Spring 2020

CSEN 1099 – Introduction to Biomedical Engineering

EMG and Muscle Activity

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Electromyogram (EMG)

- References for this lecture are:

  - K. Blinowska and J. Zygierewicz, “Practical Biomedical Signal Analysis Using Matlab,” CRC Press, Boca Raton, FL, USA, 2011 (Chapter 4: Section 4.3)

  - J. D. Bronziono, “Biomedical Engineering Handbook,” CRC Press, Third edition, 2006 (Chapter 25)

Electromyogram (EMG)

- Movement and position of limbs are controlled by electrical signals traveling back and forth between the muscles and the peripheral and central nervous system

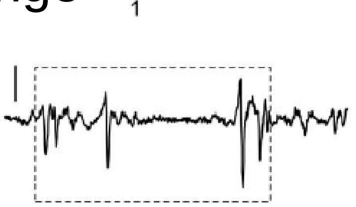
- Electromyogram (EMG) is a record of electrical muscle activity

Needle Electrode

Surface Electrode

- When a disease arises in the motor system, the characteristics of the electrical signals in the muscle change

Normal EMG

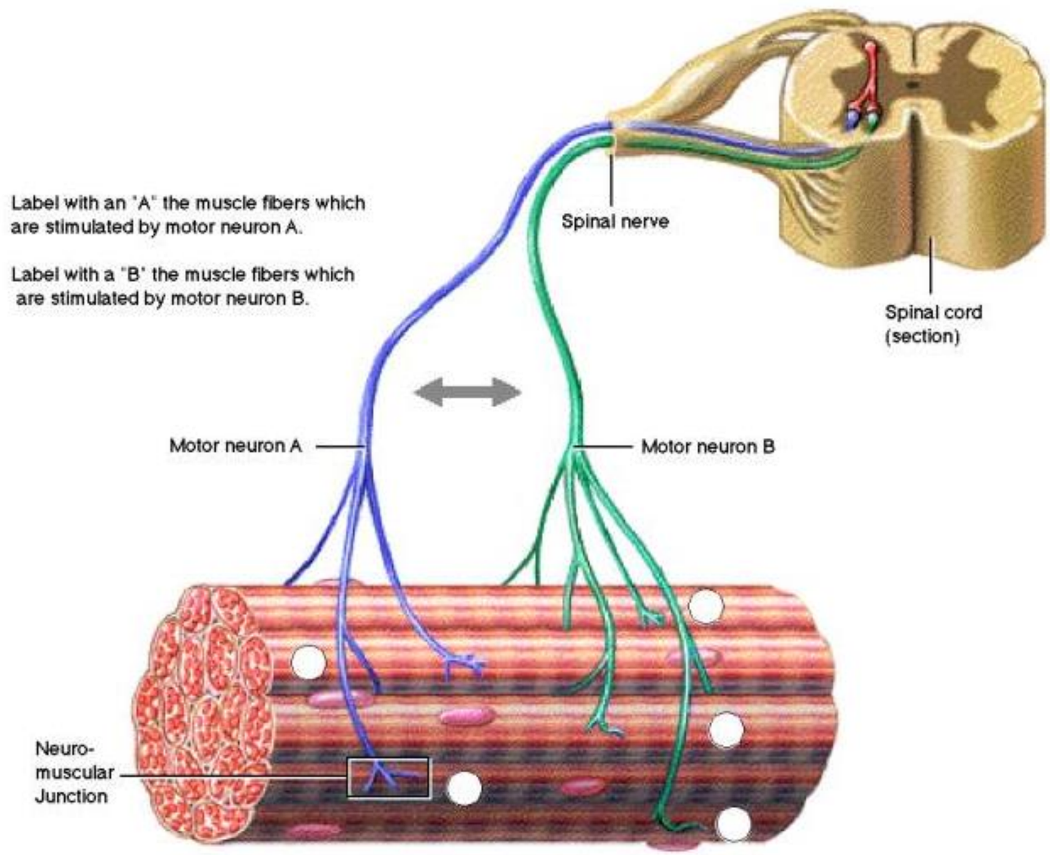


Diseased EMG

Motor Unit

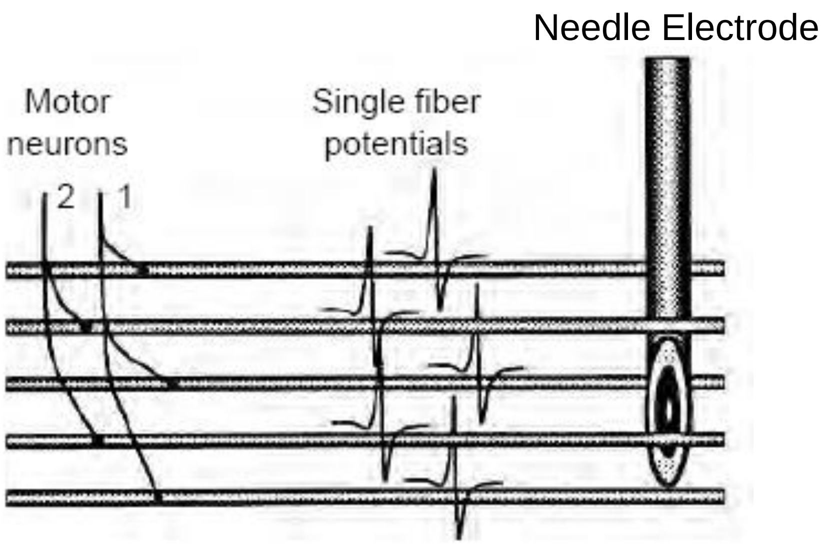
- A **motor unit** (MU) is made up of a motor neuron and the muscle fibers controlled by that neuron

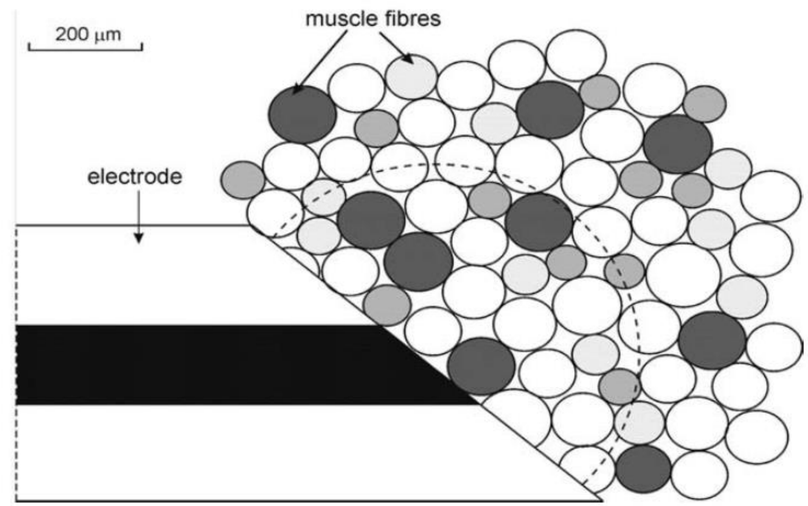
- Groups of motor units often work together to coordinate the contractions of a single muscle



Motor Unit

- Every motor neuron discharge evokes contraction of all its muscle fibers which is detected as a waveform called motor unit action potential (MUAP)



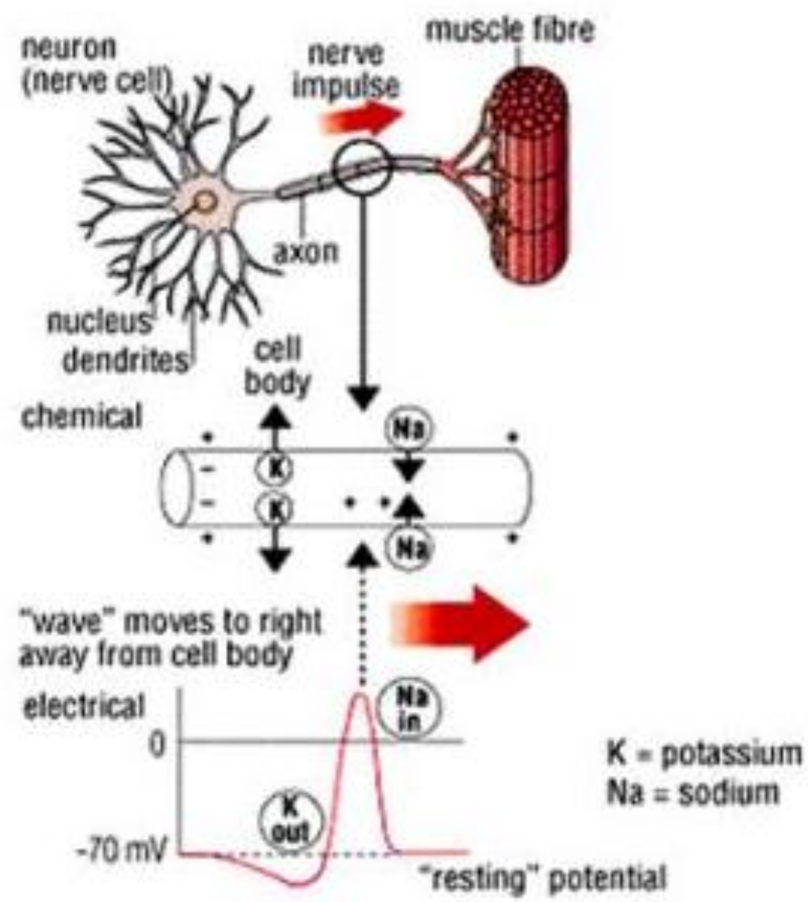


Fibers belonging to the same MU are marked by the same shade

- A needle electrode typically detects the activity of several muscle fibers within its pick-up area, which belong to a few different MUs

Motor Unit

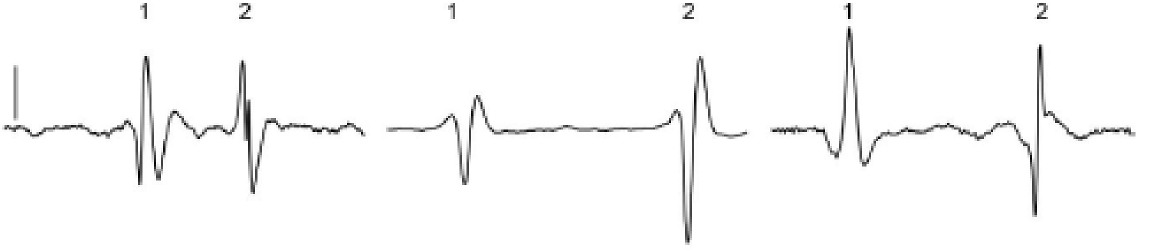
- A single fiber potential is generated similar to any other action potential through the movement of ions across the fiber membrane



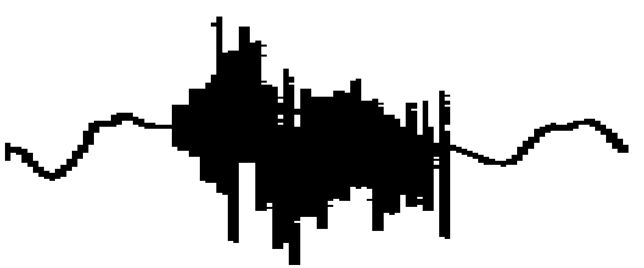
Motor Unit

- The shapes of MUAPs are different since they depend on the geometrical arrangement of the fibers of given MU with respect to the electrode

- At low force levels single MUAPs can be easily distinguished

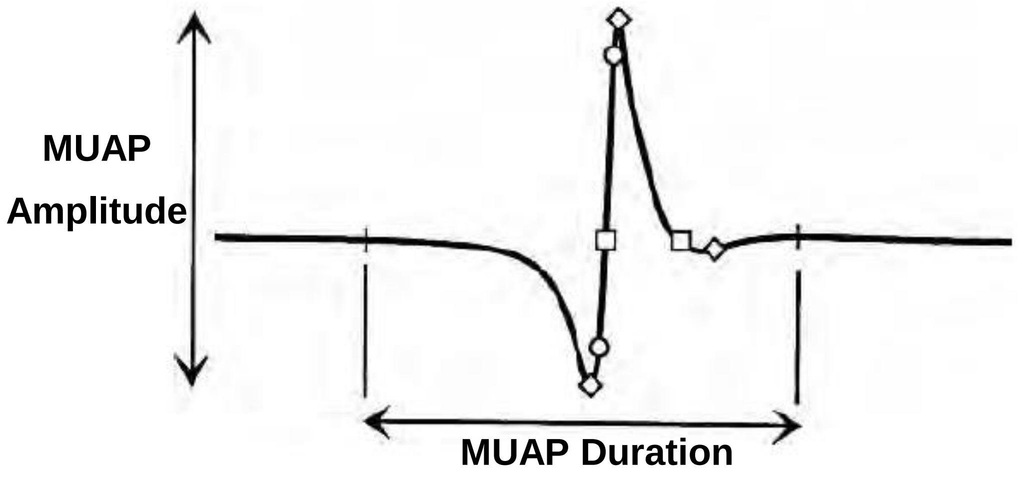


- With the increasing force of muscle contraction, MU firing rate increases, so the probability of superposition of single MUAPs increases and the EMG shows a rise of amplitude and density



EMG Features Quantification

- The wave shape of MUAPs is assessed on the basis of quantitative waveform features

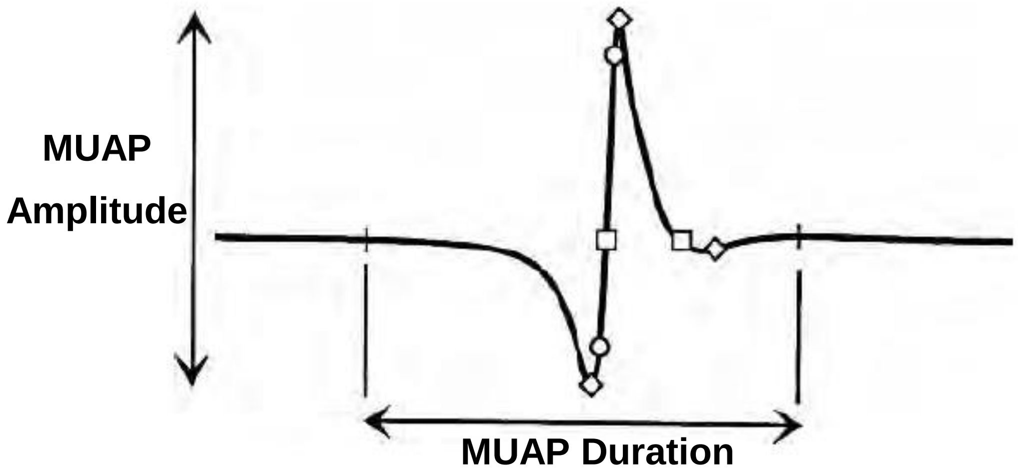


- Amplitude is determined by the presence of active fibers within the immediate vicinity of the electrode tip

- Rise time is the time interval between the 10% and 90% deflection (marked with ○)

EMG Features Quantification

- The wave shape of MUAPs is assessed on the basis of quantitative waveform features

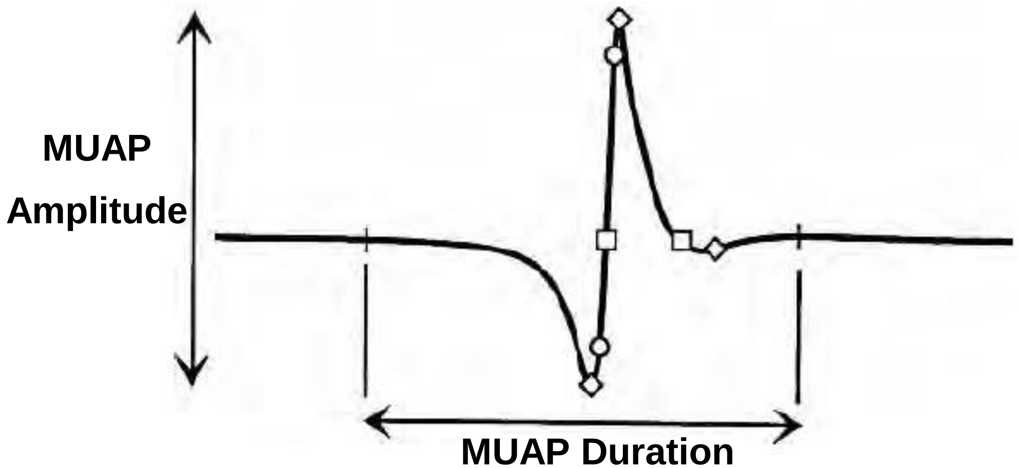


- Number of phases indicates the complexity of the MUAP and the degree of misalignment between single fiber potentials. It is measured by the number of baseline crossings +1 (in the example above = 3 as number of crossings (□) = 2)

- Duration is the time interval between the first and last occurrence of the waveform exceeding a predefined amplitude threshold, for example, 5 μV

EMG Features Quantification

- The wave shape of MUAPs is assessed on the basis of quantitative waveform features



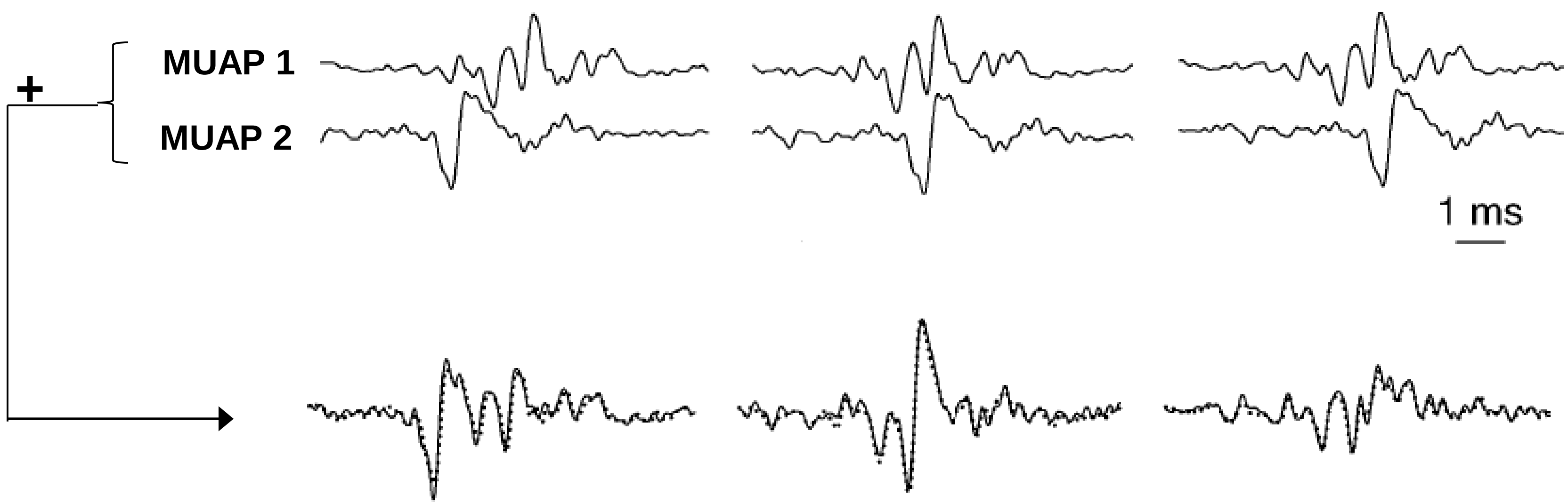
- Area indicates the number of fibers adjacent to the electrode

- Turns is a measure of the complexity of the MUAP. Since a valid turn does not require a baseline crossing like a valid phase, the number of turns is more sensitive to changes in the MUP waveshape (marked with ◊)

Needle EMG Decomposition

- Individual MUAPs sum together to produce a superimposition

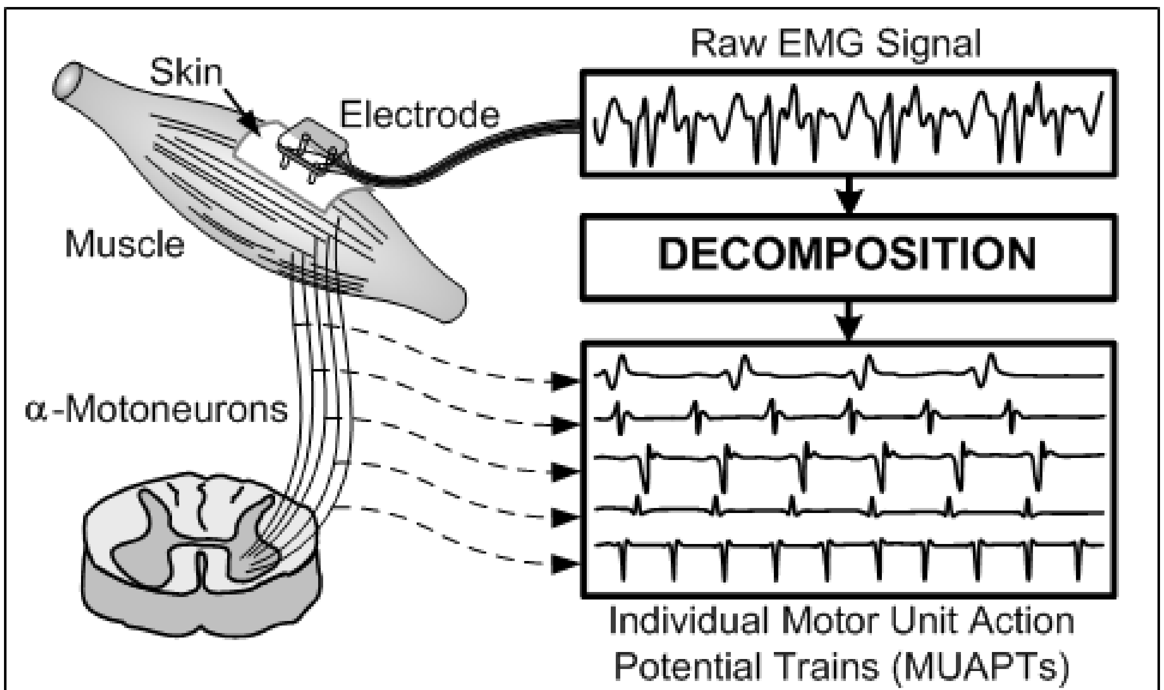
- Depending on the precise timing, superimpositions can range in complexity from partial ones in which the individual constituents are still largely recognizable, to full ones in which the constituents are unrecognizable



Needle EMG Decomposition

- Automatic decomposition of an EMG signal refers to obtaining the MUAP trains that form a single EMG recording

- Decomposition is important not only for medical diagnosis, but also for basic studies of the neuromuscular system



Needle EMG Decomposition

- There are multiple ways to do EMG decomposition

- The first approach is to use template matching in which a template is created for each MUAP

- Algorithm:

  Step 1: Locate the next MUAP in the EMG signal

  Step 2: Determine which one (if any) of the previously detected MU's has produced this MUAP. Alternatively, the MUAP may be skipped or designated as belonging to a new MU

  Step 3: Use this MUAP and its time of occurrence to update the template and the firing statistics of the MU whose firing has been detected. If this MUAP is produced by a new MU, the MUAP is used as the initial estimate of the MU template

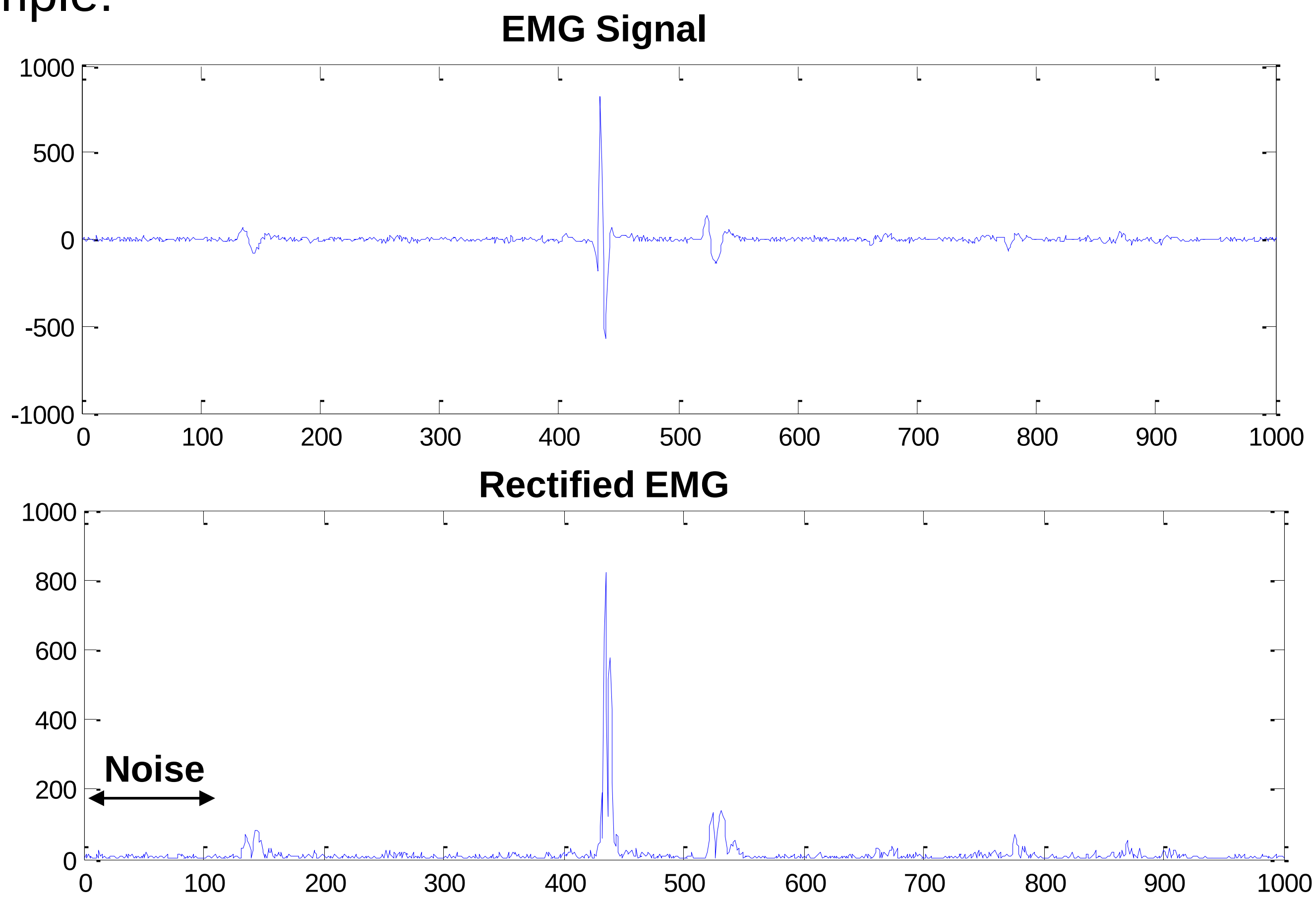
  Return to Step 1

Needle EMG Decomposition: Technical Details

- In step 1, a threshold has to be defined first to detect MUAPs
- The EMG signal is first rectified (compute the absolute value of the signal)
- The threshold can be set at 3 times the standard deviation of the noise
- The noise can be taken as any part of the signal that does not include MUAPs
- The beginning of an MUAP is detected if the average of the rectified EMG in a window of length T samples exceeds the threshold (Moving Average)

Needle EMG Decomposition: Technical Details

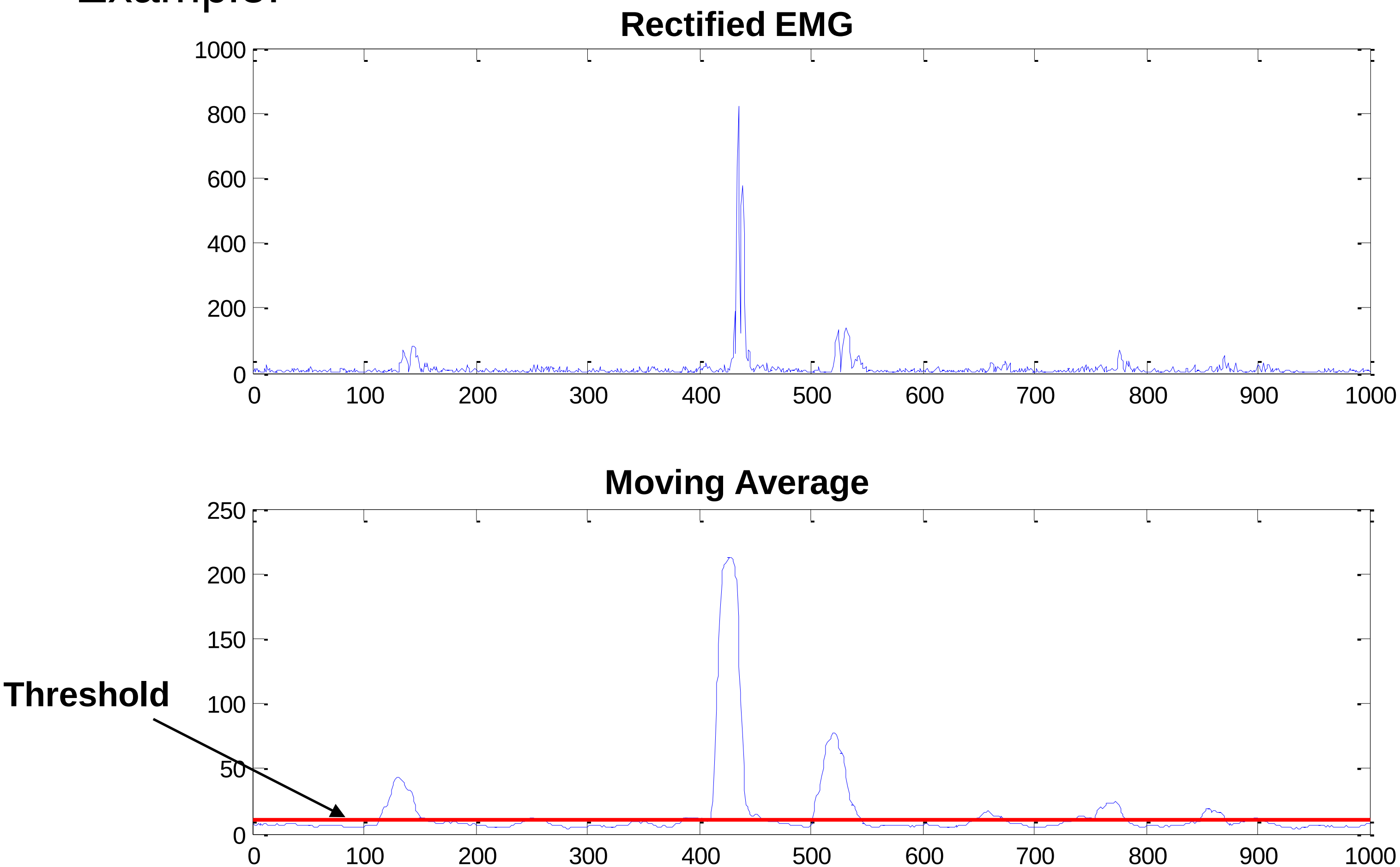
- Example:



3 * std(Noise) = 11.7

Needle EMG Decomposition: Technical Details

- Example:



A problem arises because many values will be above the threshold although they belong to the same MUAP

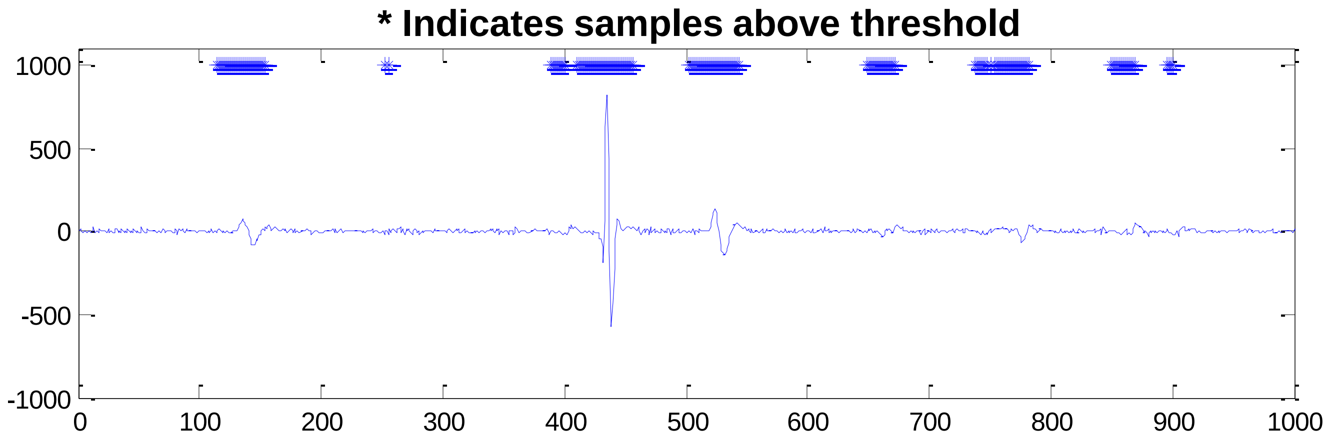
Needle EMG Decomposition: Technical Details

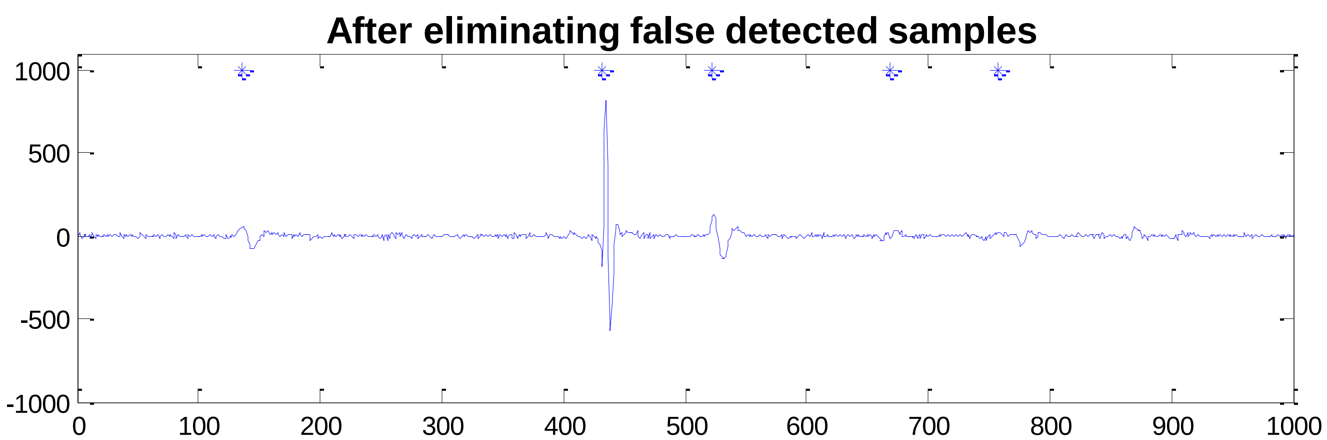
- To solve this problem:

  - Detect the first occurrence of a moving average window exceeding the threshold

  - Skip all the next T samples from the comparison with the threshold

  - If the sample occurring at $T + 1$ exceeds the threshold, do not consider it as a detected MUAP (because it is probably a continuation of the previous MUAP)





Needle EMG Decomposition: Technical Details

- In step 2, any detected MUAP should be compared to previously detected templates

- Let the detected MUAP be denoted by M and a template denoted by K, the difference between them can be computed as

$$D = \sum_{i=1}^{T} \left(M(i) - K(i) \right)^2$$

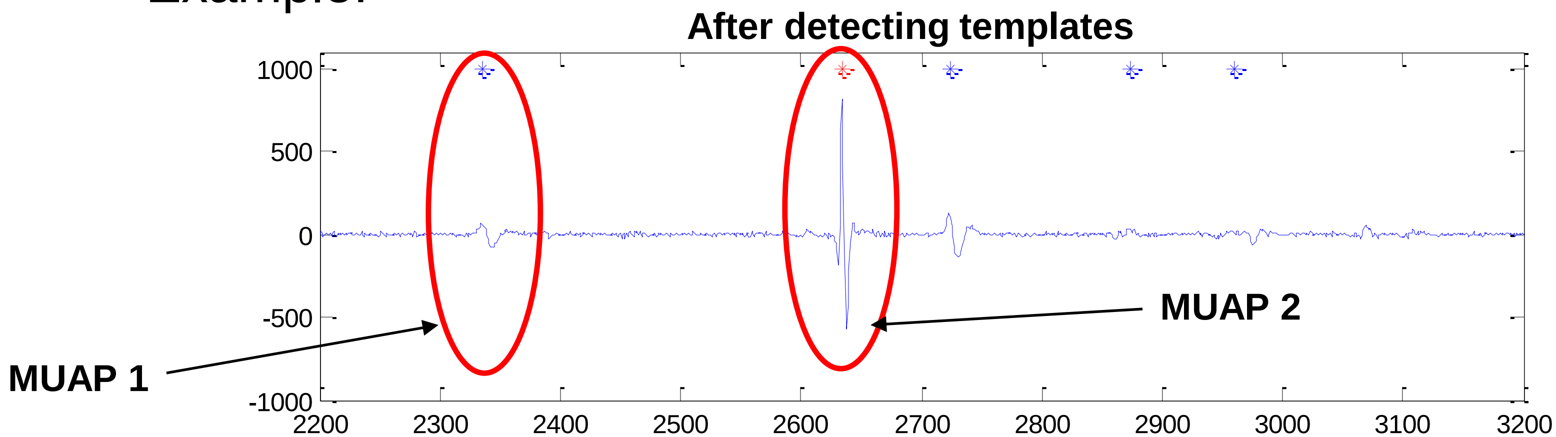
- If the difference is less than a predefined threshold ($DiffTh$), then M should be considered to belong to the template K

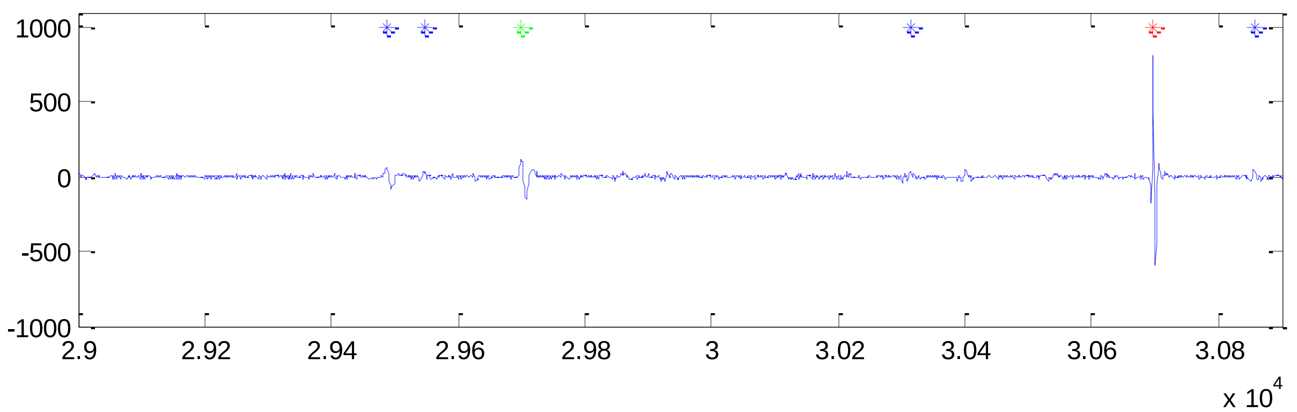
- Before computing D, the detected MUAPs should be registered (synchronized) together

- This could be done by making sure the peak of each MUAP is in the center of window (at T/2)

Needle EMG Decomposition: Technical Details

- Example:

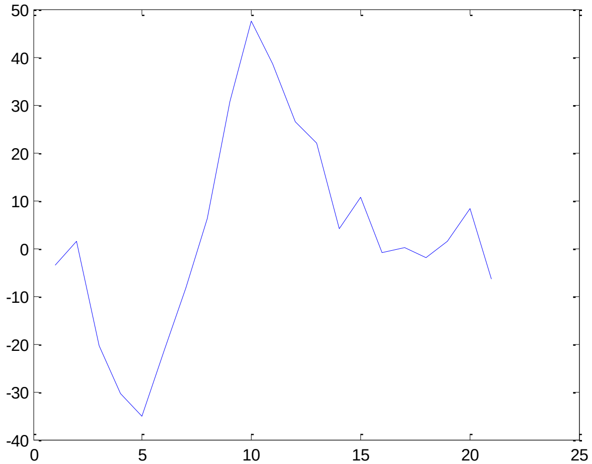




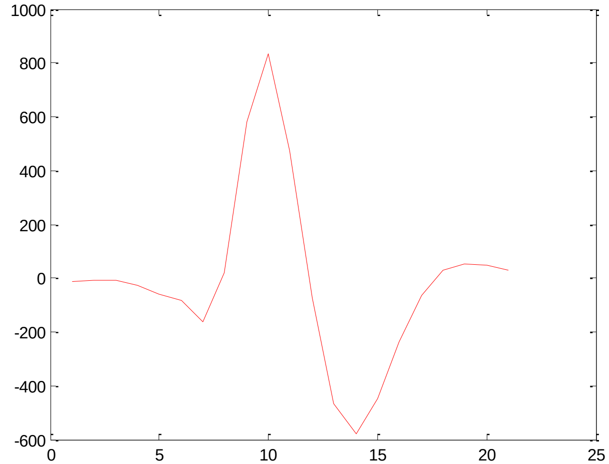
Needle EMG Decomposition: Technical Details

- For this example, three templates are detected (T = 20, $DiffTh$ = 12.65[5])

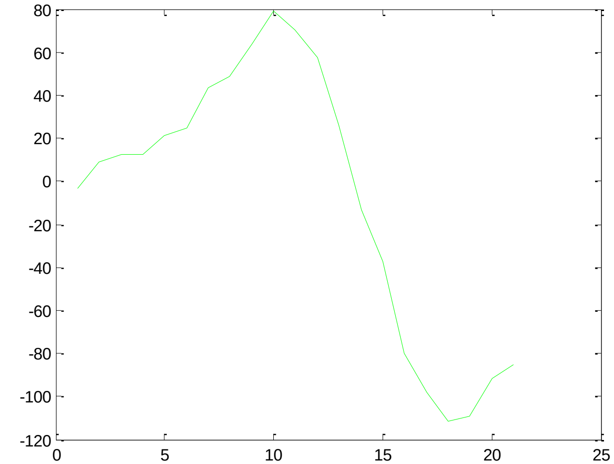
MUAP 1



MUAP 2



MUAP 3



K-means Clustering

- Another way to group together MUAPs that belong to the same MU (steps 2 and 3) is K-means clustering

- Cluster: A group of data points whose inter-point distances are small compared with distances to points outside the cluster

- Objective Function: Minimize J

$$J = \sum_{n=1}^{N} \sum_{k=1}^{K} r_{nk} \|\mathbf{x}_n - \boldsymbol{\mu}_k\|^2$$

$\mathbf{x}_n$: Input data

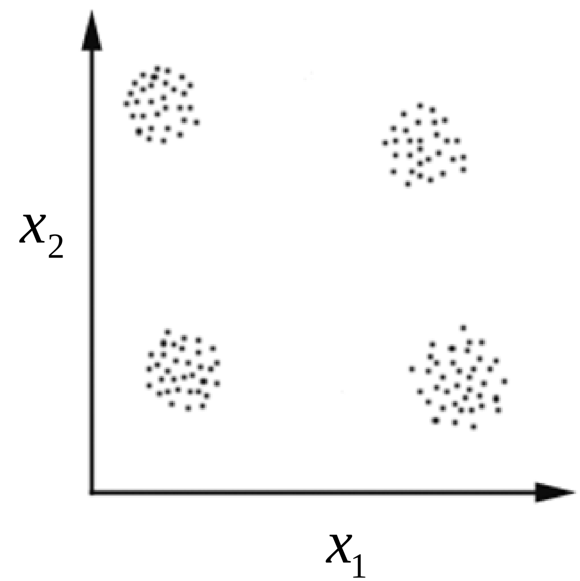
$\boldsymbol{\mu}_k$: Center of cluster k

r_{nk}: Cluster membership $= 1$ if $\mathbf{x}_n \in C_k$

$= 0$ if $\mathbf{x}_n \notin C_k$

N : Number of data points

K : Number of clusters to look for



K-means Clustering

- Algorithm steps:
  - Step 1: Randomly choose clusters center $\boldsymbol{\mu}_k$

  - Step 2: Compute r_{nk}

$$r_{nk} = \begin{cases} 1 & \text{if } k = \arg\min_j \|\mathbf{x}_n - \boldsymbol{\mu}_j\|^2 \\ 0 & \text{otherwise.} \end{cases}$$

(Assign $\mathbf{x}_n$ to the cluster with closest center)

  - Step 3: Update $\boldsymbol{\mu}_k$

    Take derivative of J w.r.t. $\boldsymbol{\mu}_k$ and equate with zero

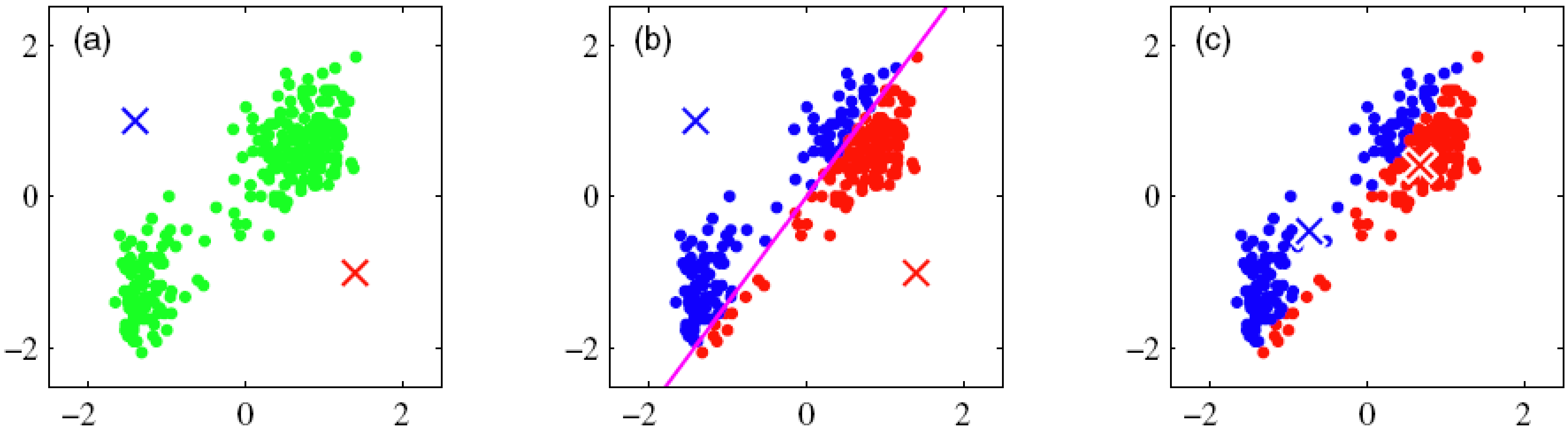
$$2\sum_{n=1}^{N} r_{nk}(\mathbf{x}_n - \boldsymbol{\mu}_k) = 0 \quad \rightarrow \quad \boldsymbol{\mu}_k = \frac{\sum_n r_{nk}\mathbf{x}_n}{\sum_n r_{nk}}$$

  - Back to Step 2 until convergence

K-means Clustering

- Example

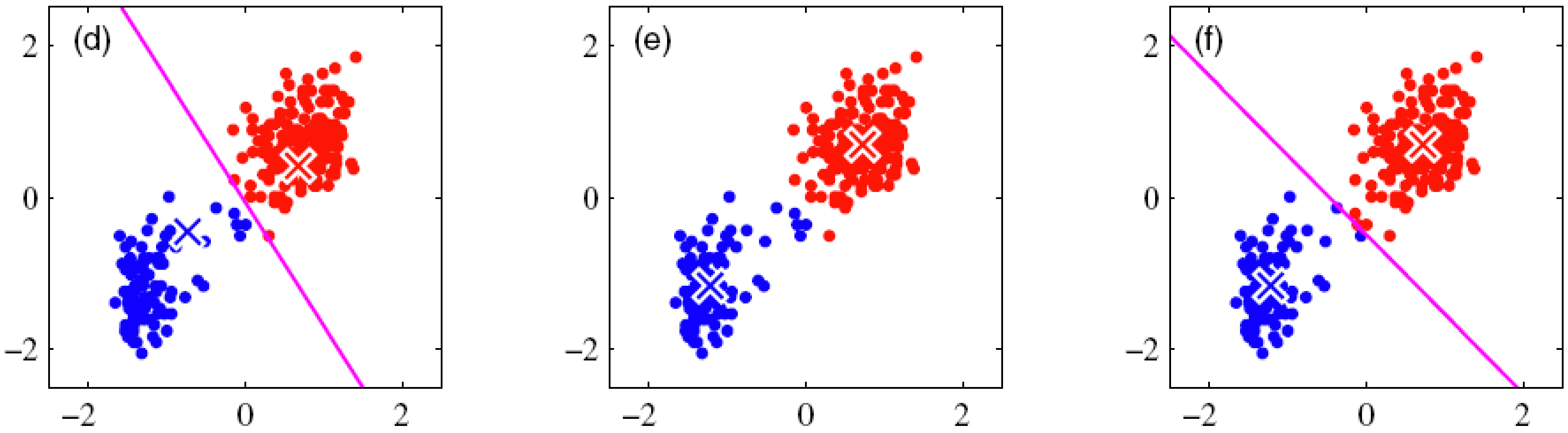
Randomly choose μ_k Compute r_{nk} Update μ_k



K-means Clustering

- Example

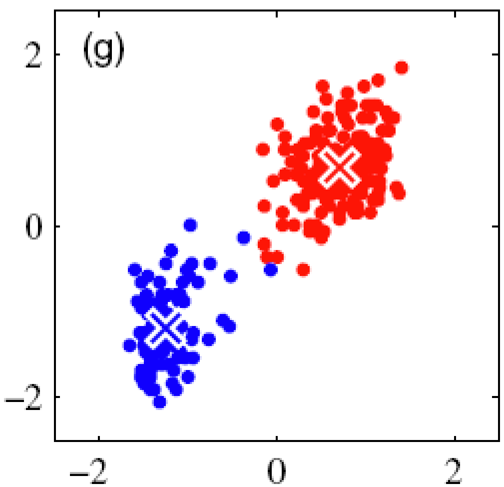
Compute r_{nk} Update $\boldsymbol{\mu}_k$ Compute r_{nk}



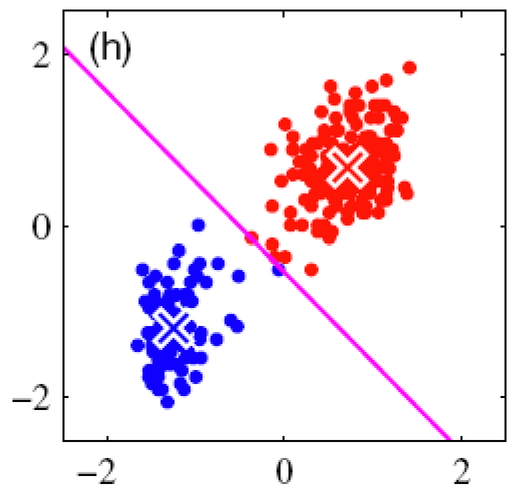
K-means Clustering

- Example

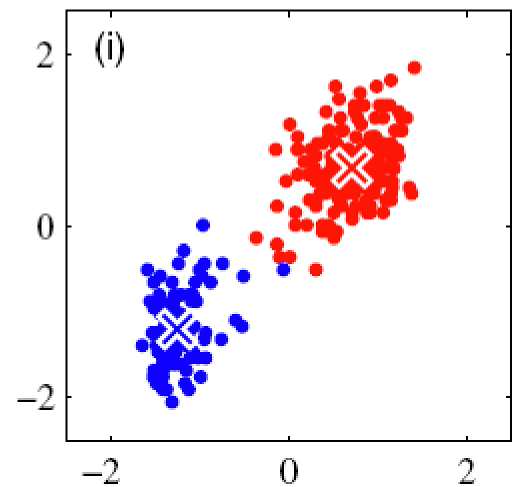
Update $\boldsymbol{\mu}_k$



Compute r_{nk}



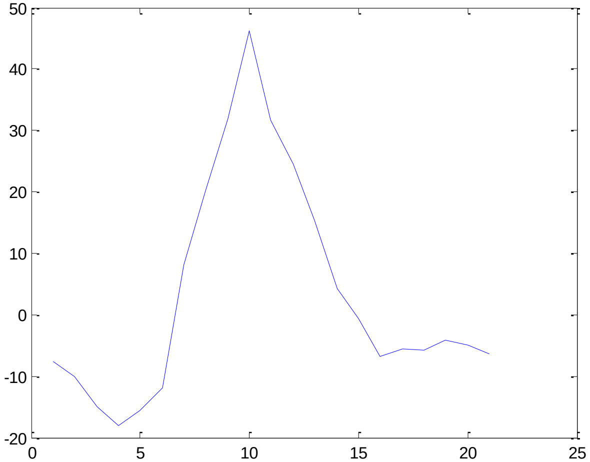
Update $\boldsymbol{\mu}_k$



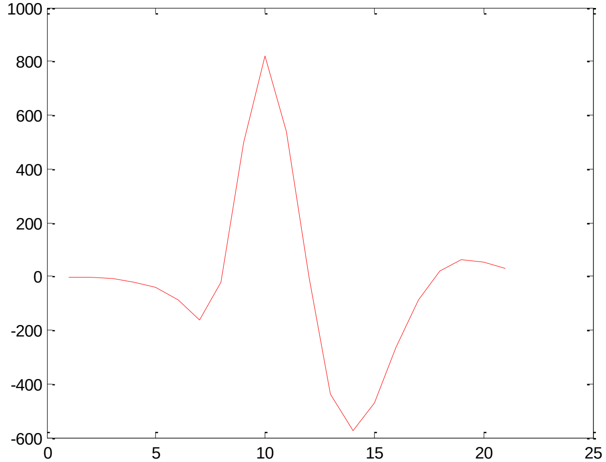
Needle EMG Decomposition: Technical Details

- Applying K-means to the same data, we get the following templates

MUAP 1



MUAP 2



MUAP 3