Anzanpour A. et al., Edge-Assisted Control for Healthcare Internet-of-Things: A Case Study on PPG-based Early Warning Score, ACM Transactions on Internet of Things, 2020.

Spectral analysis of PPG

- The respiration and heart cycles can be tracked in the frequency domain
- Features can be extracted:
  - Dominant frequencies of heart and respiration cycles => Real-time heart/respiration rate detection
- However, noise might cover the respiration

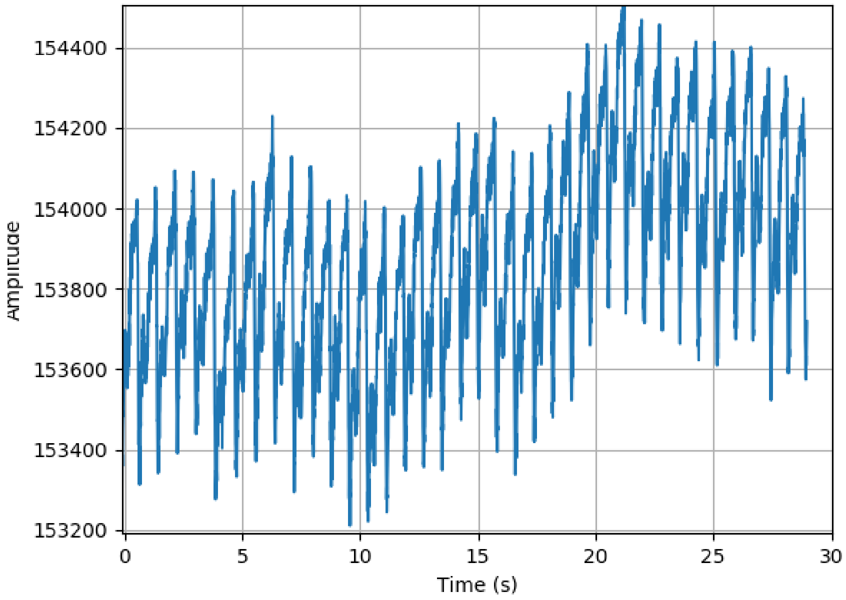
Simulated signal with 0.2 Hz modulation respiratory frequency (12 breaths/min), 1 Hz cardiac frequency (60 beats/min)

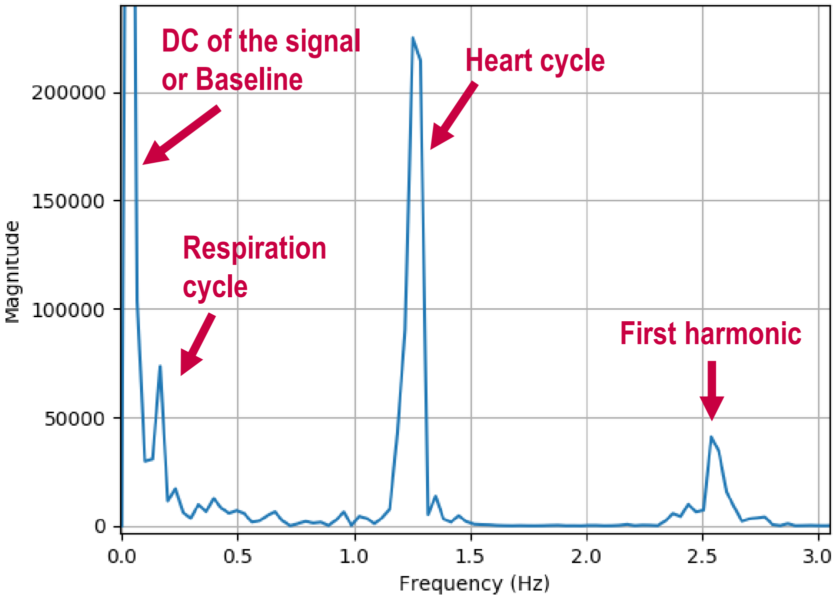


Garde, Ainara, et al. "Estimating respiratory and heart rates from the correntropy spectral density of the photoplethysmogram." PloS one 9.1 (2014): e86427.

Heart rate and respiration rate

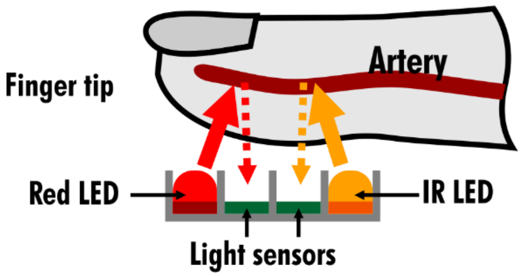
- ❑ PPG signal (IR) and PSD of the signal

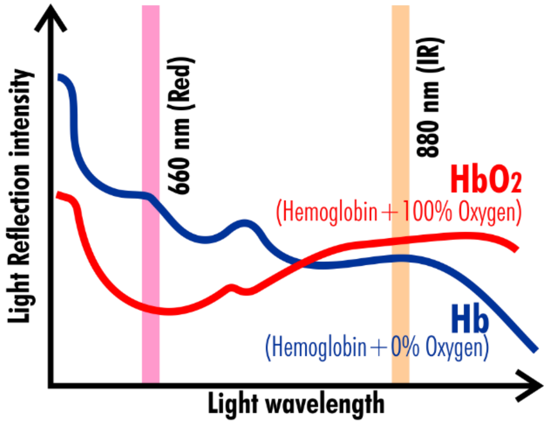




PPG - SpO_2 (1)

- SpO_2, also known as oxygen saturation, is the amount of oxygen-carrying hemoglobin in the blood relative to the total hemoglobin
- Red and infrared light are used





Anzanpour A., Amiri D., Azimi I., Levorato M., Dutt N., Liljeberg P., Rahmani A., Edge-Assisted Control for Healthcare Internet-of-Things: A Case Study on PPG-based Early Warning Score, ACM Transactions on Internet of Things, 2020.

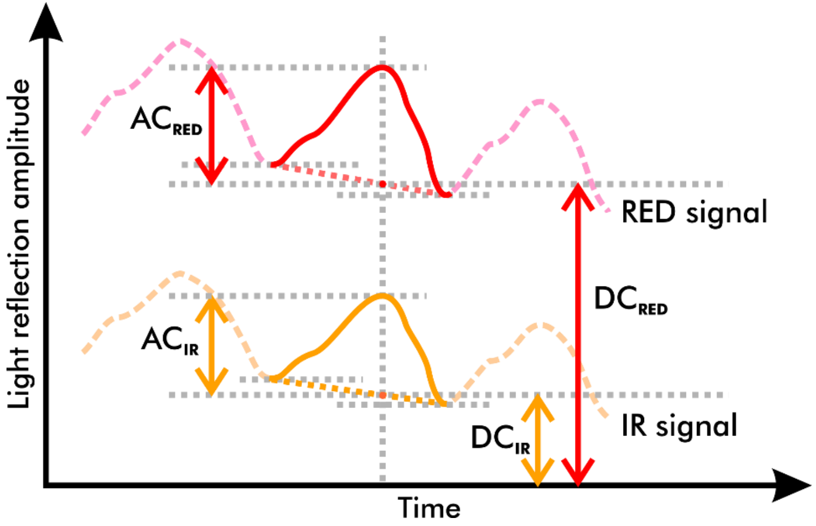
PPG - SpO_2 (2)

- SpO_2 is calculated from the alternative currents and direct currents of the IR and red signals

$$R = \frac{AC_{red}.DC_{IR}}{AC_{IR}.DC_{red}}$$

$$SpO_2 = \alpha R^2 + \beta R + \gamma$$

α, β, γ and are constants retrieved from the sensor's specification



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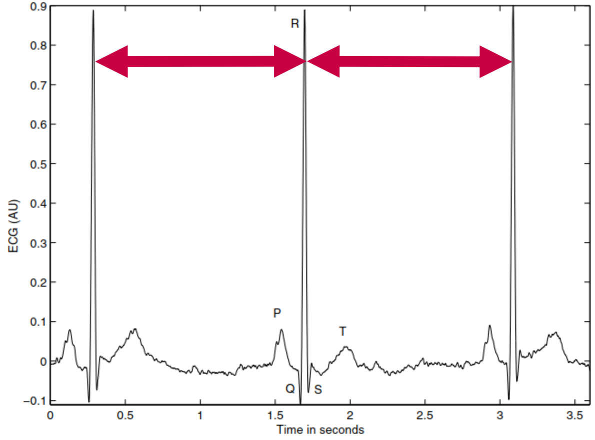
Interbeat interval (IBI)

- Interbeat interval (IBI) is the time interval between two successive peaks in the signal

ECG



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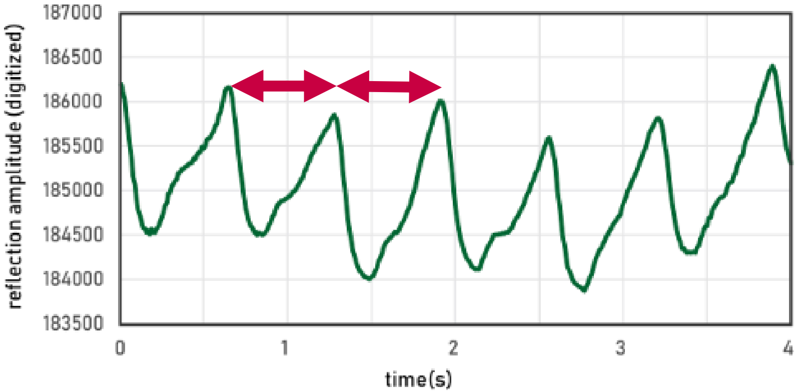
PPG



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Heart rate variability – time domain

- From the **HRV** signal, different time-domain parameters [1] can be extracted:
  1. Root Mean Square of Successive RR-interval Differences (RMSSD)
     - Values can be affected by age, stress, diseases, etc.
  2. Standard deviation of NN intervals (SDNN)
  3. Percentage of successive RR intervals that differ by more than 50 ms
     - Diagnostic information in a wide range of conditions (e.g., lower in hypertensive patients)

1. Shaffer, F., & Ginsberg, J. P. (2017). An overview of heart rate variability metrics and norms. Frontiers in public health, 5, 258.

Heart rate variability – frequency domain

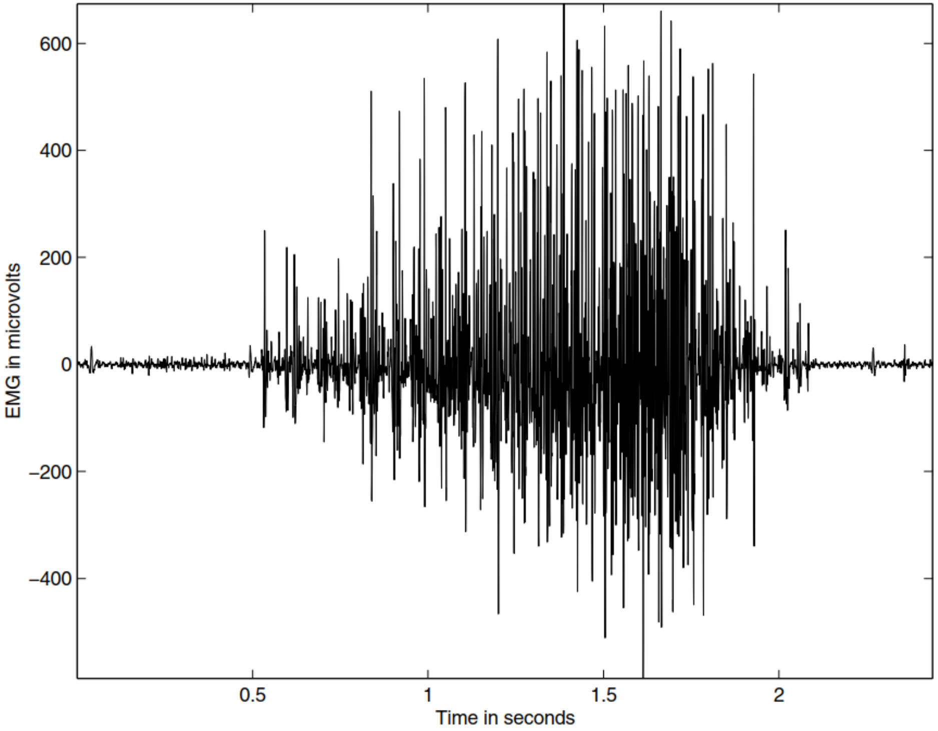
- From the **HRV** signal, different frequency-domain parameters [1] can be extracted:
  1. Absolute power of the very-low-frequency band (0.0033–0.04 Hz)
  2. Absolute power of the low-frequency band (0.04–0.15 Hz)
  3. Absolute power of the high-frequency band (0.15–0.4 Hz)
  4. Ratio of LF-to-HF power

1. Shaffer, F., & Ginsberg, J. P. (2017). An overview of heart rate variability metrics and norms. Frontiers in public health, 5, 258.

Waveform analysis of PCG and EMG

EMG and PCG waveform analysis

- Signals with complex patterns such as the EMG and PCG may not permit direct analysis of their wave shape
- In these signals, the general trends in the level of the overall activity might be important



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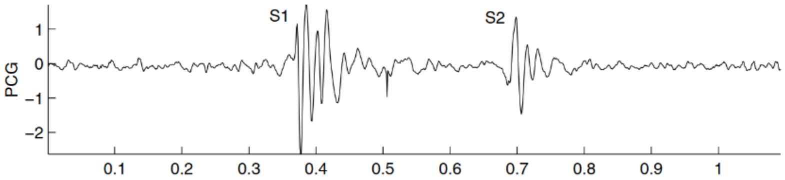
The RMS value

- The root-mean-square (RMS) value shows average power of the signal

$$RMS(n) = \left[\frac{1}{M}\sum_{k=0}^{M-1} x^2(n-k)\right]^{\frac{1}{2}}$$

- M is size of the window which is much less than duration of the signal.
- The RMS is for short-time analysis of nonstationary signals
- It can be used to identify systolic and diastolic segments of the signals



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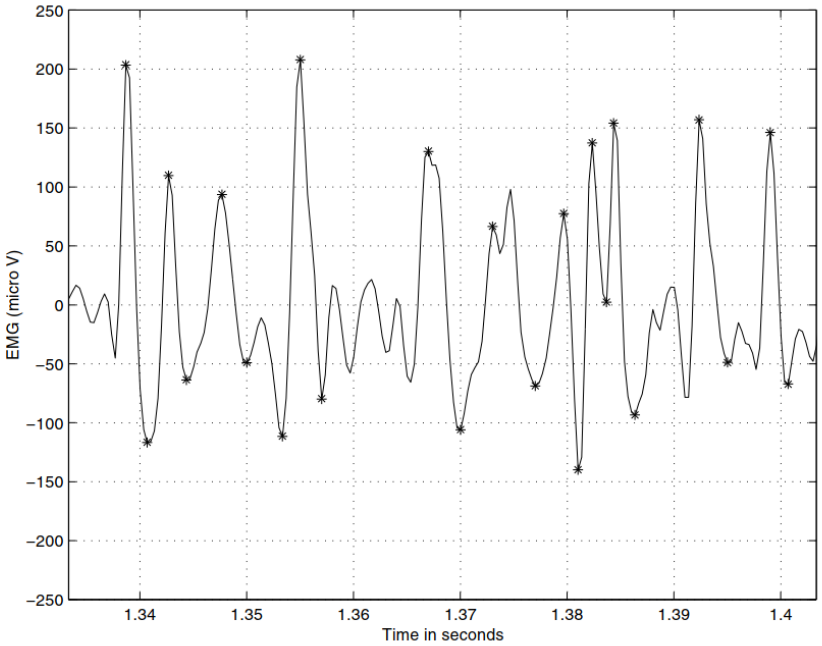
Zero crossing rate

- It is the number of times the signal crosses the reference (e.g., zero-activity line) within a specified interval
- It could be easily affected by DC bias or baseline wander.
- ZCR has been used in practical applications such as
  - Speech signal analysis to perform speech-versus-silence decision and to discriminate between voiced and unvoiced sounds
  - PCG analysis for the detection of murmurs

Turns count

- It is the number of turning point in the signal
- Turns that are greater than a threshold is considered to avoid fluctuations due to noise
- It can be used to analyze the level of activity in EMG signals



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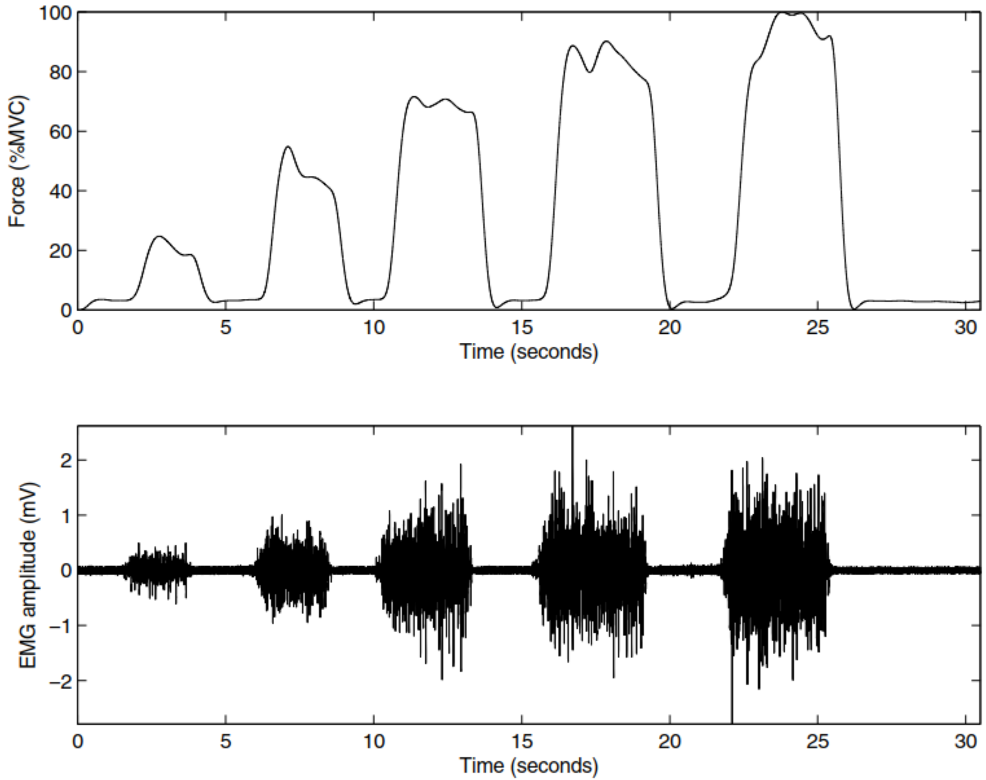
Example – EMG (1)

- ❑ Force and EMG signals recorded from the forearm muscle of a subject
- ❑ Contractions using a gripping device



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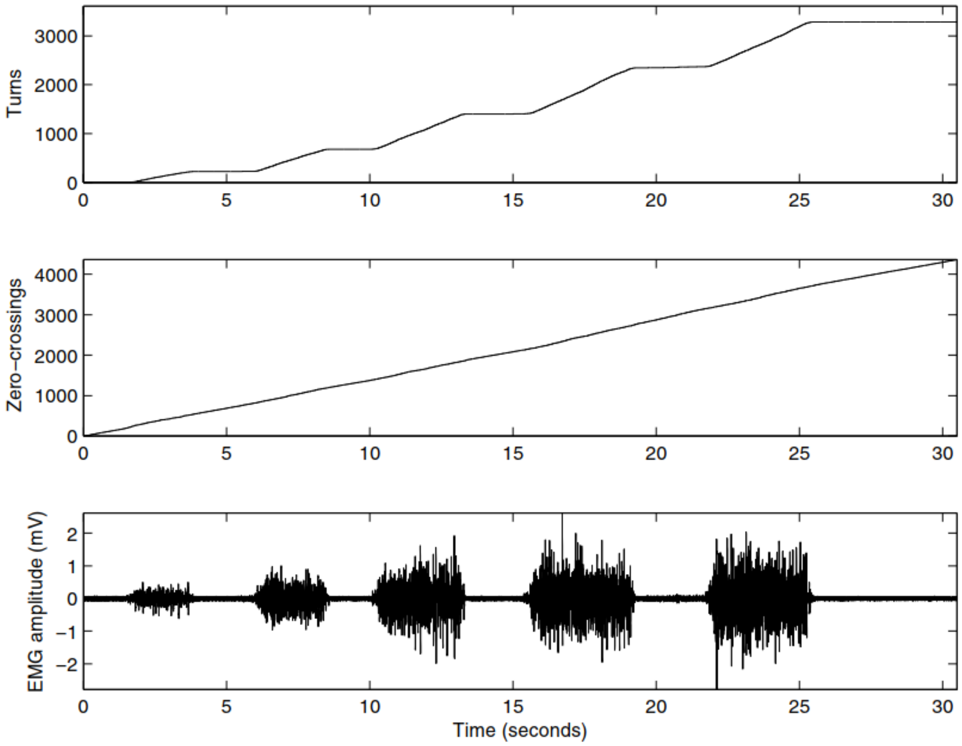
Example – EMG (2)

- The cumulative number of significant turns detected increases **only** during the periods of contraction and not during the periods of rest.
- Therefore, in this example, turns count is a better indicator of muscular force in comparison to zero-crossing rate

Cumulative count of zero-crossings, and cumulative number of significant turns



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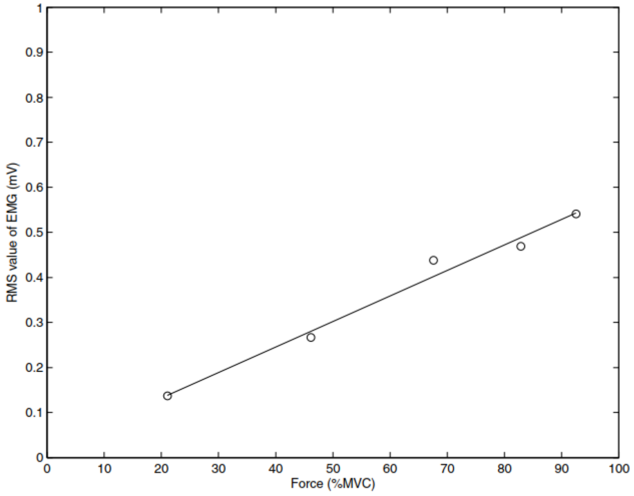
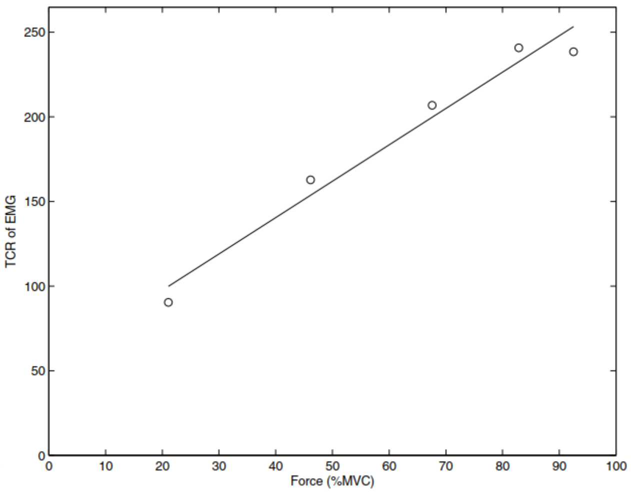
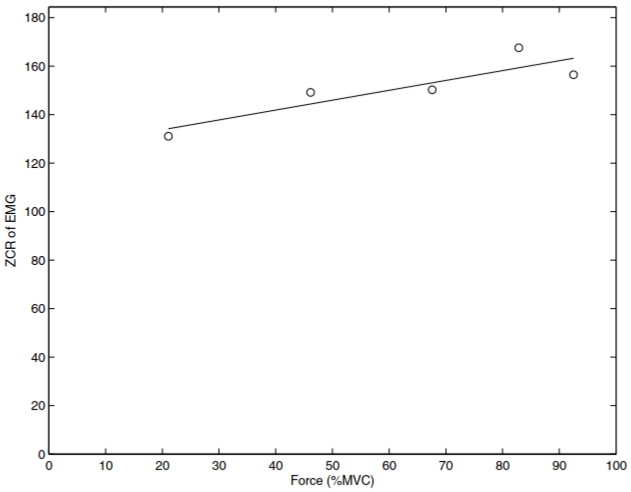
Example – EMG (3)

- Variation of the RMS value, Turns count and Zero-crossing rate in EMG in each contraction







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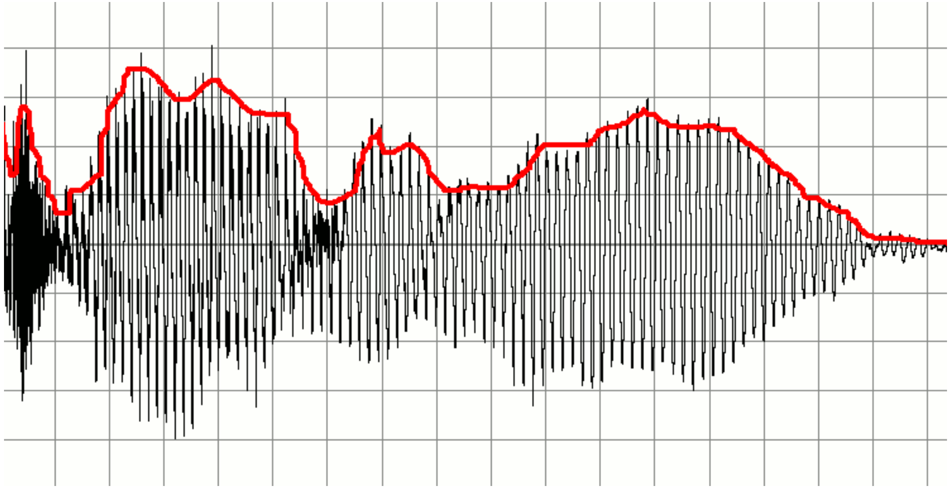
Envelope of the signal (1)

- The **envelope** of the overall signal carries important information
- It represents the total averaged activity
- In this feature, high-frequency variations may not be of interest



https://en.wikipedia.org/wiki/File:C_Envelope_follower.png

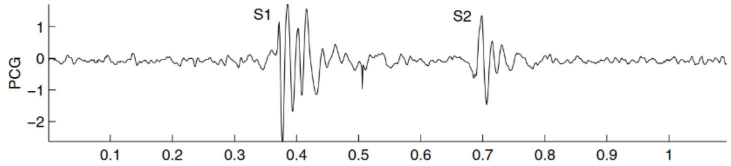
Envelope of the signal (2)

- The envelope of a signal is to obtain the absolute value of the signal at each time instant
- This procedure will create abrupt discontinuities at time instants when the original signal values change sign
- The discontinuities create high-frequency components of significant magnitude. This calls for the application of a lowpass filter with a relatively low bandwidth in the range of 0−10 or 0−50 Hz

Envelope extraction

- There are different methods to extract the envelope of the signal:
  1. Synchronized averaging
  2. Amplitude demodulation
  3. The envelogram
     - Using Hilbert transform
     - The magnitude of the analytic signal

Synchronized averaging of PCG envelopes



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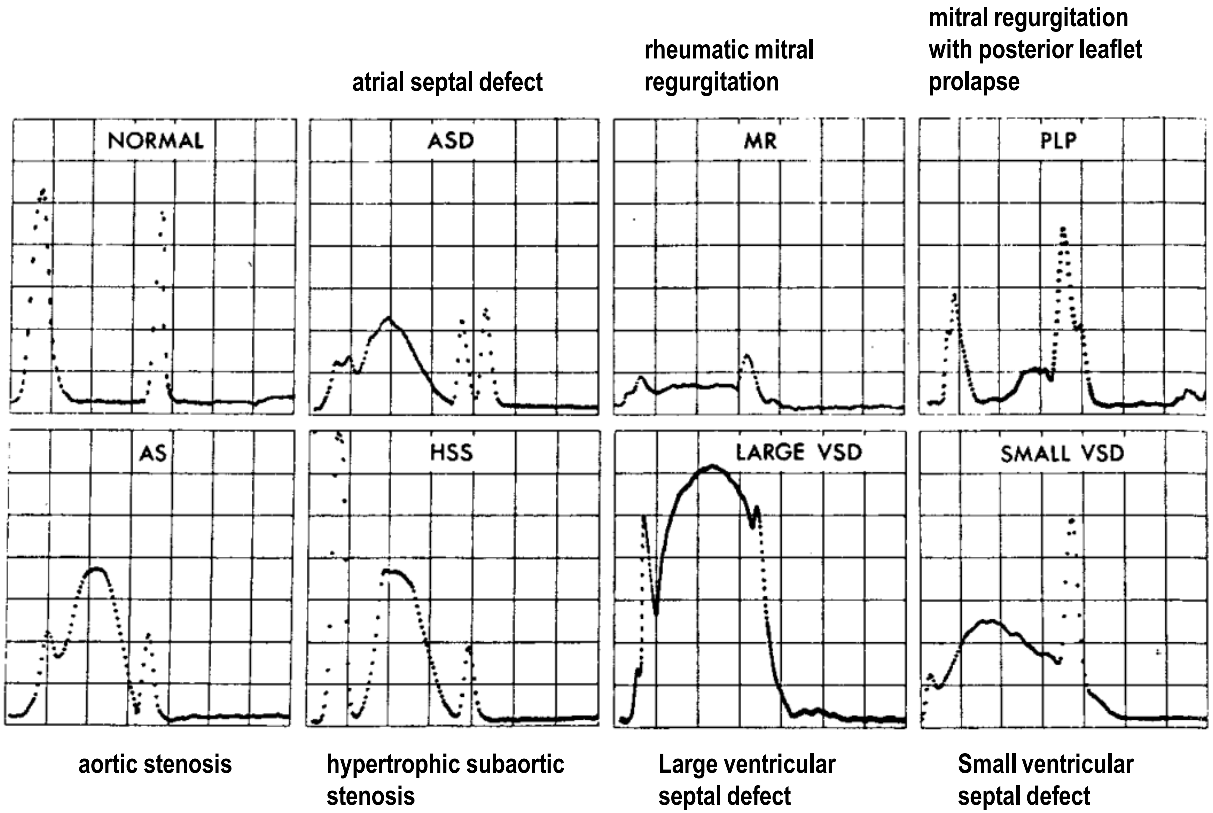
- In this method:
  1. The PCG signal is smoothed using a low-pass filter
  2. The heart cycles are extracted
     - ECG signal can be used to detect the position of S1
  3. Synchronized averaging is performed

  The output is the envelop
- The PCG envelopes were averaged over up to 128 heart cycles to get repeatable averaged envelopes
  - Reduce the effects of noise but the time boundaries of heart events are blurred if the heart rate is not constant during the averaging procedure

Example 1

- Averaged envelopes of the PCG signals of a normal subject and patients with diseases
- Different features can be extracted from the envelopes:
  - Number of peaks
  - Duration
  - Height



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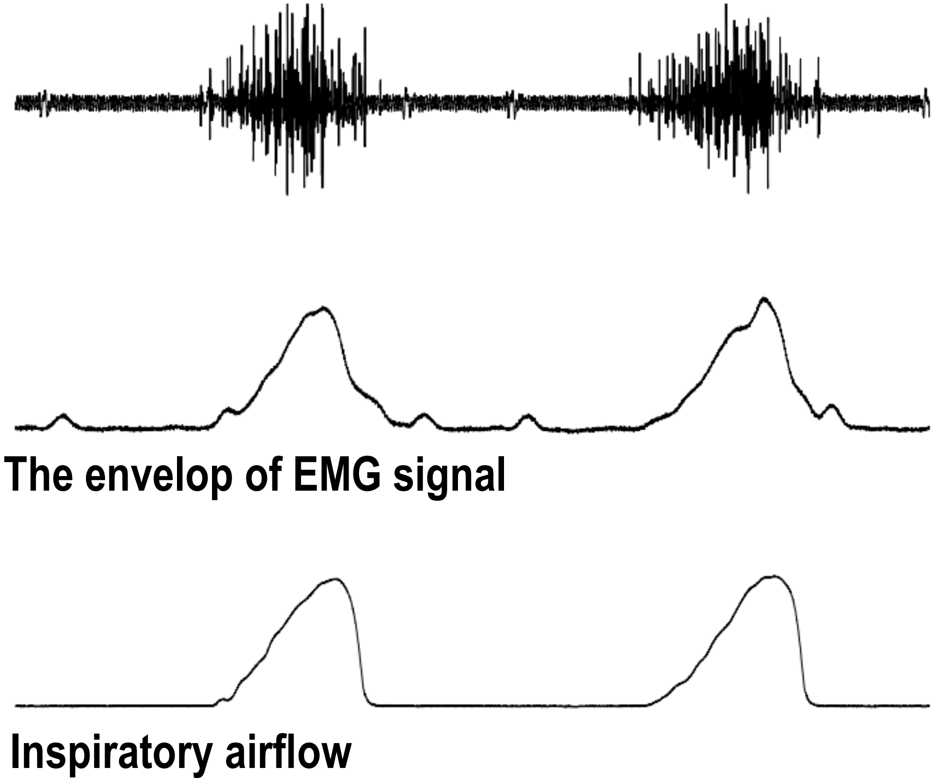
Example 2

- EMG signal over two breath cycles from the parasternal intercostal and diaphragm muscles of a dog recorded via implanted electrodes
- The envelop is correlated with the inspiratory airflow
- Respiration rate can be obtained using a peak detection method



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Conclusion

In this session, we learned about:

- ❑ Frequency domain analysis
- ❑ The analysis of different signals, including PCG, PPG, and EMG

In the next lecture, we will learn about:

- ❑ Time-Frequency Analysis
- ❑ Analysis of SCG and GCG
- ❑ Classification techniques

Thank You

Questions?

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