



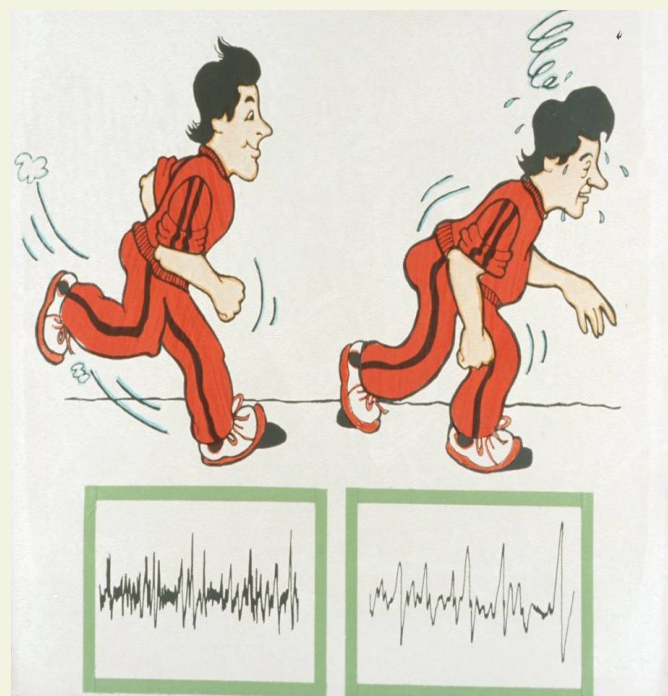
*Section 5:*  
*Peripheral Muscle Fatigue*



## *74: Fatigue*

- **Changes in the sEMG signal during sustained contractions**
  - Spectral compression
- **How to monitor and measure the change**
  - Median Frequency
- **Limitations**
  - Constant force isometric contractions
- **Recommendations**

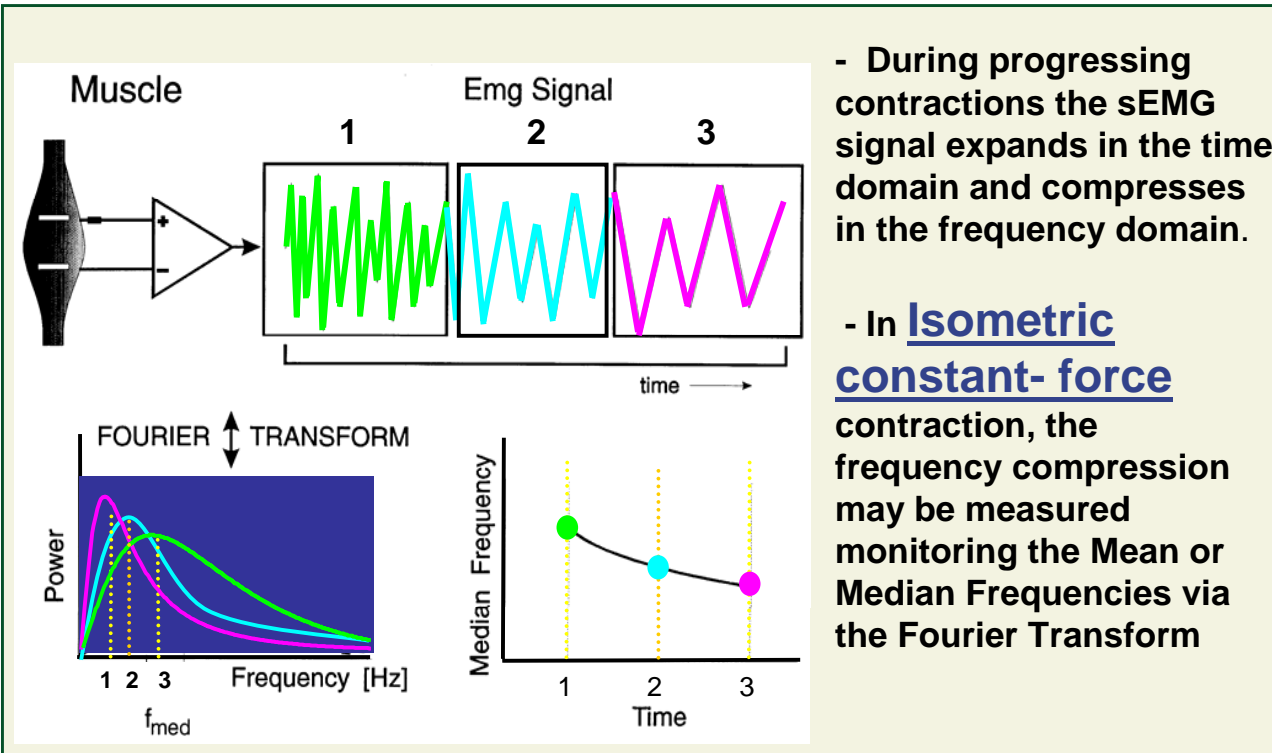
**DELSYS®** I.P. of Carlo J. De Luca *75: Fatigue and sEMG Signal Characteristics*



*Modifications of the  
sEMG signal  
characteristics  
accompany the  
progressing physical  
activity.*



## 76: Effect of Fatigue on sEMG Signal



- During progressing contractions the sEMG signal expands in the time domain and compresses in the frequency domain.

- In Isometric constant-force contraction, the frequency compression may be measured monitoring the Mean or Median Frequencies via the Fourier Transform

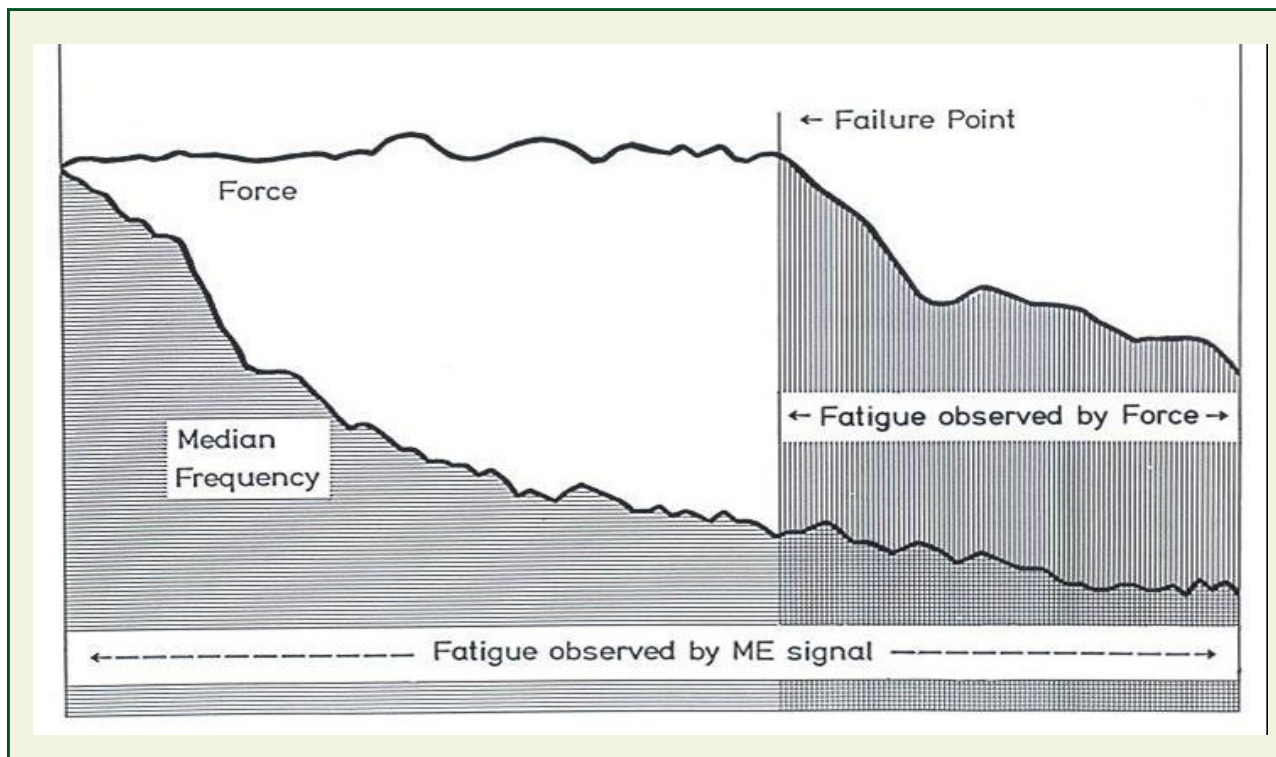
Effect of fatigue on sEMG signal:

This is a schematic representation of the effect of fatigue on the sEMG signal during progressing physical activity. The signal expands in the time domain and compresses in the frequency domain.

The compression of the frequency spectrum can be monitored by using the Fourier Transform if the sEMG signal is stationary, i.e., it is time invariant. In practice quasi-stationary is sufficient for useful calculations. As a practical rule of thumb, the signal is quasi-stationary if the amplitude varies less than 2% over 2 s. If this condition is not satisfied, than a more mathematically complex technique, time-frequency analysis, must be used.



## 77: Why use the sEMG Fatigue Index?



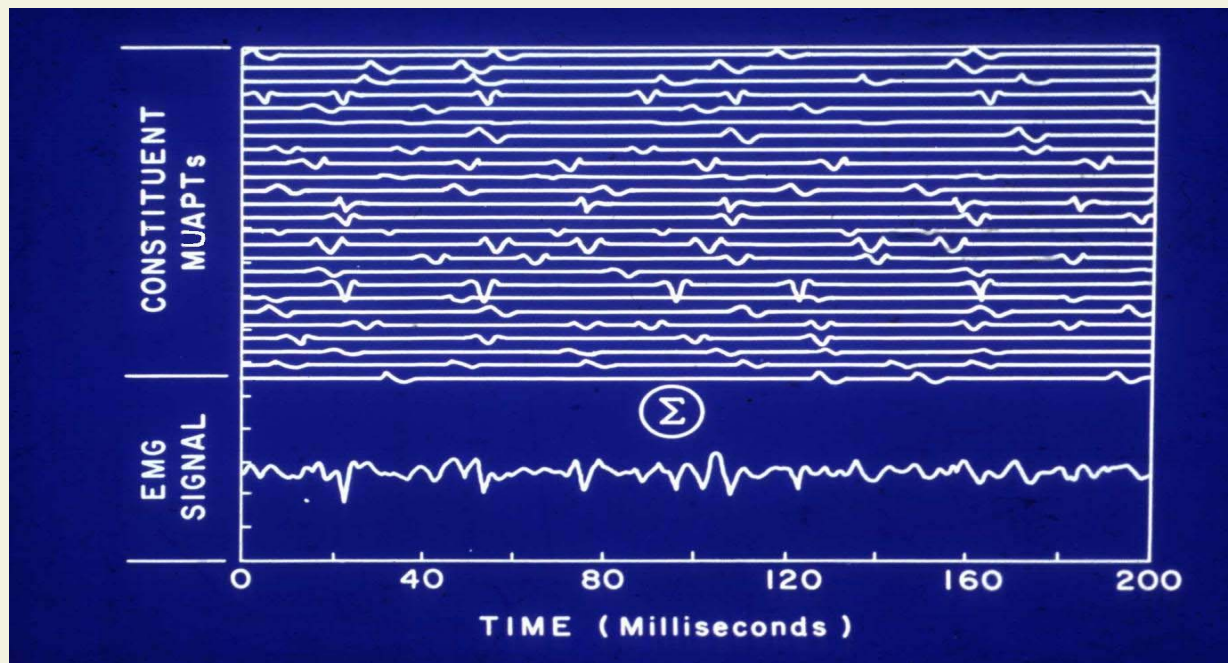
Why use the sEMG fatigue index?:

The slide shows a cartoon of voluntary constant-force contraction that is sustained up to a failure point, where the desired force level cannot be maintained and it decreases. By normal physiological convention this would be considered the point of fatigue. This convention is inconsistent with that used in physics and engineering. In those disciplines fatigue is a time dependent process that leads to a failure point. For example consider the crystalline structure of the steel alloy used in I-beams of a bridge. As time passes the crystalline structure is altered losing binding strength. At some point, the I-beam fails and fractures.

The time course of the median frequency of the sEMG signal presents a behavior that is consistent with the notion of fatigue used in physical sciences and engineering.



**78: What Causes Spectral Compression?:  
Consider the Synthesized EMG Signal**



Basmajian JV and De Luca CJ. *Muscles Alive (5<sup>th</sup> edition)*, Williams and Wilkins, Baltimore, MD, 1985.

What causes spectral compression? Consider the synthesized EMG signal:

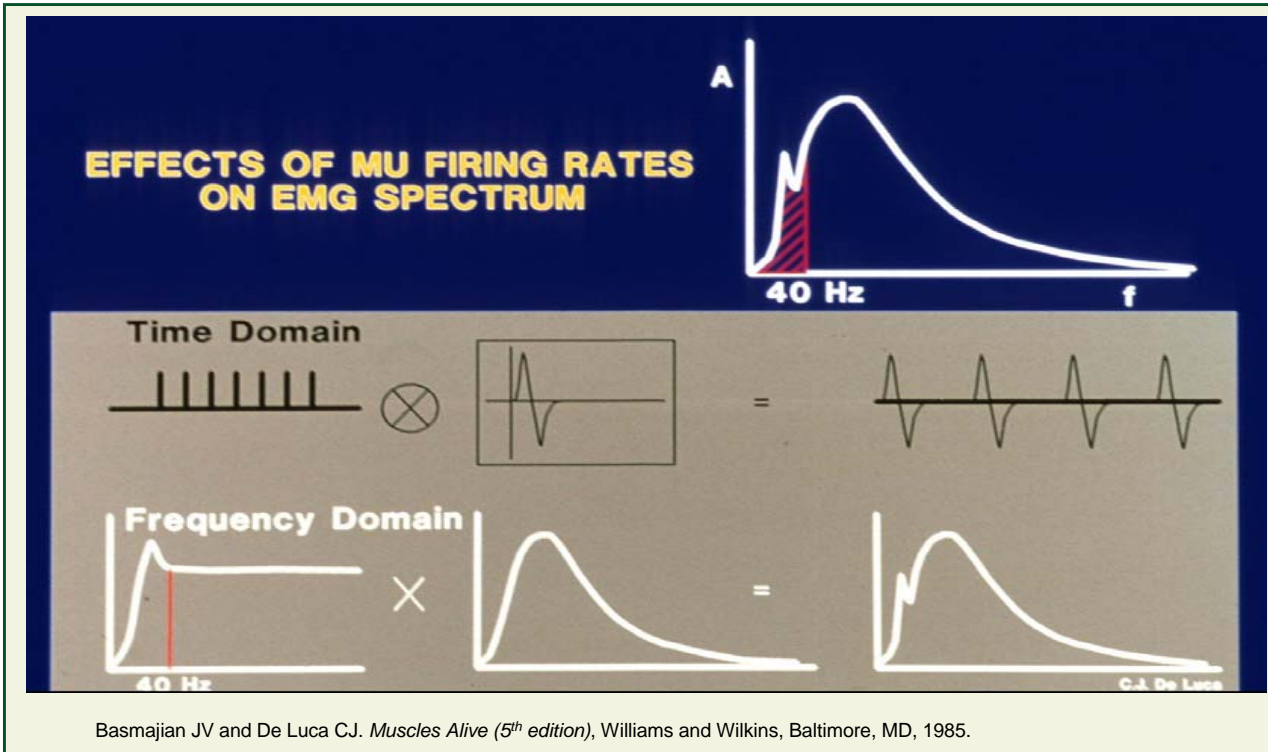
It is useful to review the construct of the sEMG signal before progressing to the next slides which discuss the spectral characteristics of the signal during sustained contractions (fatigue).

Note that the sEMG signal can be effectively modeled as a linear superposition of the individual Motor Unit Action Potential Trains which are generated by the repetitive firings of motor units.

In the following slides we will show that the modifications which occur to the sEMG signal during fatigue are related to physiological and biochemical factors that transpire within the muscle.



### 79: Contribution of Motor Unit Firing Rates on EMG Frequency Spectrum



Contribution of motor unit firing rates on EMG frequency spectrum:

The shape of the frequency spectrum of the Motor Unit Action Potential Train is determined almost entirely by the shape of the motor unit action potential. The firing rate has minor influence in the frequency range below 40 Hz (shown in red in the top plot). Even in this range the influence is not systematic, as the location of the frequency corresponding to the average value of the firing rate wobbles because the firing intervals of the motor unit is a Quasi-random process.

Thus, the compression of the sEMG frequency spectrum during fatigue is related to the modifications that occur to the motor unit action potential shape.

The Motor unit Action Potential Train shown as a time series of biphasic pulses can be represented mathematically by a convolution of the train of impulses (Dirac Delta functions) and a pulse representing the Action Potential. Below these time domain representations are the corresponding Fourier Transforms. Note that the transform of the impulse train is flat except for the range below 30 to 40 Hz.

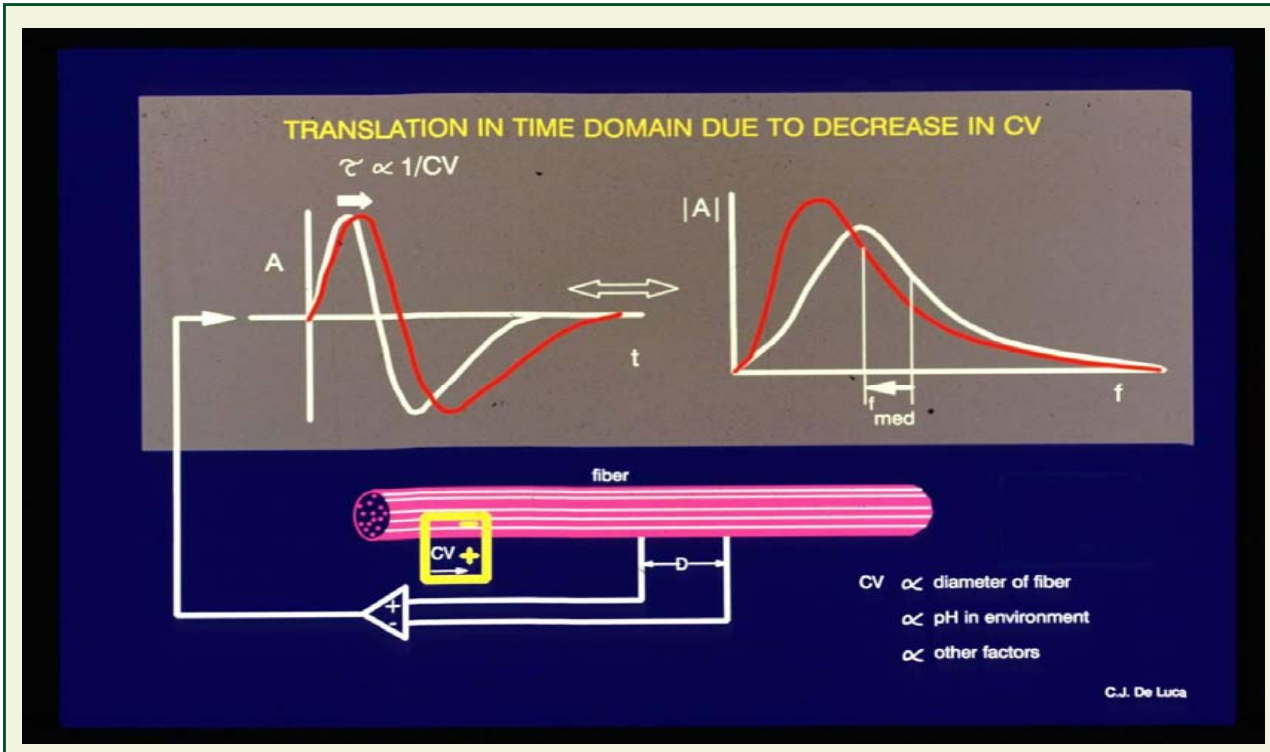


*80: What Causes the Changes in the Shape of the MUAP?*

- **Conduction velocity of action potential**
- **Distance between the origin of the action potential (muscle fiber) and the sensor**



## 81: Dominant Factor: Influence of Conduction Velocity



Dominant factor: influence of conduction velocity:

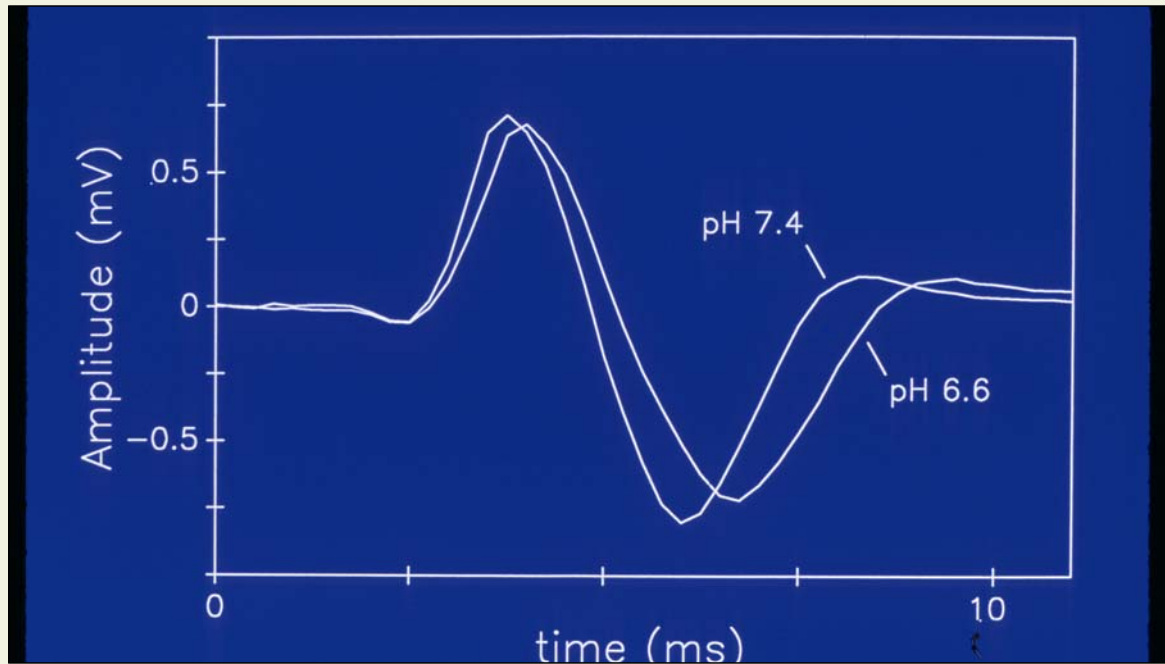
The shape of the action potential can be modified by changing the conduction velocity (CV) along the muscle fibers as shown in the diagram. Consider a single differential sensor with inter-electrode spacing "D". As the depolarization moves near and past the sensor, the detected action potential has a time duration that is a function of the inter-electrode spacing "D", the CV, the voltage decrement function of the depolarization zone (shown as a yellow square) as it radiates through space, and the charge distribution along the depolarization zone.

When the depolarization zone is approximately in the middle of the distance between the electrodes the action potential amplitude has a value of zero.

Note that as the CV decreases, the time duration of the action potential increases (red curve) and the frequency spectrum presents an amplitude increase in the lower frequencies and an amplitude decrease in the higher frequencies.



**82: Effect of pH on the Action Potential**



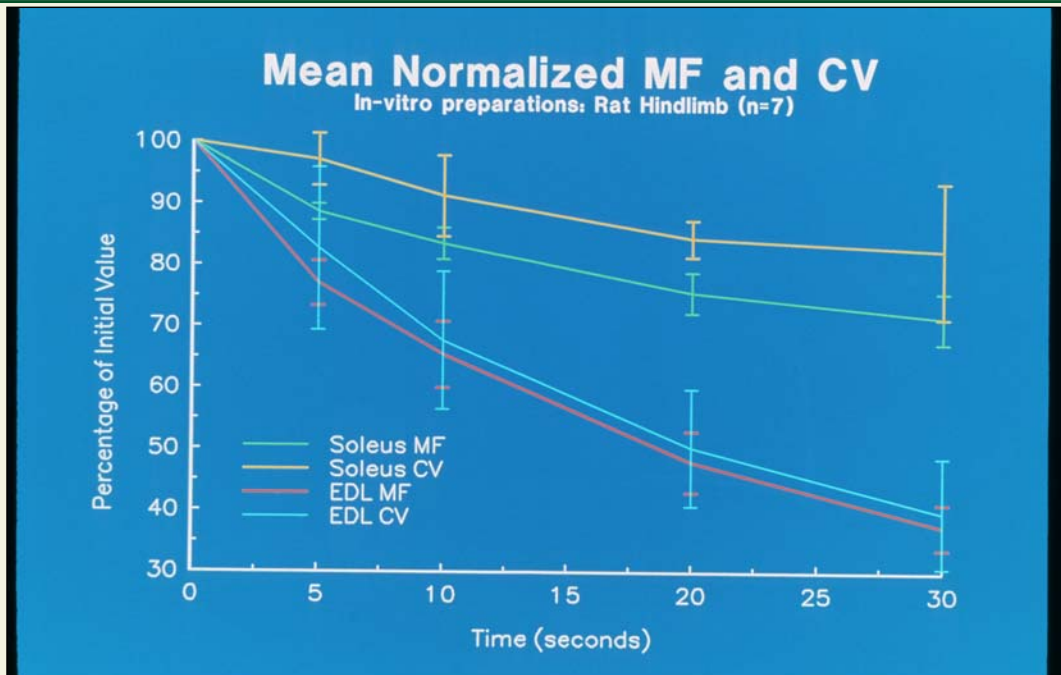
[Brody LR, Pollock MT, Roy SH, De Luca CJ, and Celli B. pH induced effects on median frequency and conduction velocity of the myoelectric signal. Journal of Applied Physiology, 71: 1878-1885, 1991.](#)

Effect of pH on the action potential:

A dominant factor in reducing the speed of the conduction velocity is the pH of the extracellular fluid. This figure shows the measured action potential in a nerve-muscle preparation placed in a bath where the pH of the bath could be artificially altered. Note that as the pH is decreased (as would be the case during a sustained contraction due to the accumulation of Lactic acid, a byproduct of the contractile biochemistry), the time duration of the action potential increases.



**83: pH Induced Effect:  
On Median Frequency and Conduction Velocity**



Brody LR, Pollock MT, Roy SH, De Luca CJ, and Celli B. pH induced effects on median frequency and conduction velocity of the myoelectric signal. *Journal of Applied Physiology*, 71: 1878-1885, 1991.

pH induced effect on median frequency and conduction velocity:

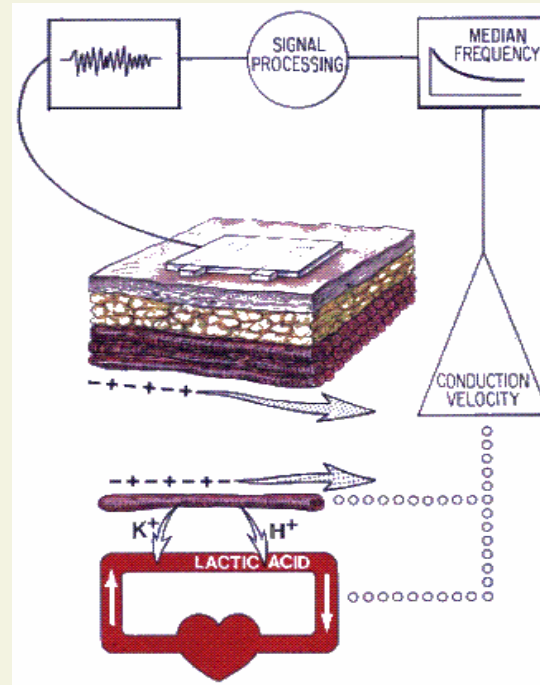
This figure shows that both the conduction velocity and median frequency of the sEMG signal decrease in concert during an electrically-stimulated sustained contraction in two muscles in the rat. The two muscles were the Soleus, which consists of dominantly red, slow twitch fibers, and the Extensor Digitorum Longus (EDL), which consists of dominantly white, fast twitch, highly anaerobic fibers. In the EDL muscle the conduction velocity and median frequency track each other closely throughout the 30s contraction and the decrease is more dramatic than in the Soleus muscle. Note that lactic acid is a byproduct of anaerobic metabolism.

There is a disparity in the decline of the median frequency and the conduction velocity during the first 5s in the soleus muscle, otherwise the two variables track each other.



## 84: Fatigue: sEMG Signal and Biochemical Origin

*The time-course of the median frequency parameter reflects changes of the conduction velocity of the muscle fibers due to the accumulation of lactic acid as it occurs during a sustained muscle contraction*



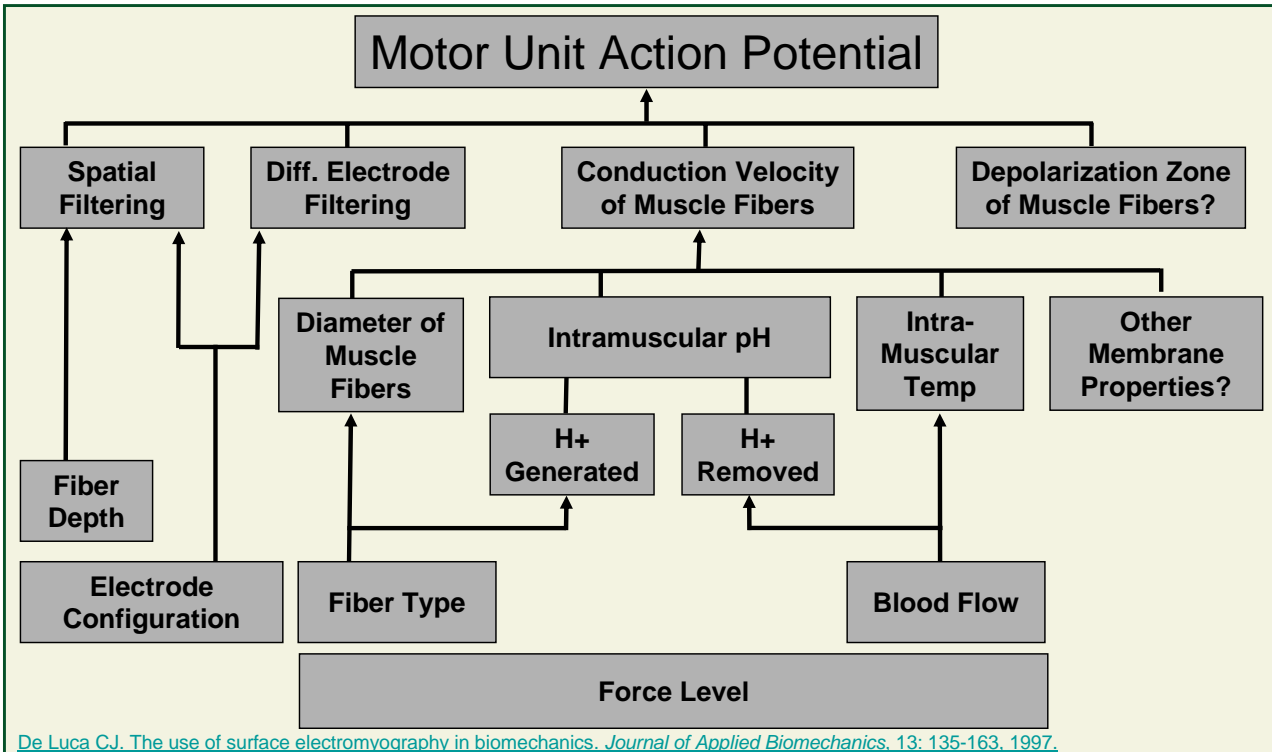
Fatigue – sEMG signal and biochemical origin:

This cartoon shows the likely process that describes the causal relationship between the accumulation of lactic acid in the interstitial fluid and the decrease in the median frequency of the sEMG signal. Note that the accumulation of lactic acid is the difference of the amount that is produced by the contraction of the muscle and the amount that is removed by the blood flow. The blood flow is also a function of the contraction level, because as it increases, the internal pressure in the muscle increases and reduces the volume of the arterioles and veins. In limb muscles, the arterioles collapse at approximately 30% MVC. At greater contraction levels, almost all the lactic acid produced is trapped in the interstitial fluid.

The increasing lactic acid decreases the pH of the extra-cellular fluid, increasing the H<sup>+</sup> concentration which increases the positive charge outside the cell. The K<sup>+</sup> inside the cell now needs to move against a stronger repelling electro-chemical gradient slowing down the propagating depolarization, therefore, the conduction velocity decreases. As previously described, the decreasing conduction velocity compresses the spectrum of the sEMG signal towards the lower frequencies.



85: Factors that affect the sEMG Signal



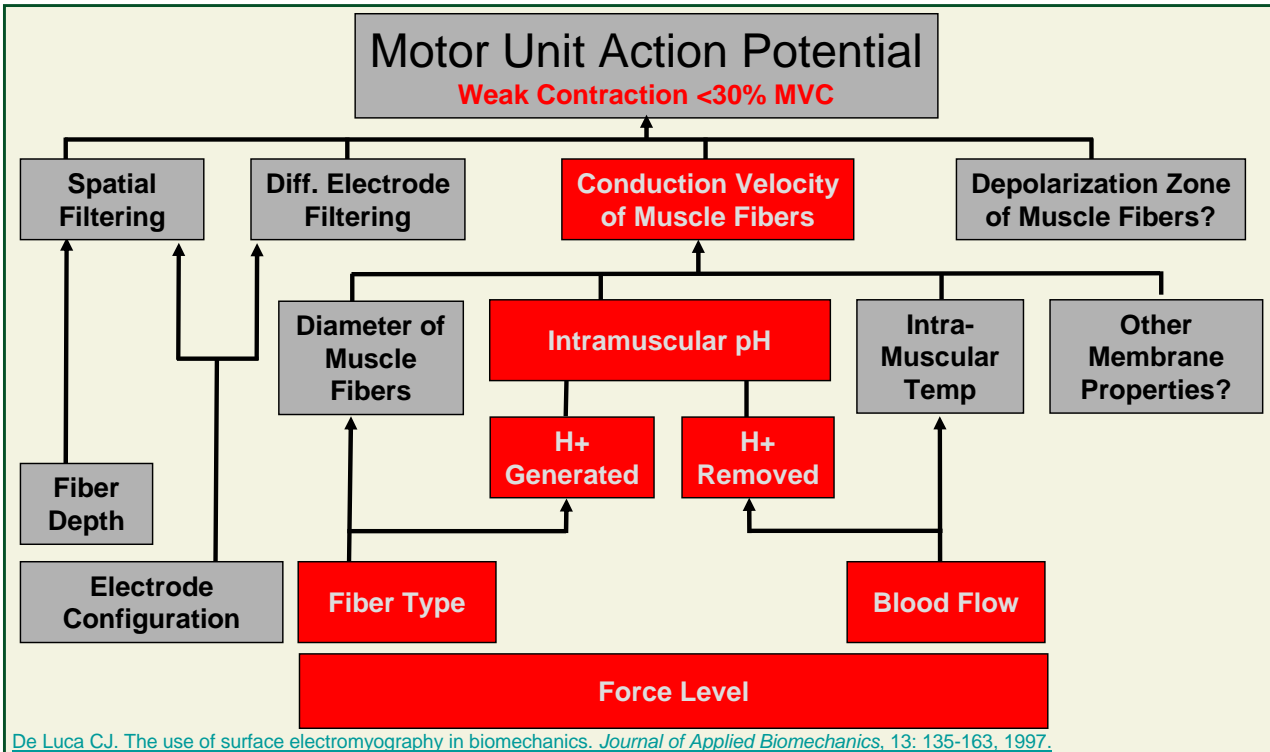
De Luca C.J. The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics*, 13: 135-163, 1997.

Factors that affect the sEMG signal:

This series of block diagram shows the relationship between force generated by the muscle at different levels and various factors that influence the shape of the action potential.



### 86: Factors that affect the sEMG Signal



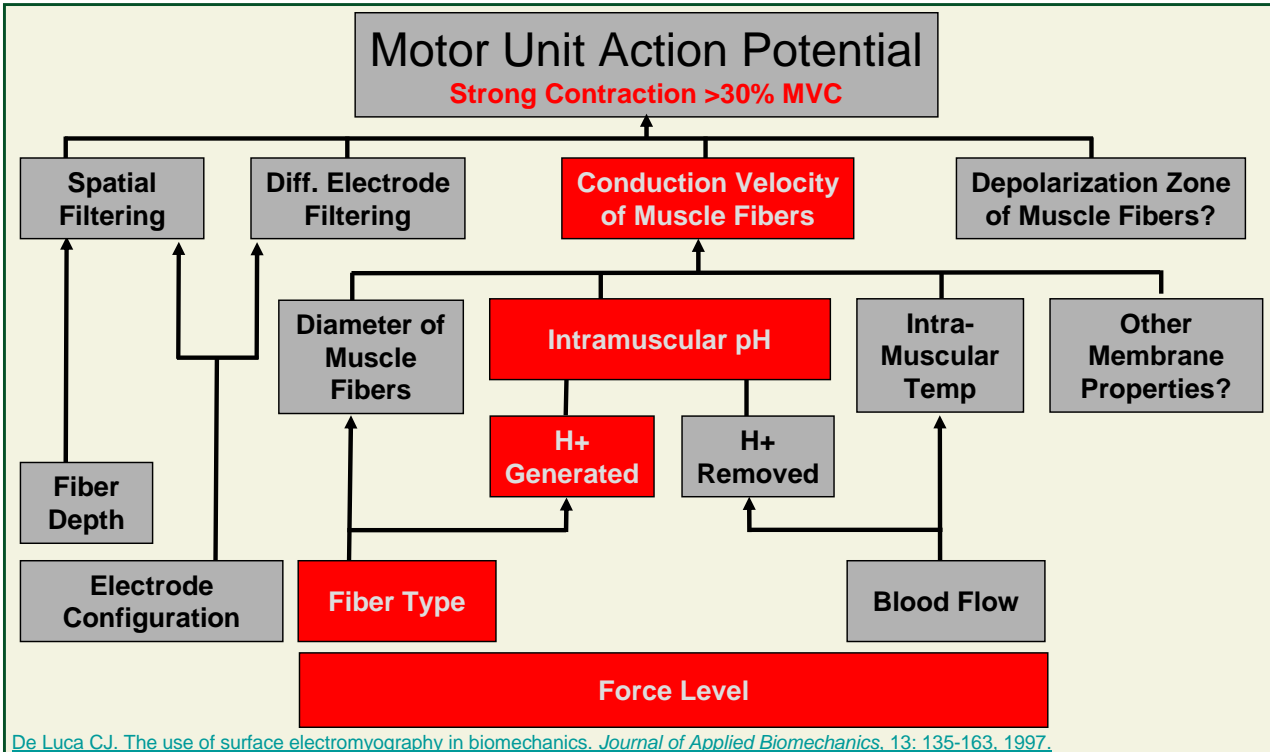
De Luca CJ. The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics*, 13: 135-163, 1997.

Factors that affect the sEMG signal:

In this slide, factors which take precedence in determining the shape of the motor unit action potential during **weak contractions** (>30% MVC) are highlighted.



### 87: Factors that affect the sEMG Signal



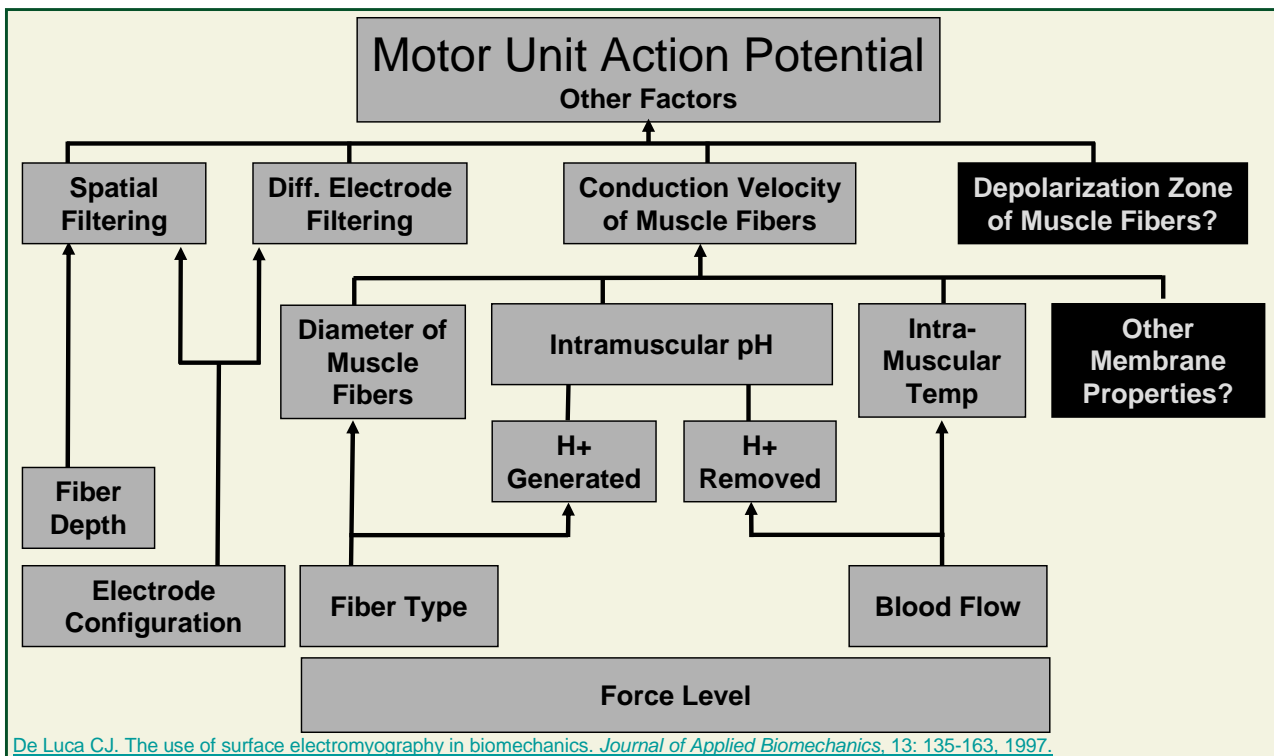
De Luca C.J. The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics*, 13: 135-163, 1997.

Factors that affect the sEMG signal:

In **strong contractions** (>30% MVC), many of the same factors influence the shape of the motor unit action potential. However, at higher contraction levels, blood vessels in the limbs collapse under pressure from the muscles, so blood flow is no longer a factor, as it is temporarily interrupted.



### 88: Factors that affect the sEMG Signal



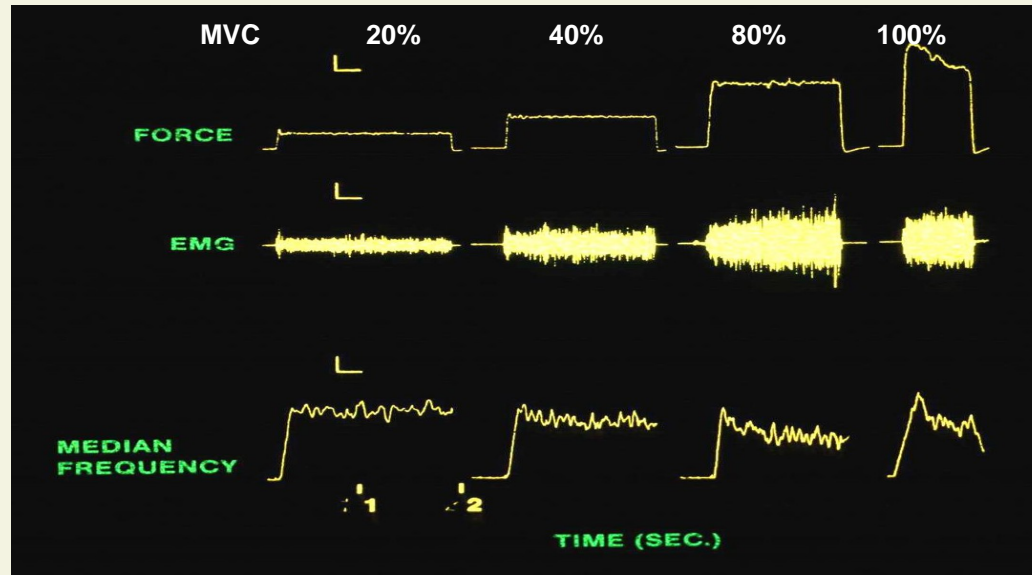
De Luca C.J. The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics*, 13: 135-163, 1997.

Factors that affect the sEMG signal:

There are still several factors influencing the shape of the motor unit action potential that are not well understood, as highlighted in black here.



## 89: Median Frequency: the Influence of Force



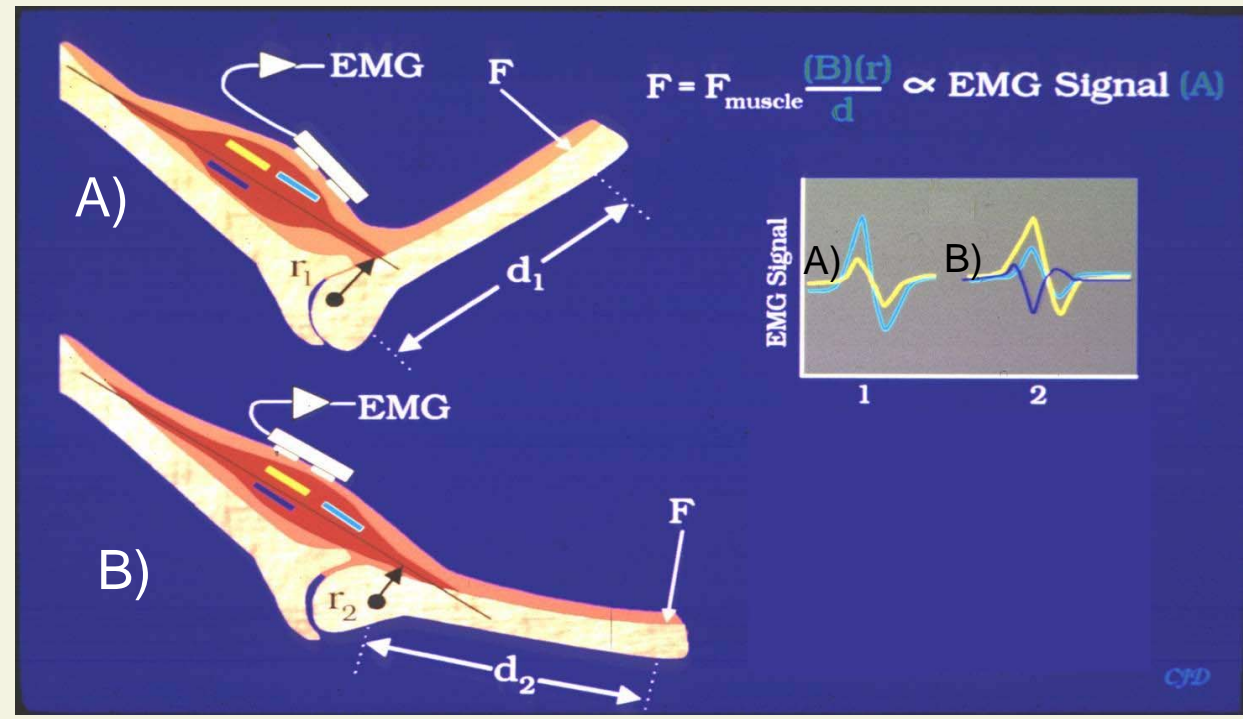
De Luca CJ, Sabbahi MA, Stulen FB, and Bilotta G. Some properties of the median frequency of the myoelectric signal during localized muscular fatigue. In Knuttgen HG, Vogel JA, and Poortmans J. (Eds) *Biochemistry of Exercise*, Human Kinetics, Inc, 13: 175-186, 1983.

Median frequency – the influence of force:

Examples of the decline of the medial frequency at different force levels during isometric constant-force contractions.



### 90: Effect of Electrode Displacement During Movement



Effect of electrode displacement during movement:

Cautionary Factor -- During a dynamic contraction the length of the muscle changes. The sensor remains affixed in a location on the skin. Thus, the distance between the electrodes and the source of the action potentials changes. There are two concerns: the shape of the action potential changes due to the different spatial filtering and some motor units may be recruited while others may be derecruited. Both these factors are shown in the right quadrant. The dark blue motor unit action potential is recruited in position (B) as it moves closer to the sensor. The shape of all the active (yellow and light blue) motor unit action potentials are modified.

The important point here is that if linear transforms such as the Fourier Transform are to be used for calculating the frequency spectrum of the sEMG signal the contraction is to remain isometric.

There are other techniques such as time-frequency analysis that can cope with some amount of movement, but that discussion is beyond the scope of this practicum.



*91: Confounding Factors for Fatigue  
Measurements*

- **Distance between action potential source and sensor**
- **Unstable number of active motor units**



## *92: Requirements for Fatigue Measurements*

- **Isometric Contractions**
  - Distance between sensor and active motor units stable
- **Constant-Force Contraction**
  - Number of Motor Units more or less stable
  - Wide-sense stationary EMG signal
  - Some leeway possible



## *93: Spectral Analysis Technique For Muscle Fatigue*

### **How it works**

- ① Lactic acid is formed as a by-product of contractile processes (pH of extracellular fluid decreases)
- ② Conduction velocity of Action Potential decreases
- ③ Time duration of Action Potential increases
- ④ Low-frequency components of EMG signal spectrum increase; high-frequency components decrease
- ⑤ Median frequency decreases

### **Advantages**

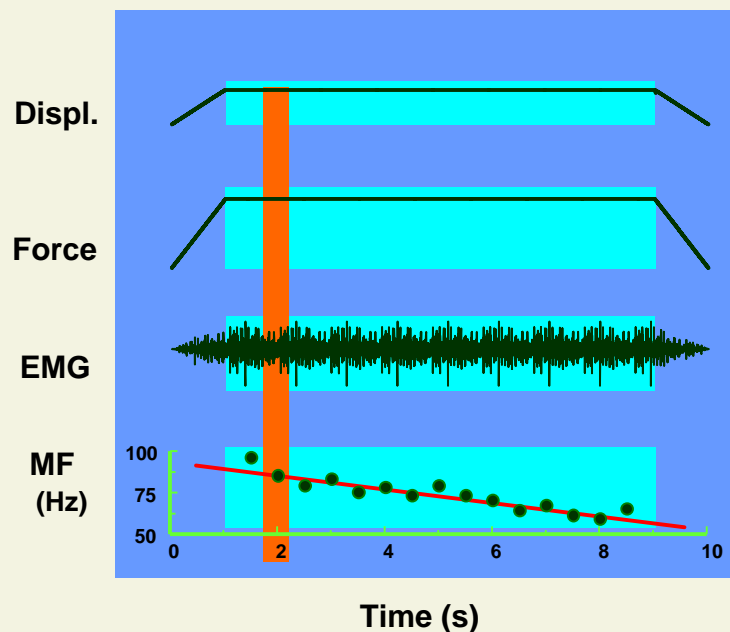
- 1) Objective
- 2) Non-obtrusive
- 3) Monitors early onset of fatigue prior to exhaustion
- 4) Interrogates individual muscles or a group of muscles

### **Disadvantages**

- 1) Requires know-how in EMG technology and interpretation
- 2) Not applicable to all types of muscle contractions
- 3) Less sensitive as fatigue increases



## 94: Static Contractions



### Requirements

- **Wide sense stationary EMG (signal characteristics change less than 2% over 2 seconds)**
  - Constant force
  - Constant position (isometric)

### Applications

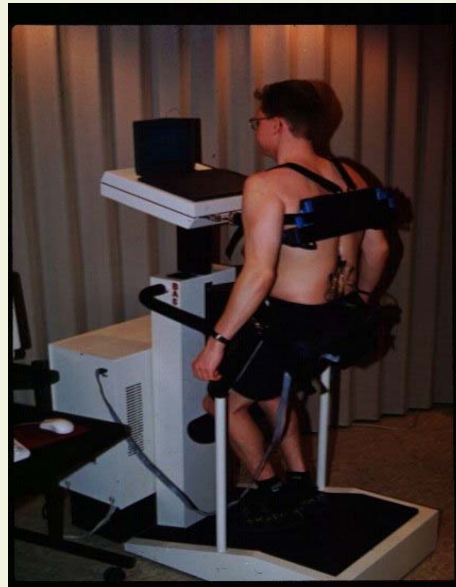
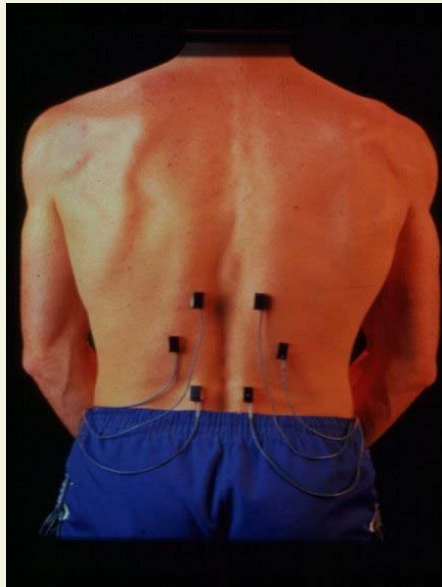
- **Tasks requiring prolong static posture:**
  - Standing tasks
  - Standing
  - Sitting
  - Lying down
  - Welding
  - Driving
  - Hand tool operation
  - Typing

Static contractions:

A cartoon of an appropriate application of the median frequency for measuring peripheral muscle fatigue. In this case the worker is holding a constant load (welding device) in an isometric position. Other examples are listed on the right of the figure.



## 95: Back Analysis System



[Roy SH, De Luca CJ, and Casavant DA. Lumbar muscle fatigue and chronic lower back pain. \*Spine\*, 14: 992-1001, 1989.](#)

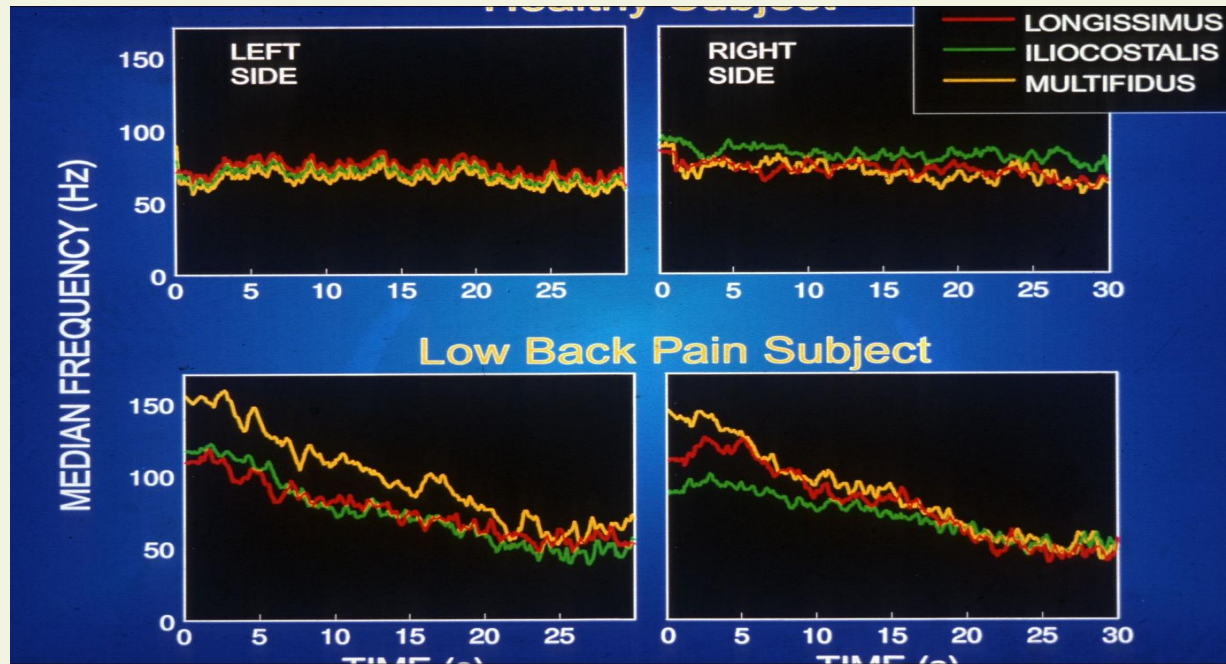
[Roy SH, De Luca CJ, and Emley M. Classification of back muscle impairment based on the surface electromyographic signal. \*Journal of Rehabilitation Research and Development\*, 34: 405-414, 1997.](#)

Back analysis system:

An arrangement for obtaining sEMG signals from several muscles in the lower back while constrained in a device that measures isometric contraction of the back.



## 96: Back Analysis



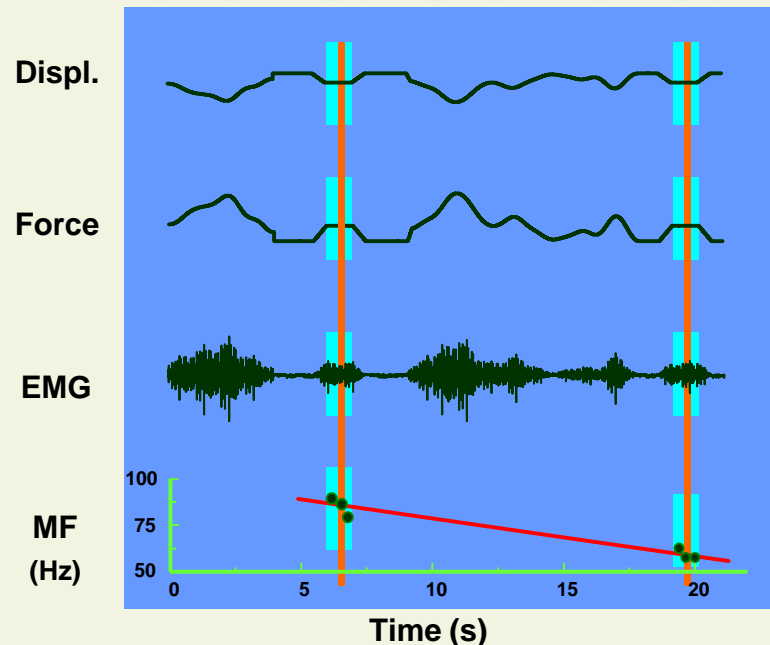
Roy SH, De Luca CJ, and Casavant DA. Lumbar muscle fatigue and chronic lower back pain. *Spine*, 14: 992-1001, 1989.

Back analysis:

Results for data obtained from the testing arrangement of the previous figure. The top two panels present the median frequency from the six sensor locations in a healthy individual. Note that the median frequencies remain reasonably constant during a 30 s contraction at 80% MVC. Whereas the same test performed on a patient with diagnosed Low Back Pain revealed median frequencies that decreased dramatically over the same time period.



## 97: Dynamic Contractions: with Static Sampling



### Requirements

- Interruptible task
- Sample period must exhibit wide sense stationary EMG
  - Constant force contraction
  - Fixed position contraction

### Applications

- All tasks which can be interrupted for a sampling period of 5 seconds

Dynamic contractions with static sampling:

It has been discussed that the Fourier Transform technique for obtaining the median frequency does not work in dynamic contractions. This cartoon presents an approach that can be used in some repetitive dynamic contractions where the activity can be paused at the same interval during the cycling task as shown at the top of the slide.



***Thank You!***