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A Practicum on the Use of sEMG Signals in Movement Sciences

Carlo J. De Luca

Curriculum Vitae available at
http://nmrc.bu.edu/fac_staff/director/cv.html

Acknowledgement – Throughout the many years over which this material has been generated, I have had the good fortune of having close collaborations with many wonderful research colleagues and students. They are too many to mention here and some are listed in the cited publications which appear on the slides. Among them, two deserve special mention: Professor Serge H Roy and Mr. L Donald Gilmore. They have made a significant part of this work possible.

A Word on Navigation pane keystrokes scroll through slide index:

Press F6 on the key board to focus on the navigation pane of Adobe. Within each of the tabbed palettes, lists of objects are organized into a tree structure.

Adobe Acrobat 5.0 follows the standard Windows keyboard behaviors for tree views. When the focus is on the navigation pane, the following keystrokes will help you move around:

Ctrl + Tab to access Bookmarks, Thumbnails, Comments, and Signature palettes.

Click on bookmarks to scroll through the page # and title of each slide or sections.

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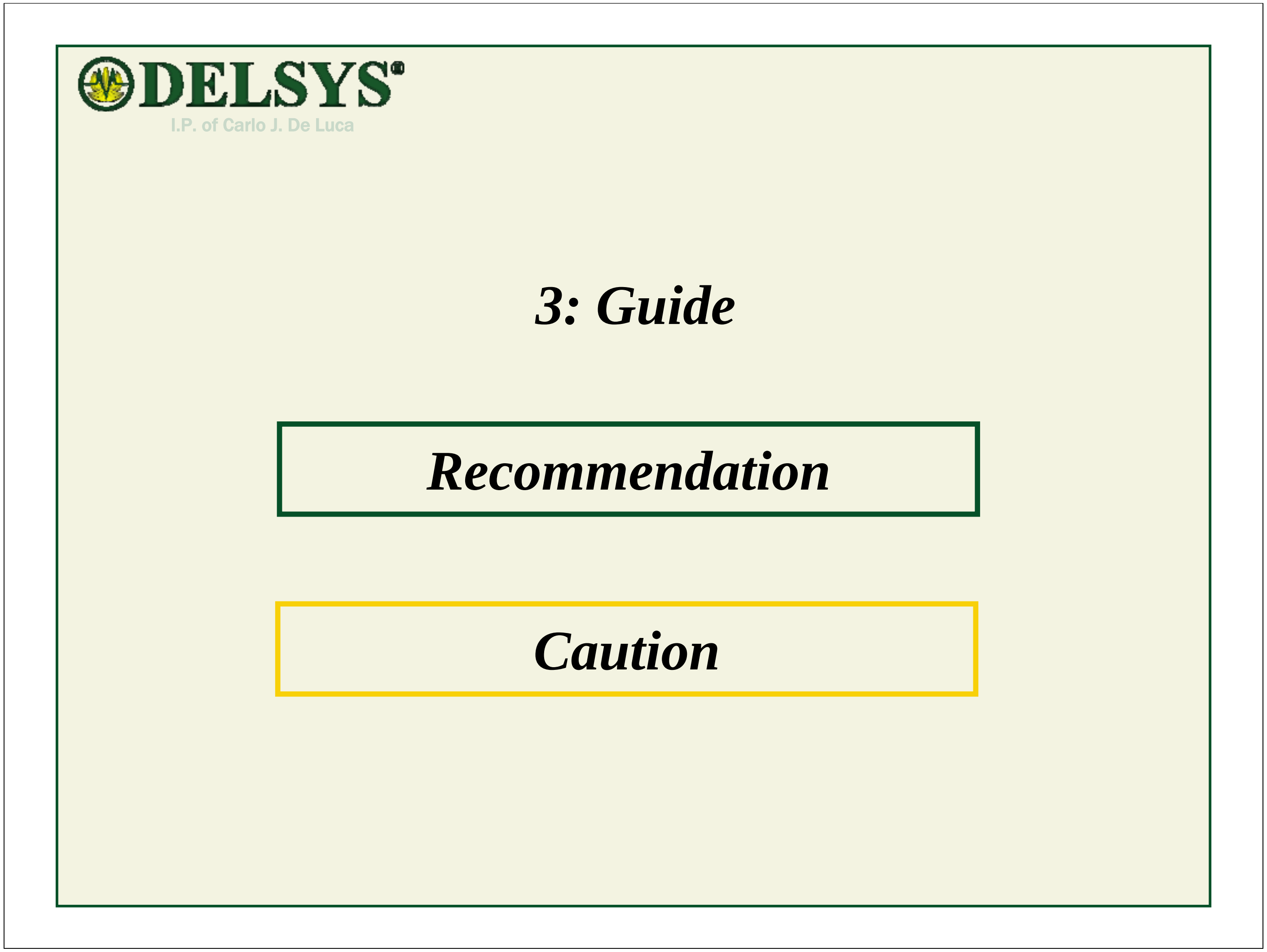
2: "*Electromyography is too easy to use and consequently too easy to abuse*"

De Luca CJ, The Use of Surface Electromyography in Biomechanics, J. Applied Biomechanics, 13: 135-163, 1997

 ISBN: 978-0-9798644-0-7



Guide to slide titles:

Slides with a heading or title without a border are informational, green ones contain recommendations; whereas those with the color yellow describe conditions and issues that should be handled with caution.

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Section 1: Basic Concepts Relevant to Understanding the Surface EMG Signal

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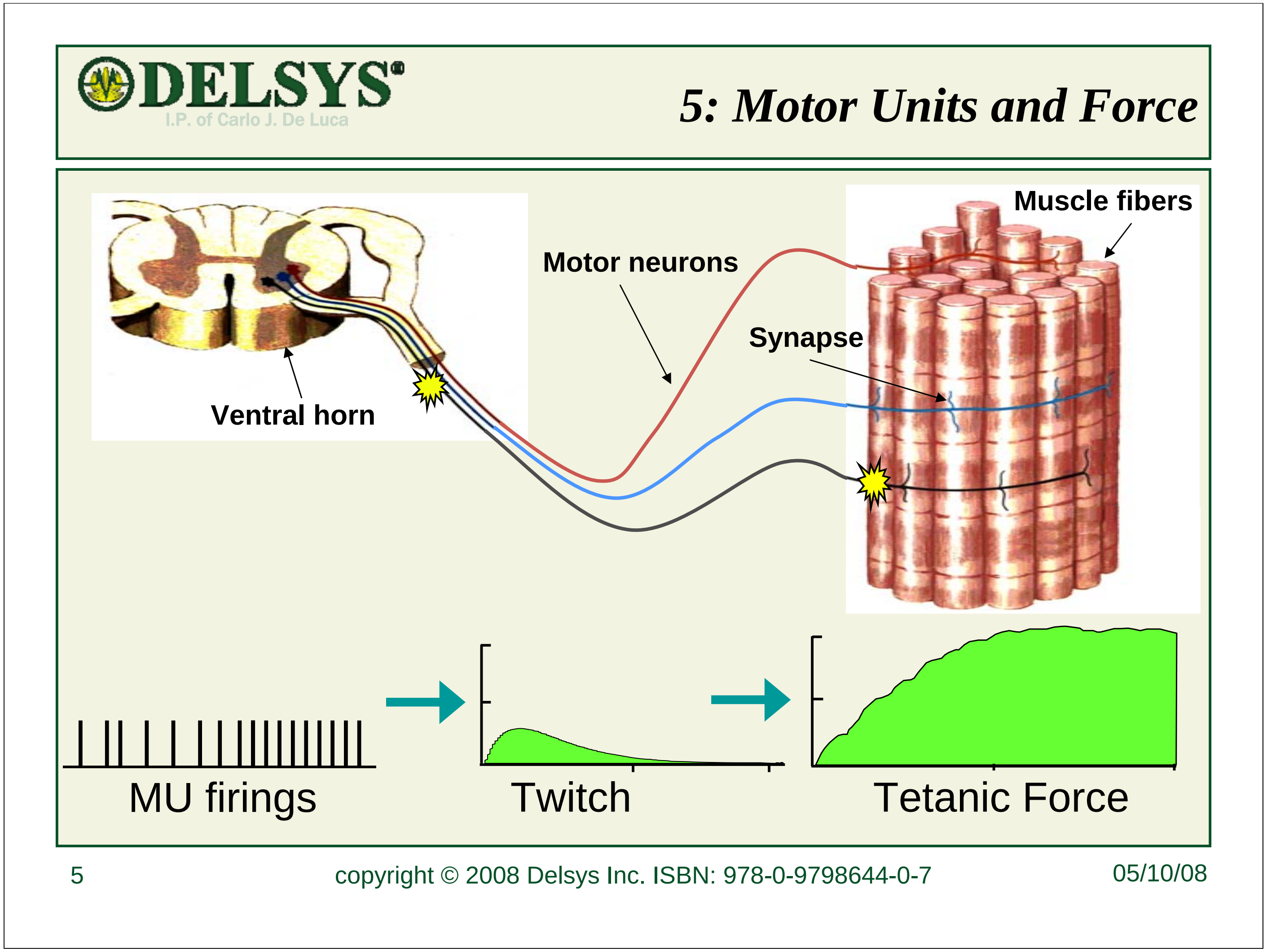


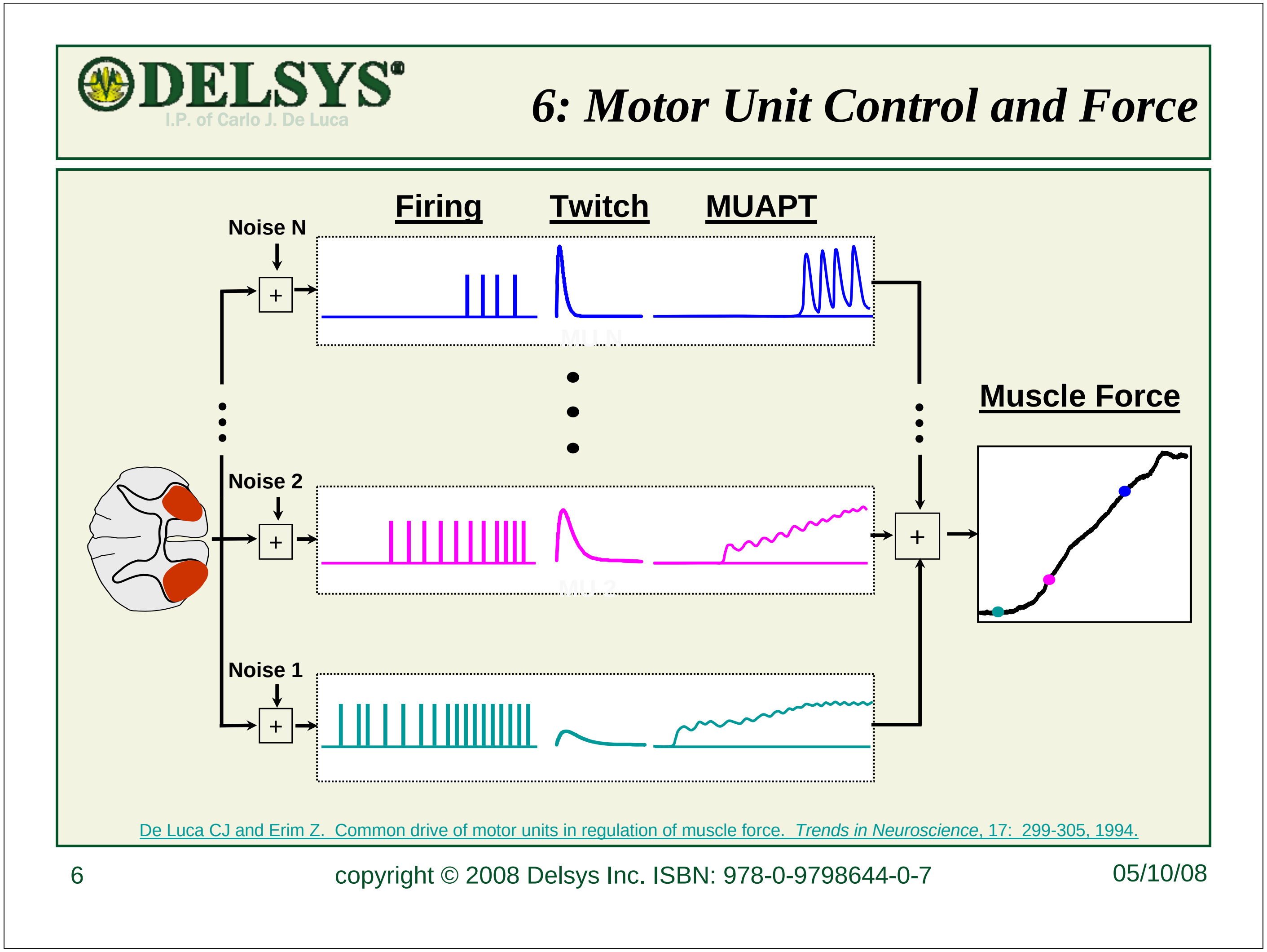
Click here to animate slide

Motor Units and Force:

Skeletal muscles are composed of individual muscle fibers that contract when stimulated by a motoneuron. Motoneurons originate in the ventral horn of the spinal cord and consist of a cell body, dendrites (not shown) and an axon. The axon projects to a muscle where it branches, forming synapses with muscle fibers.

A motor unit is the smallest functional subdivision of a muscle. It consists of the motoneuron, its axon and all the muscle fibers that are innervated by its branches. When motor units are activated, the corresponding muscle fibers contract.

Each firing of a motoneuron produces a force twitch in its motor unit. When force twitches occur in close enough succession they superimpose, producing a tetanic (sustained) force. This sustained force is the mechanism which moves our limbs, enables us to breathe, circulates our blood, and enables us to interact with our environment.



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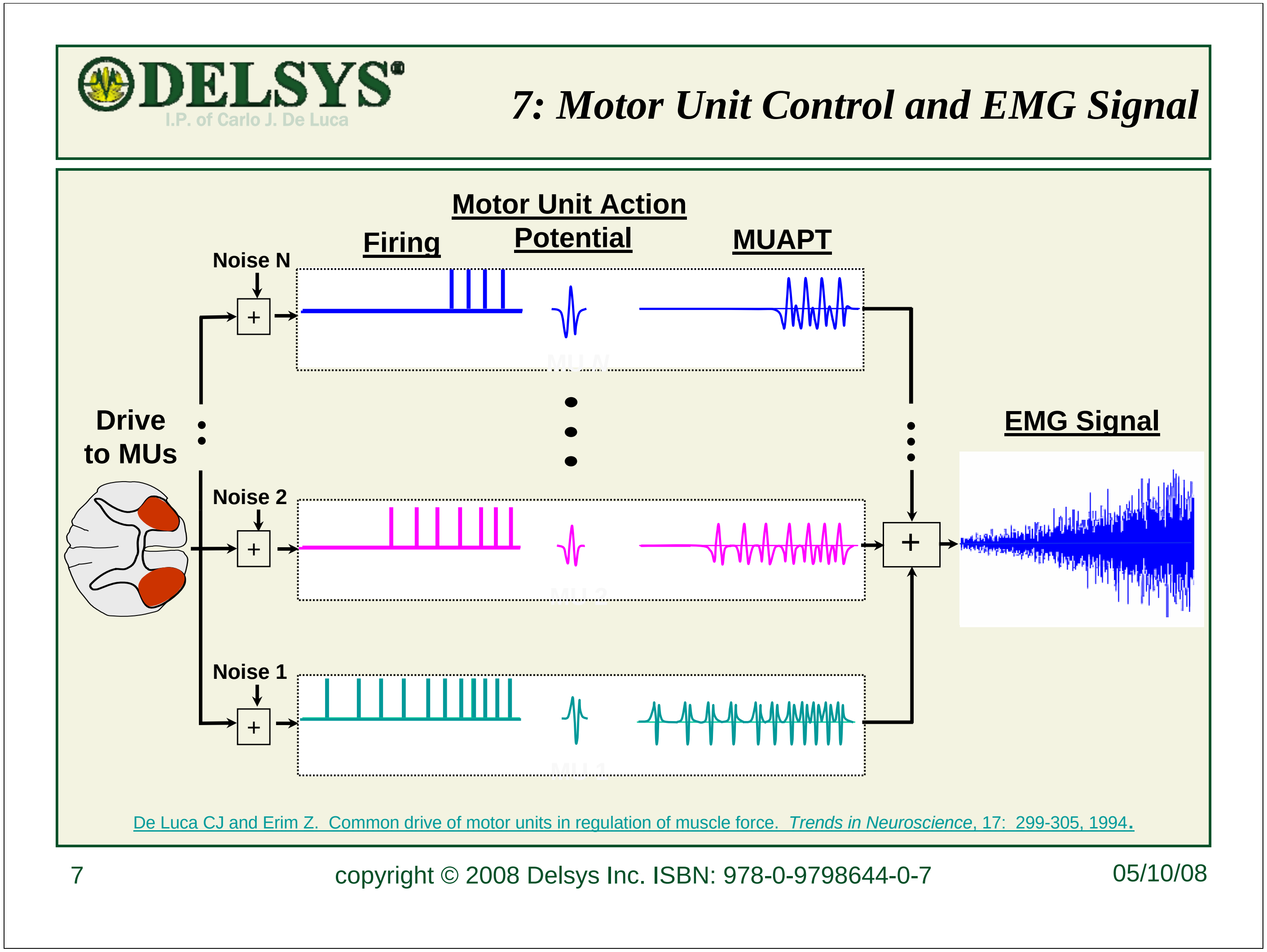
Motor Unit Control and Force:

The force output of the muscle is modulated by the recruitment of motor units and the regulation of their firing rates. The diagram presents physiologically correct concepts that relate the excitation at the anterior horn of the spinal cord to the force output of the muscle. Consider a set of motor units (1, …, n). Each motor unit is activated by a **Common Drive** (*see cited reference*) that provides a net excitation to the motoneuron pool in the anterior horn. However, each motoneuron has a noise component (noise N) that consists of background neural activity from the Peripheral Nervous System and from the Central Nervous System. As the excitation increases, motor units are progressively recruited and all the active motor units simultaneously increase their firing rates (mediated by common drive). In this fashion the earlier recruited motor units have greater firing rates than later recruited motor units. (Note that the firing rate of motor unit #1 is greater than MU #2 and MU #n.). Also note that in the above example the earlier-recruited motor units (slow twitch) tend to tetanize, whereas the later-recruited (fast twitch) motor units do not.



Motor Unit Control and EMG Signal:

This figure demonstrates how the EMG signal is generated while the **Common Drive** (*see cited reference*) excitation to the anterior horn cell increases. The relationship between recruitment and firing rates is similar to that in the previous companion diagram. Note that as the excitation increases, additional motor units are recruited and the firing rates of all active motor units increases simultaneously. Note that the higher threshold motor units have action potentials of higher amplitude and fire at lower firing rates. Additionally, in sustained contractions at high force levels, the accumulating effects of fatigue may cause the excitation to fluctuate about a set value, then motor units of relatively high amplitudes are sequentially recruited and derecruited causing the variance of the EMG signal (and the force) to increase.

The time sequence of the firings of one motor unit is referred to as a Motor Unit Action Potential Train (**MUAPT**).

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8: Synthesized EMG Signal

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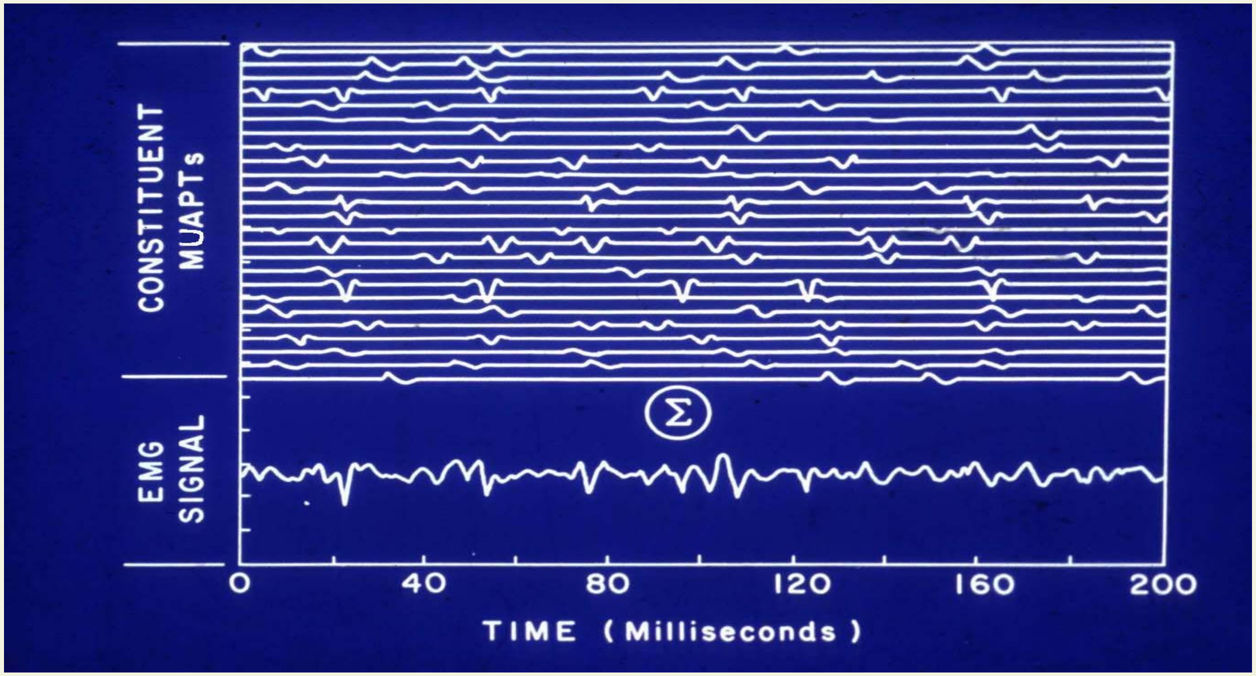

Basmajian JV and De Luca CJ. *Muscles Alive (5thedition)*, Williams and Wilkins, Baltimore, MD, 1985

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Synthesized sEMG Signal:

An expanded version of the **surface EMG (sEMG)** signal consisting of 25 Motor Unit Action Potential Trains (MUAPT). These are synthesized signals with shapes that closely represent the characteristics of real action potentials. The signal at the bottom is the mathematical sum of all the action potentials which appear in the time sequences above.

The signal at the bottom is what the sensor sees and the roster above it is the code sent by the CNS that is seen by the muscle fibers. The purpose of EMG signal decomposition is to find, from the signal recorded by the sensor, individual MUAPTs. Being able to do this allows a closer investigation of the control mechanisms governing motor activity.

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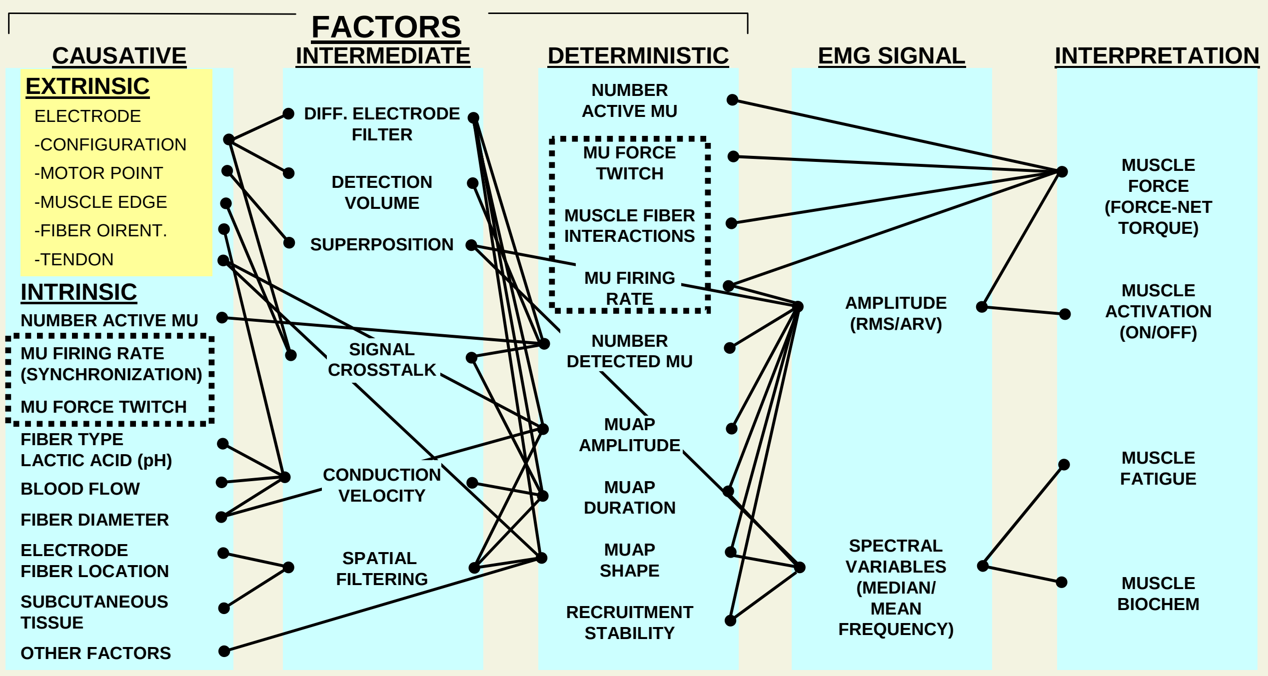
9: Factors that Influence the EMG Signal



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

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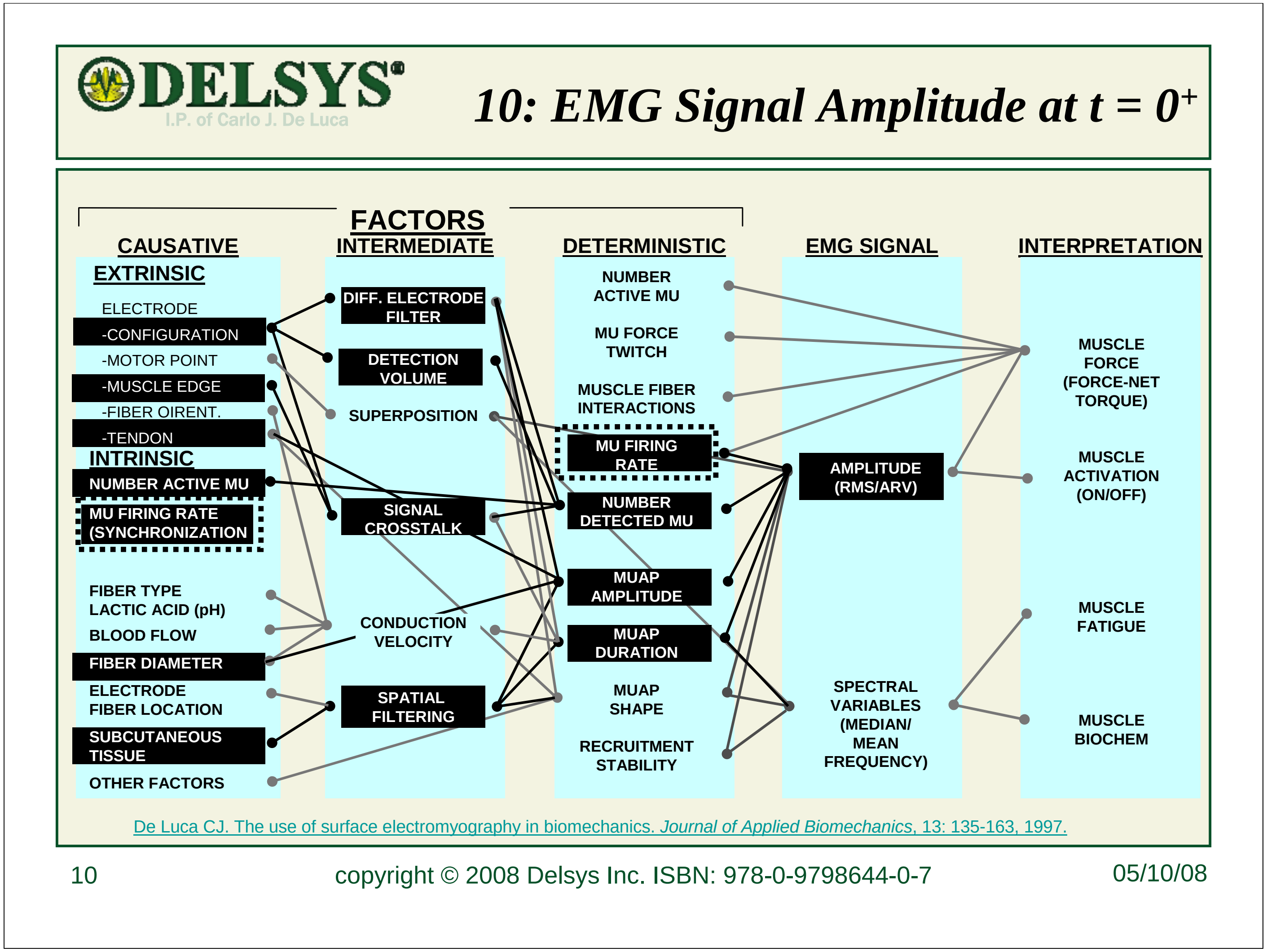
Factors that Influence the EMG Signal:

Schematic diagram of the factors that affect the EMG signal. The arrangement of factors is designed to demonstrate the flow of influences and interactions among the factors, as well as the complexity of their interaction. The section highlighted in yellow (the extrinsic factors) refers to the sensor design and the manner used to attach the sensor on the skin. These are factors that can be controlled by the sensor manufacturer and sensor user. **How and where** one locates the sensor on the skin above the muscle has **dramatic** effect on the signal quality. This topic will be discussed in greater detail in Chapter 3. The intrinsic factors as well as the remaining groups of factors refer to anatomical, physiological, and electrical properties that are not controllable by the user, but must be taken into account when interpreting sEMG results.

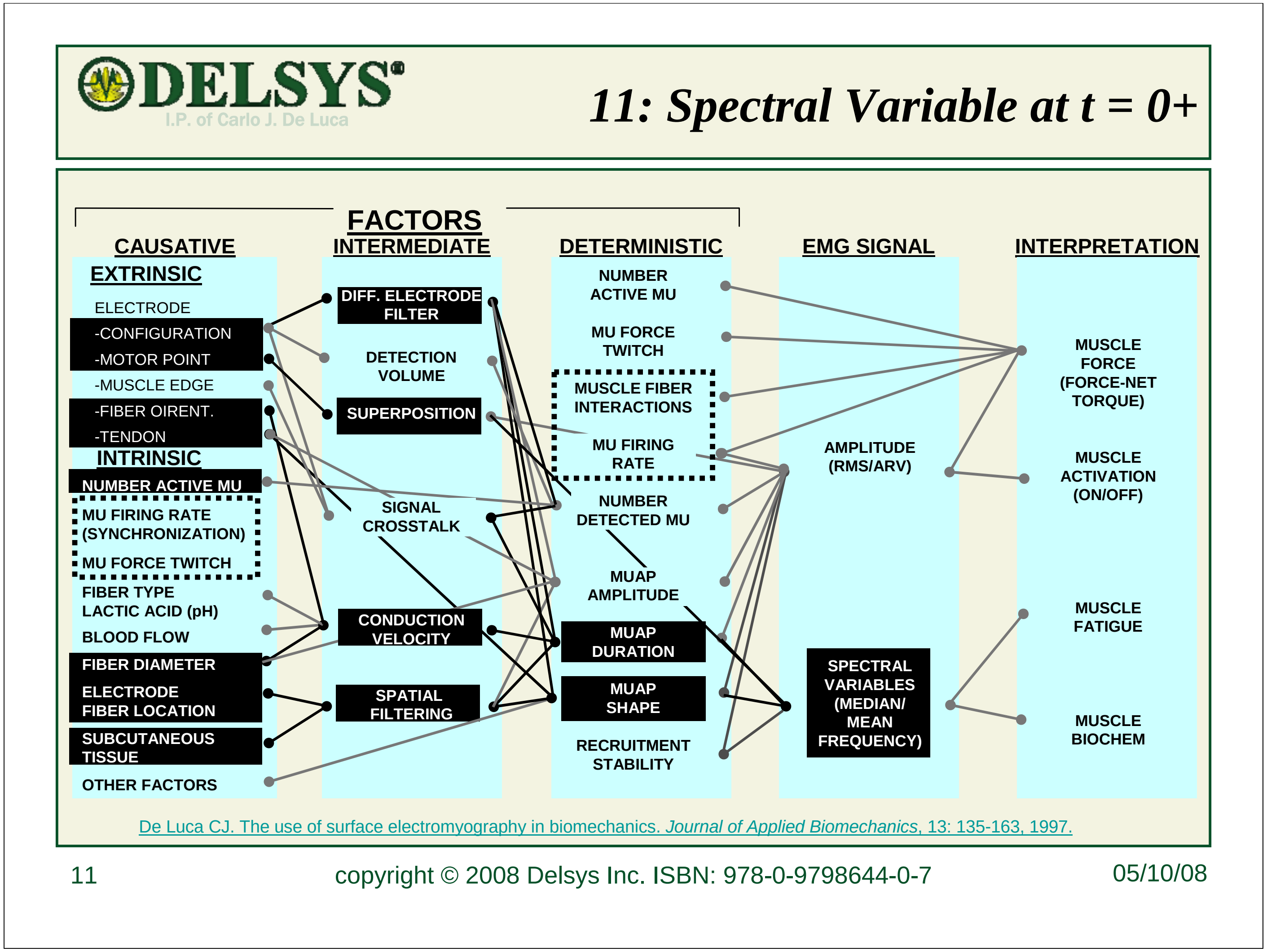
For additional details explaining the remainder of the diagram please refer to the cited reference.



EMG Signal Amplitude at t=0+:

The segments highlighted in black show the interrelationship of factors affecting the EMG signal amplitude at the beginning of a contraction (t=0+), that is when no fatigue is present. Factors which are active at this stage of contraction are shown. The time-dependent (fatigue influencing) factors that would be influential during a sustained contraction are not shown.

For further explanation about the remainder of the diagram please refer to the cited reference.



Spectral Variable at t=0$^+$:

Factors that influence the frequency spectrum of the sEMG signal at the beginning of a contraction (t=0$^+$), when the influence of fatigue is not present, are shown highlighted in black.

For more on muscle fatigue, skip to slide 87.

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12: Why Use the sEMG Signal?

As complex as it may appear from the previous slides, the sEMG signal can be used in the following applications

Note that some applications are limited to isometric contractions and/or constant-force contractions

A) Obtain parameters from individual or groups of muscles

- Force (isometric contractions)
- Activation Time (ON – OFF)
- Fatigue (constant-force, isometric)

B) Compare behavior of different muscles

- Relative amount of contribution
- Co-activation
- Pattern identification (tasks)

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Why Use the sEMG Signal?:

From the perspective of Movement Science, these are the main applications of the sEMG signal:

Muscles produce force. Biomechanical studies often require us to know the force contribution of individual muscles. Mechanical instrumentation which records this data is complicated and almost always invasive. Under proper conditions the sEMG signal detected from **individual** muscles can provide this information.

The relationship between the sEMG signal and force is valid only for isometric contractions (those for which the muscle length remains constant). sEMG fatigue parameters calculated with Fourier transforms are valid only for constant-force, isometric contractions.

The detected sEMG signal **must** contain the least amount of contamination from adjacent muscles, otherwise the **individuality** or **relativity** of the information in the sEMG signal is not maintained. The relationship between force and the sEMG signal is also used for biofeedback and for controlling external electro-mechanical devices such as prosthesis, robots, and household appliances.

The timing of activation and contraction between different muscles is often a useful parameter that can be obtained from the sEMG signal. The activation timing can be used to address issues concerning the fine tuning of muscle use in skilled performance or for assessing the discordant activation in neurologically impaired patients.

As a muscle contraction is sustained the chemical activity within the muscle alters some parameters of the sEMG signal. The non-invasive and real-time nature of the assessment of these parameters makes the signal useful in some applications in ergonomics and clinical assessments.

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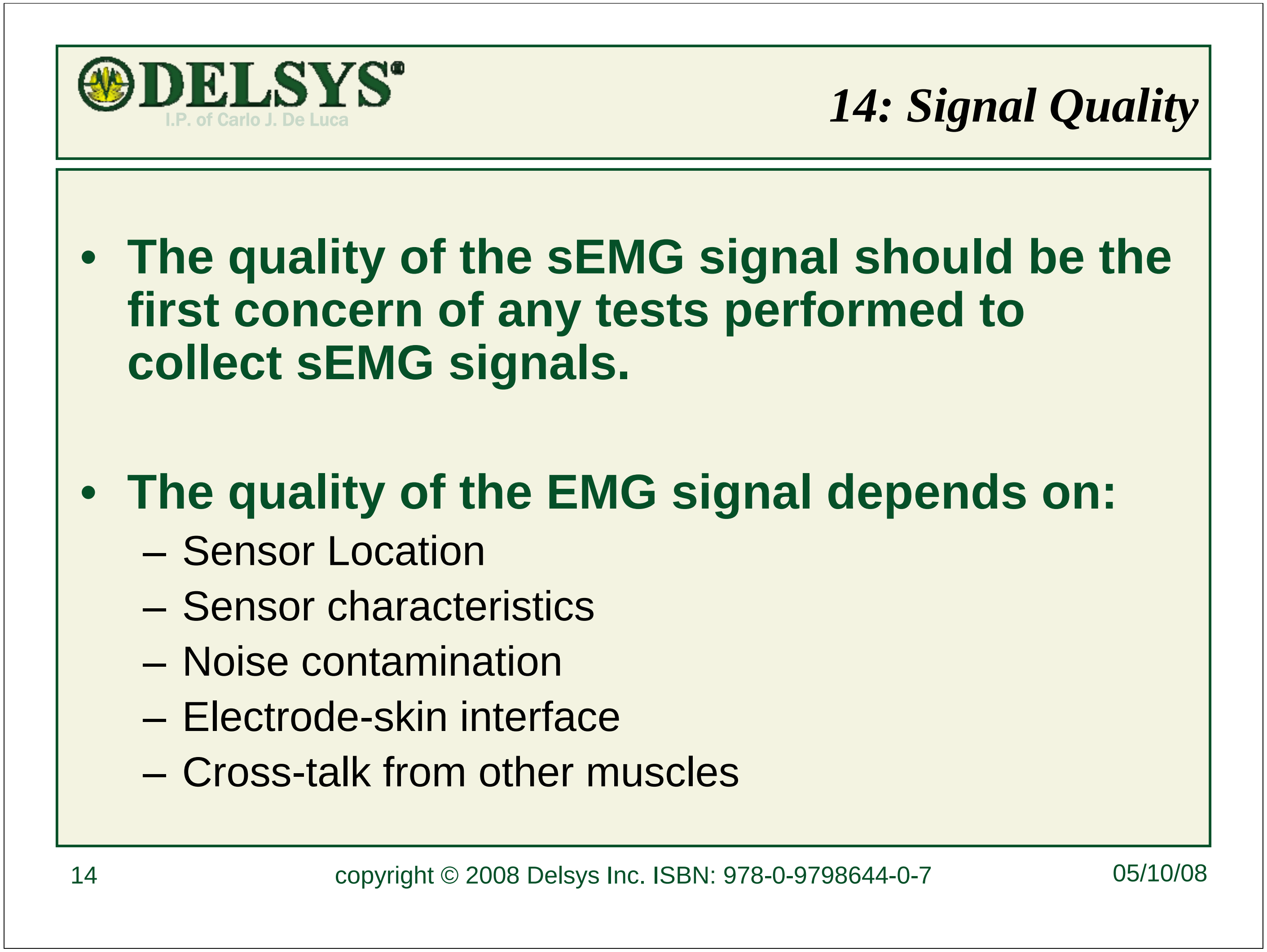
Section 2: Technology and the Quality of the sEMG Signal



Signal Quality:

The quality or the fidelity of the detected sEMG signal determines the usefulness of the information extracted from the sEMG signal. Bad data yield contaminated results and compromised interpretation. The dominant factors are listed in the slide and are explained in the following slides.

The single best effort that can be performed by the user is to maximize the quality of the acquired signal. This is achieved by using superior equipment, by properly applying the sEMG sensor and reference electrode to the skin, and most importantly by placing the sEMG sensor in the middle of the belly of the muscle.

This last action by itself increases the signal to noise ratio and reduces the cross-talk from other muscles. Proper sensor location accomplishes more than any other procedure towards providing a high-quality sEMG signal.

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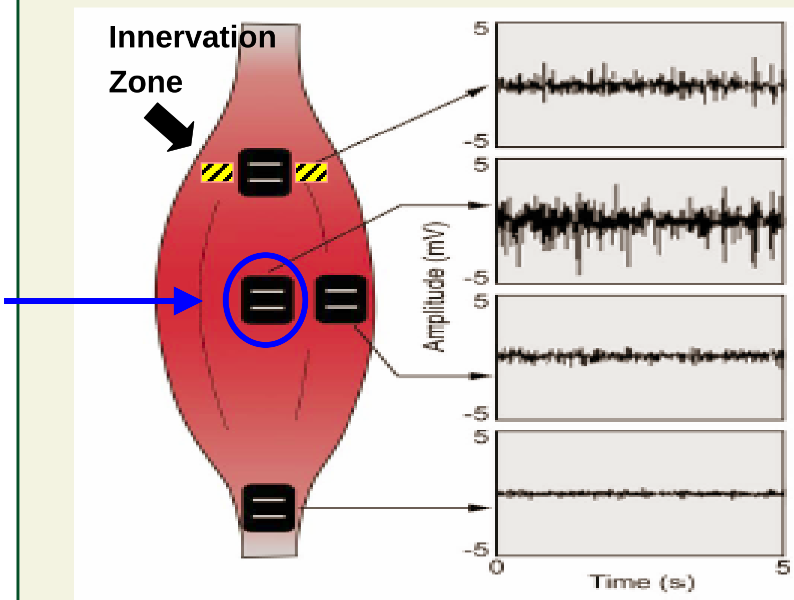
15: Sensor Location:
Signal Amplitude Variation



Proper
sensor location

- *Increases the signal*
- *Increases the signal to noise ratio*
- *Reduces cross-talk*

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

Sensor Location and Signal Amplitude Variation:

The location of the sensor on the muscle renders dramatically different sEMG signal characteristics. Note that locating the sensor in the proximity of the tendon origin, the innervation zone, and the perimeters of the muscle yields lower amplitude signals. The fibers in the middle of the muscle have a greater diameter than those at the edges of the muscle or near the origin of the tendons. Because the amplitude of action potential from the muscle fibers is proportional to the diameter of the fiber, the amplitude of the EMG signal will be greater in the middle of the muscle. A sensor located on the innervation zone will detect the cancellation of the action potentials traveling in opposite direction, and will generally have a lower amplitude.

The preferred location is away from all these boundaries, towards the middle of the muscle surface.

The location of the sensor on the muscle is the single most important factor for obtaining the best signal to noise ratio with the least amount of cross-talk.

Means for locating the innervation zone, as well as known locations of the innervation zones on some muscles, are discussed later. The reported localizations of the innervation zones is in the periphery of the muscle.

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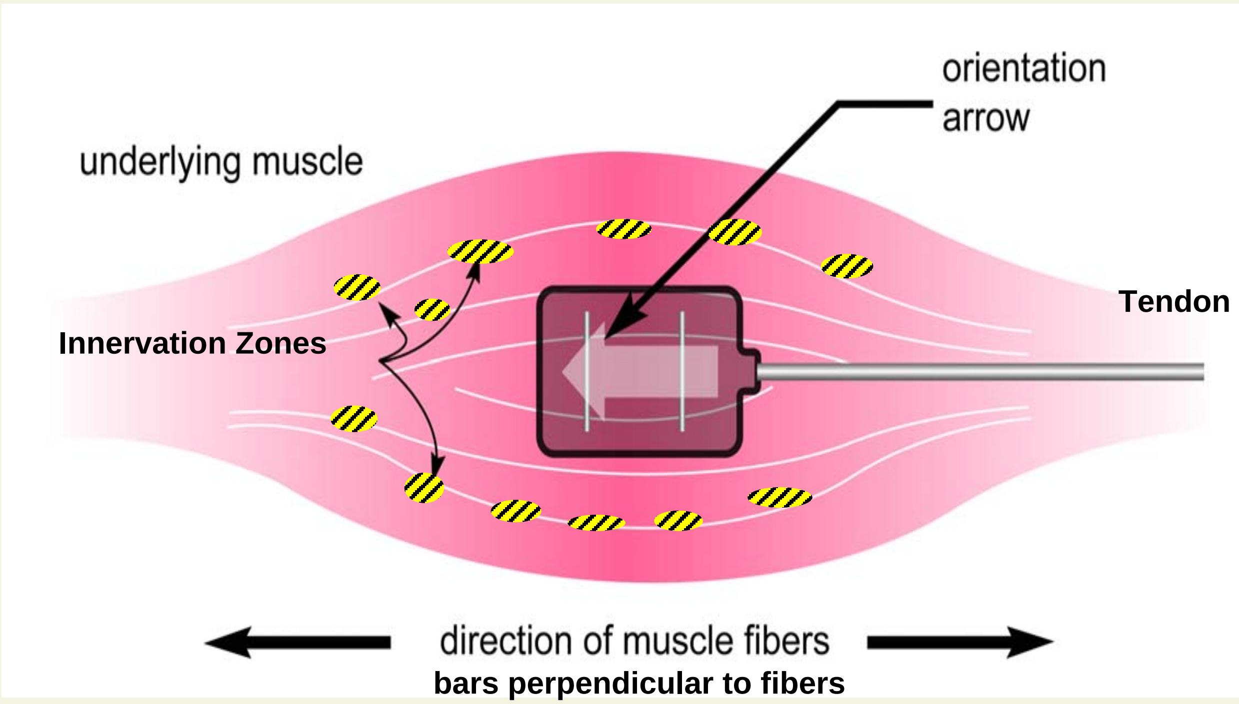
16: Where to Locate the EMG Sensor for a High-Fidelity Signal?



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Where to locate the EMG sensor for a high-fidelity signal?:

This cartoon indicates the preferred location for placing the sensor -- in the middle of the muscle surface and as far away as possible from the innervation zones and tendon origins. The small yellow striped areas indicate the innervation zones which in large muscles are located around the periphery, as discussed earlier. For better signal quality, the bars of the sensors should be aligned perpendicularly to the muscles fibers when possible. Admittedly, in multi-pennate muscles, this alignment is not possible.

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17: Sensor Location:

How do you Determine the Innervation Zone?

- **Direct Surface stimulation (motor point)**
- **Measurement of inverting action potentials on the surface with an array sensor**
  – Masuda T. and Sadoyama T. Topographical map of innervation zones within single motor units measured with a grid surface electrode. *IEEE Trans. Biomed. Eng.*, 35:623-628, 1988.
- **Location of highest value of the initial (t=0) Median frequency on the surface of the muscle**
  – Roy, S.H., De Luca, C.J. and Schneider, J. Effects of electrode location on myoelectric conduction velocity and median frequency estimates. *Journal of Applied Physiology*, 61: 1510-1517, 1986

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How do you determine the innervation zone?:

The location of the innervation zone is not identifiable by visual observations. There are at least three methods for locating it.

- The oldest method is to find the motor point on the surface of the muscle. This is achieved by locating the point(s) where the muscle begins to twitch with the lowest amount of current applied. It is not a very sensitive technique, as the innervation zone may be deep in the muscle, requiring relatively high levels of current to activate the innervation zone, sufficient to excite some stray motor nerve fibers that may be located near the surface that would cause muscle fiber twitching. (Note that less current is necessary to activate nerve fibers than muscle fibers.)
- The second method was introduced by Masuda and Sadoyama (see cited reference). It relies on using an array sensor consisting of a series of electrode bars to detect the action potential of a motor unit during a weak contraction. The location where the phases of the action potential invert or the amplitude approaches zero is the location of the innervation zone for that motor unit.
- The third method is to locate the position on the surface of the muscle where the median frequency at the beginning of a muscle contraction is the greatest. This location coincides with an innervation zone.

Method #2 is the most sensitive and accurate. Massuda and colleagues have provided the location of the innervation zones for various muscles commonly used in EMG studies. Examples are shown in the next 2 slides.

- The location of the innervation zone is not identifiable from visual observations.
- There are at least three ways to calculate it.

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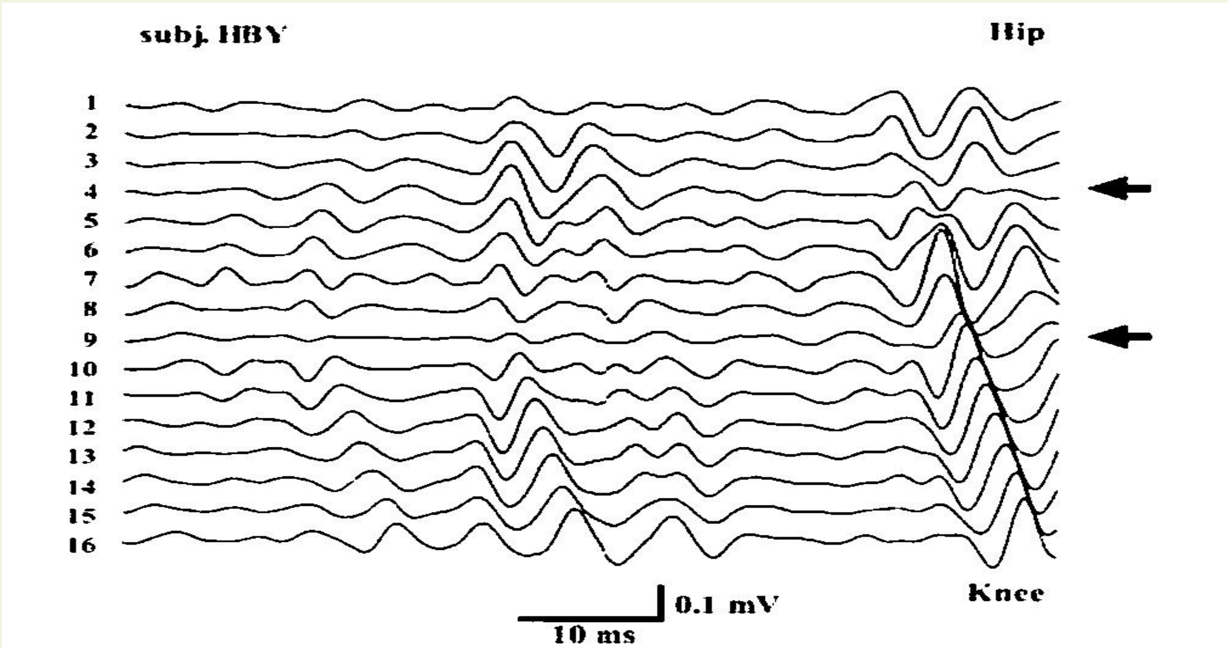
18: Sensor Location:

Method for Finding Innervation Zones



Saitou K, Masuda T, Michikami D, Kojima R, and Okada M. Innervation zones of the upper and lower limb muscles estimated by using multichannel surface EMG. J Human Ergol, 29: 35-52, 2000. (Used with the permission of the publisher)

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Method for Determining the Proximity of the Innervation Zone (from Masuda and Sadoyama):

1. A linear sensor array of 16 electrodes is placed on the skin above a muscle. A mild contraction is made, sufficient to generate motor unit action potentials that can be visibly identified. The figure shows the time course of three motor unit action potentials

2. The action potential travels in both directions from the neuromuscular junctions that constitute the innervation zone. Thus when differential recordings are made between adjacent electrodes, the pair on top of, or in the near proximity of, the neuromuscular junction will detect the lowest amplitude action potential. (If the neuromuscular junction is located precisely between two electrodes and the tissue between the muscle fiber and the electrodes is isotropic, then the amplitude will be zero.)

3. The two arrows in the figure indicate the location where the amplitude of two different action potentials is the smallest, indicating the proximity of the innervation zone.

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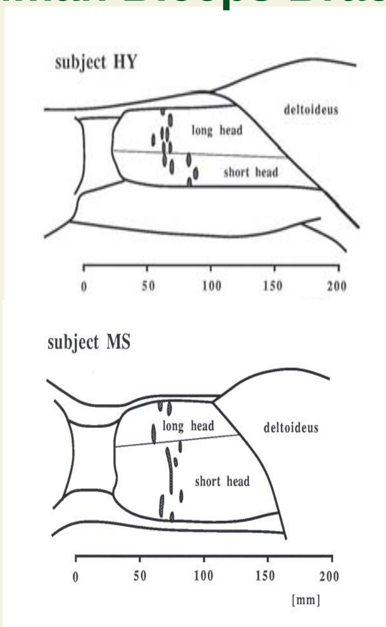
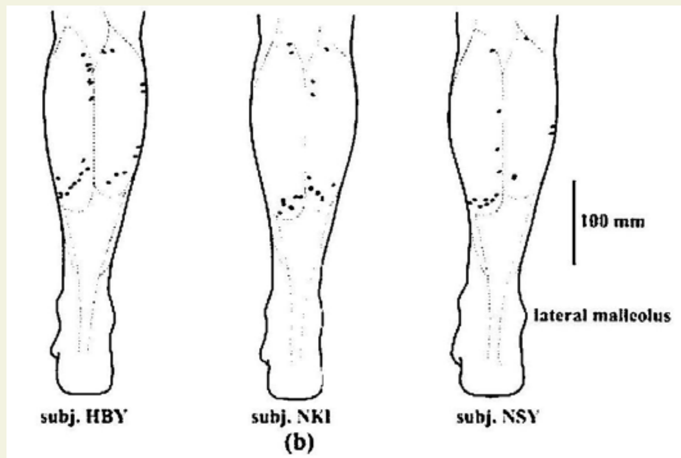
19: Sensor Location:

Examples of Innervation Zone Locations

Human Biceps Brachii



Soleus and Gastronemius



Masuda T and SadoyamaT. Distribution of innervation zones in the human biceps brachii. Journal of Electromyography and Kinesiology. 1 ;107-115, 1991. (Used with the permission of the publisher)

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Note that:

1. The innervation zones are located either at the perimeter of the muscle or at one end of the muscle.
2. The middle of the muscle is generally devoid of innervation zones, leaving it a clear location for placing the sensor.
3. The location of the innervation zones is similar across subjects.

Examples of Innervation Zone Locations in Upper and Lower Limb Muscles:

1. The innervation zones are located either at the perimeter of the muscle or at one end of the muscle.
2. The middle of the muscle is generally devoid of innervation zones, leaving it a clear location for placing the sensor.
3. The location of the innervation zones is similar, but not identical among subjects.

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20: Noise Contamination

- **Physiological Noise**
  - EKG, EOG, respiratory signals, etc.
    - Reduced by judicious location of the sensor and by rotation of the sensor
- **Ambient Noise**
  - power line radiation (50, 60 Hz)
    - Removed by differential detection
  - Cable motion artifact
    - Removed by high quality technology
- **Baseline Noise**
  - Electro-chemical noise (skin-electrode interface)
    - Reduced by effective skin preparation
  - Thermal noise (property of semiconductors)
    - Reduced but not eliminated by modern technology
- **Movement Artifact noise**
  - Movement of electrode with respect to the skin (induced by force transients or movement of the skin)
  - This is the most obstreperous noise
    - Reduced by effective skin preparation and filtering

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Noise Sources:

There are several sources of noise with which we must be concerned: The physiological noise, the ambient noise, the baseline noise and the movement artifact noise.

The physiological noise originates from other tissues that generate electrical signals, such as EKG, EOG, respiratory muscles, and the like. It can be reduced by location the sEMG sensor further away from the source of the noise, by rotating the sensor so that the electrodes align on equipotential planes (that is: both electrodes are equidistant from the source), and by some filtering.

The ambient noise (power line noise and cable motion artifact) originates from the electromagnetic radiation that is pervasive in all environments. The *power line noise* (50 or 60 Hz) is generally not a concern because modern differential amplification technology (see next slide) and proper circuit design combined with judicious location of the reference electrode on the subject can virtually eliminate this ambient noise. The *cable motion artifact* originates when the cable(s) from the electrodes or sensor to the amplifier moves and cuts an electromagnetic field in the environment to generate a potential that is subsequently amplified by the recording system. Modern EMG technology now uses sensors that have the first-stage of amplification located on-board or within centimeters of the site of the electrodes. The output of the first-stage amplification has a low-impedance, rendering the cable ineffective in generating a cable motion artifact. Thus, present technology virtually eliminates the first two sources of noise, which in previous decades were a difficult-to-deal-with nuisance.

The baseline noise originates in the electronics of the amplification system and at the skin-electrode interface. It is can be observed when a sensor is attached to the skin and the muscle is completely relaxed. The ionic exchange between the metal in the electrode and the electrolytes in the salts of the skin (also known as the electrolyte-electrode interface) generates an *electro-chemical noise*. The magnitude of this noise is proportional to the square root of the resistance of the electrode surface [Huigen et al., 2002]. Thus, it can be reduced by increasing the electrode area and by cleaning the electrode surface, but it cannot be eliminated. The *thermal-noise* is generated by the first stage of the amplifiers and is due to a physical property of the semiconductors. It also cannot be eliminated. Both noises are referred to as 1/f noises, with the amplitude of the frequency spectrum greatest at 0 Hz and continuously decreasing with increasing frequencies [Huigen et al., 2002]. According to Fernandez and Pallas-Areny [2000] the electrochemical noise is generally greater than the thermal noise.

The ambient noise and the baseline noise can be substantially reduced to the level that they are not significant contaminants by using well designed modern technology, by effective preparation of the skin below the sEMG sensor, and by using effective reference electrodes.

The movement artifact noise also originates at the electrode-skin interface. This noise is the most obstreperous and requires the most attention. There are two common sources. One occurs when a muscle contracts and relaxes causing the length and cross-section to change. This volumetric morphing stretches and relaxes the skin which alters the electro-chemical balance of the two skin-electrode interfaces causing a time-varying voltage across the two electrodes. The other, often much more significant, source occurs when a force impulse originating within the muscle, as in the case of a jerk movement, or from outside the limb, as in the case of a heel-strike while walking, is transmitted to the electrodes. This phenomenon is amplified considerably by the presence of hydrophilic gel that is at times placed between the electrode and the skin [Roy et al., 2007]. It is difficult to reduce and almost impossible to eliminate. A good electrode-skin preparation and appropriate filtering are helpful.

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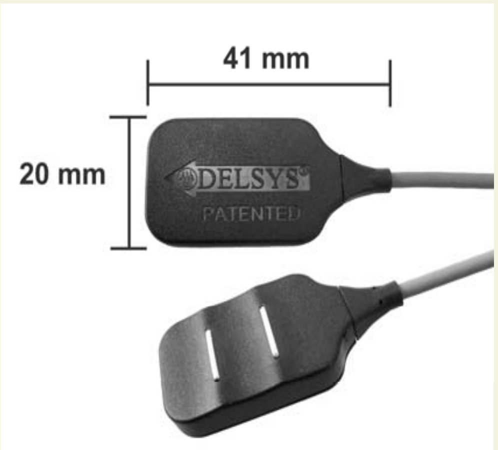
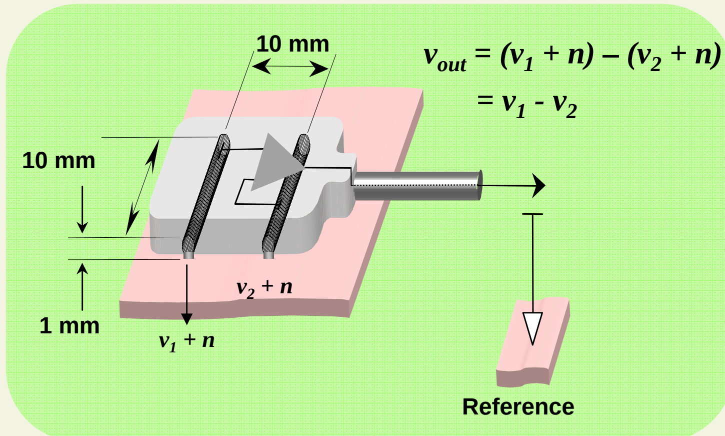
21: Single Differential Electrode Removes Power Line Noise





- Ambient (power line) noise (*n*) is almost similar on both electrodes (common mode source)
- System subtracts two signals -- ambient noise is removed, resultant EMG signal is amplified
- High input impedance, low output impedance

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Definition - The electrode is the metallic detection surface that exchanges ions with the salts in the skin. The sensor is the complete unit that provides the sEMG signal.

The sensor used to detect the sEMG signal is the most important component of the recording system. The fidelity of the signal obtained from the sensor determines the quality of the signal that is provided by the recording system. The remainder of the system can only worsen the quality of the signal. Because the sEMG signal originating in the muscle is much smaller than the ambient electrical signals that originate from surrounding sources, it is strongly recommended (insisted) that the sensor detect "differential" signals.

Single Differential Electrode with low output impedance Removes Ambient Noise:

As may be seen in the green panel, each sensor has two electrodes which detect two different potentials (v_1 and v_2, which are represented in the figure as voltages) with respect to a reference located some distance from the sEMG sensor. These potentials are caused by the ionic currents that travel along the muscle fibers below the electrodes. Both potentials are contaminated by the noise sources described in the previous slide.

Ambient noise (***n***) that originated much further away (such as 50 or 60 Hz power line radiation and higher frequency radiation from electronics communication systems, such as radio stations, TV stations, etc.) from the sensors than the interelectrode distance will arrive at the electrodes nearly at the same time, or "in phase". These noises are also known as common – mode signals. Whereas, because the EMG signal travels at speeds of only 2.5 to 5 m/s the two sensors "see" different potentials due to muscle activity. Thus, by subtracting the two potentials, the ambient noise is removed and the difference ($v_1 - v_2$) is detected as an sEMG signal. This "difference" potential is the result of "differential" detection. The effectiveness of the circuitry to eliminate the common-mode signals is measured by the Common-mode rejection ration (CMRR).

Note that differential amplification will not remove noise contributions from other noise sources such as the EKG, which are local events like the sEMG signal.

FOR MORE INFORMATION ON SENSORS go to Appendix A "sEMG Sensor Factors" located at the end of the practicum.

For more information on the Delsys DE 2.1 sensor go to

http://www.delsys.com/Products/EMGSensors.html

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22: Sensor Characteristics:

Importance of Fixed Electrode Spacing

- **Fixed inter-electrode spacing is essential because:**
  - Amplitude of signal is **directly** proportional to spacing
  - Bandwidth of signal is **inversely** proportional to spacing
- **1 cm is a preferred compromise**

Lindstrom LR, Magnusson R and Petersen I. Muscular Fatigue and action potential conduction velocity changes studied with frequency analysis of EMG signals. Electromyography, 4: 341-356, 1970.

Importance of fixed electrode spacing:

By maintaining a fixed inter-electrode spacing, the bandwidth of the sEMG signal will remain constant. The band-width of the sensor determines how much of the signal energy and the noise energy constitutes the acquired signal. If the electrode spacing is varied as may occur with sensors that have separate electrodes that may be attached with variable spacing at each application, then the information content in the acquired sEMG signal will not be constant and comparison among muscles and subjects will be unreliable.

A small inter-electrode spacing is preferable as it will reduce the amount of crosstalk signal detected from adjacent active muscles. Remember that the differential recording amplifies the difference between the potentials at the two electrodes. The greater the spacing of electrodes the greater the difference of the propagating cross-talk signal. Additional advantages of the 1 cm spacing will become more apparent later in the presentation.

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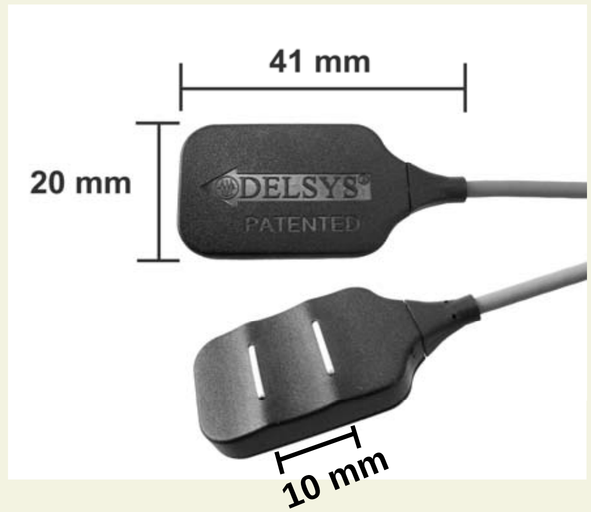
23: Sensor Characteristics



– Dry electrode (no electrolyte)
– Use as a probe
– Noise < 1.2 uV RMS (0-500 Hz)

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sEMG sensor characteristics:

The Delsys DE 2.1 parallel bar differential sEMG sensor is presented in the slide. For additional information go to http://www.delsys.com/Products/EMGSensors.html

In addition to the electrical characteristics of the sensor, the design of the sensor should address other practical factors such as:

1. Effectiveness of the electrical contact between the electrode and the skin
2. Facility of attaching the sensor to the skin
3. Durability of the adhesion to the skin
4. Insensitivity of the electrical and mechanical performance to the presence of sweat.
5. Insensitivity to movement artifact
6. Ease of use on small muscles

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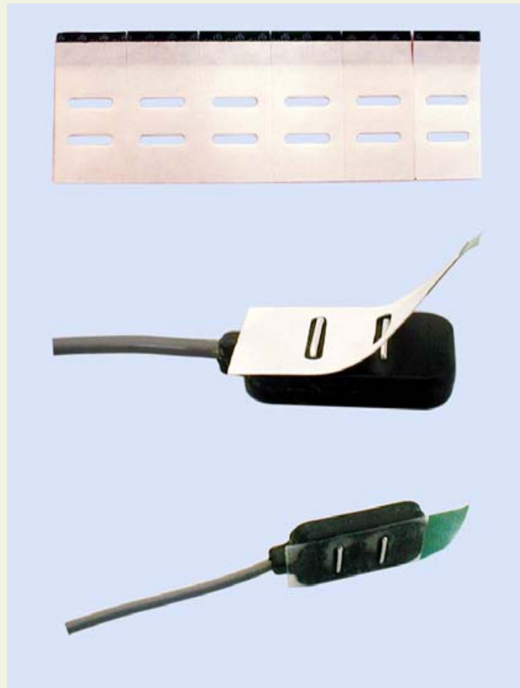
24: Electrode-Skin Interface

- **Maintains proper electrical contact with the skin during**
  - **Movement**
  - **Sweating**
- **Tested on various skin types**
- **Worn by Boston Marathon runners**
- **Worn for over 24 hour periods**



Use of a good sensor-skin interface:

Next to placing the sensor in the middle of the belly of the muscle, an effective electrode-skin contact will provide great benefits in assuring a high quality signal.

Method of application:

1. Shave excessive hairs, although in most cases the hair can simply be moved aside or sensor can be placed over hair.
2. Clean skin with alcohol to remove skin debris. Allow alcohol to evaporate. (When using Delsys sensors, abrasion of the skin is NOT required.)
3. In most cases (depending on skin type) no electrolyte is required.
4. Attach sensor-skin interface. Press hard to assure maximal adhesion to the skin.

The quality of the adhesive capability of the sensor and its response to mechanical perturbations have been tested as shown in the following slides.

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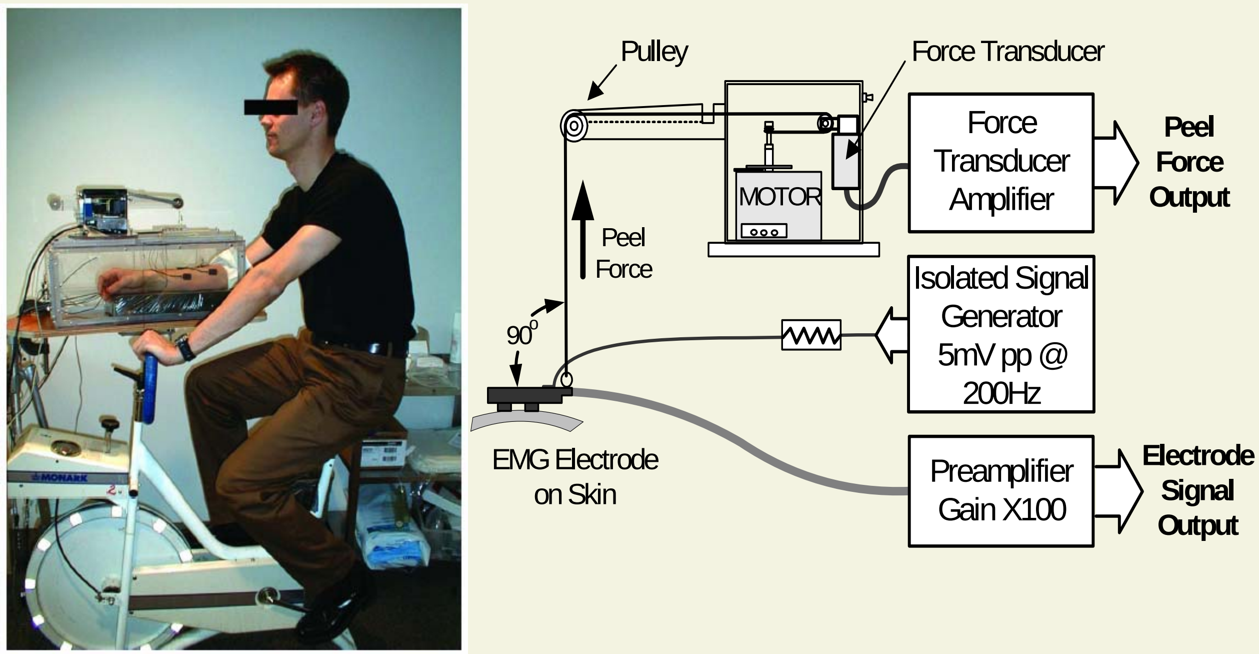
25: Electrode-Skin Interface:

Tests of Sensor Adhesion to Skin



Roy SH, De Luca G, Cheng S, Johansson A, Gilmore LD, and De Luca CJ. Electro-mechanical stability of surface EMG sensors. Medical & Biological Engineering & Computing, 45: 447-457, 2007.

Tests of sensor adhesion to skin:

In the referenced study, we developed tests and procedures for designing the contact surface of sEMG sensors. Specifically we evaluated different sensor designs and different interfaces between the sensor and the skin to determine how they affected sensor performance under conditions of sweat accumulation on the skin (sweat test) and when mechanically disturbed by impact and sinusoidal forces.

In one series of tests we evaluated how well the sensor remains affixed to the skin when differently shaped sensors were peeled by a mechanical device (shown above). We were specifically interested in evaluating whether contouring the skin surface of electrode improves performance.

In another series of test we evaluated the effect that conductive gels and other preparations have on reducing artifact when the sensors are perturbed.

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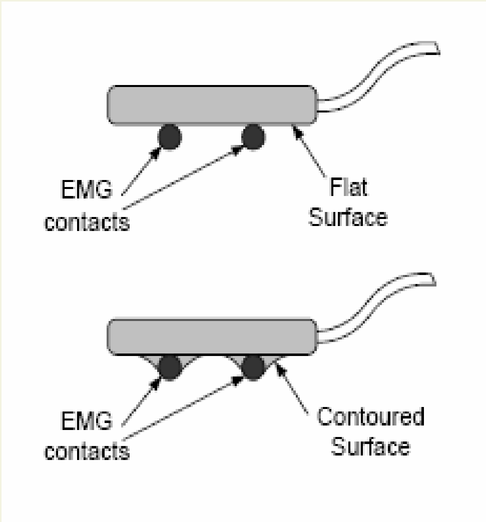
26: Electrode-Skin Interface:
Contoured Electrodes



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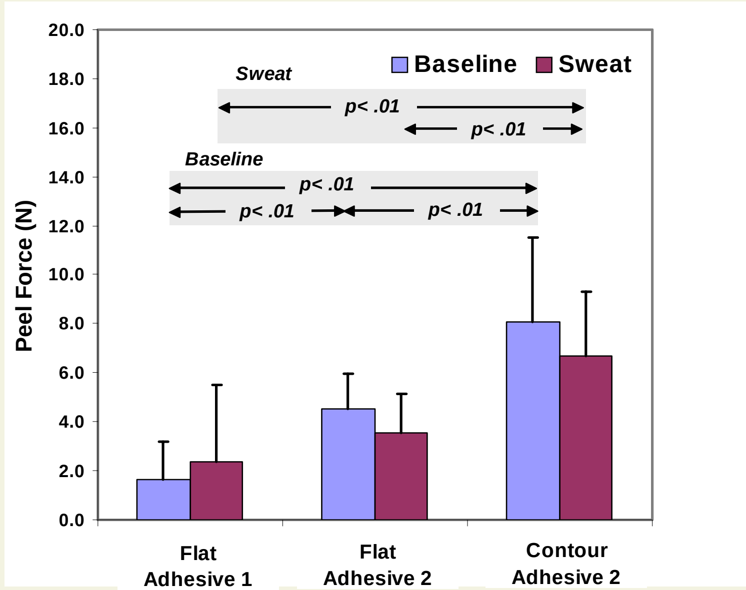

Roy SH, De Luca G, Cheng S, Johansson A, Gilmore LD, and De Luca CJ. Electro-mechanical stability of surface EMG sensors. Medical & Biological Engineering & Computing, 45: 447-457, 2007.

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Contoured electrodes improve ability of adhesive to attach:

The contoured edges around the electrodes significantly increased the amount of force required to peel the sensor away from the skin, implying that it enables a better contact between the sensor and the skin.

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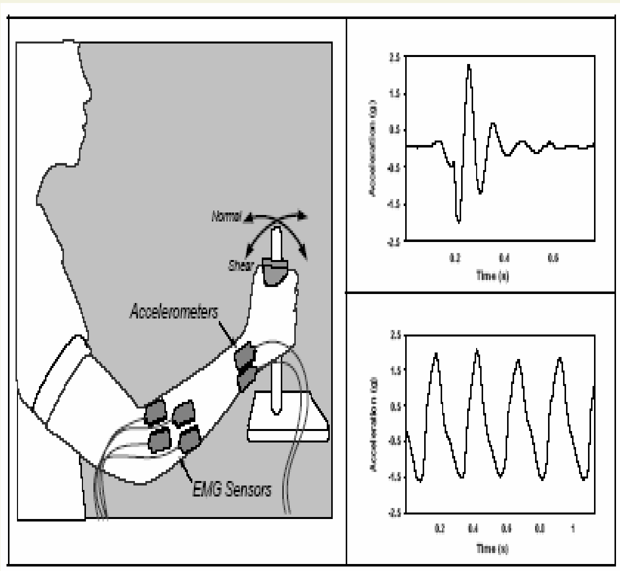
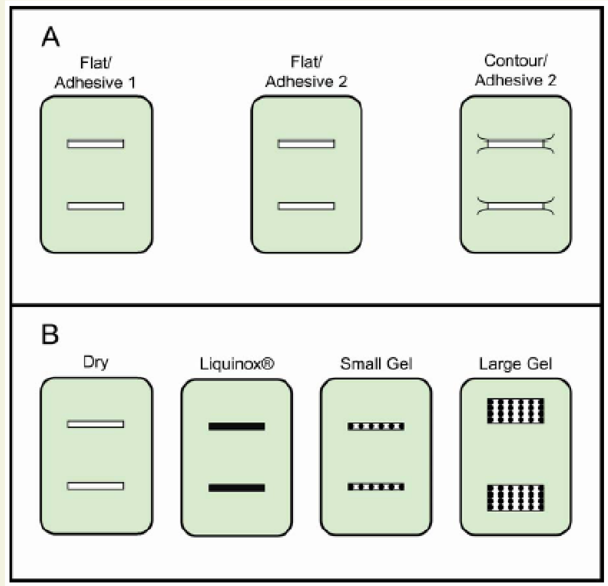
27: Mechanical Perturbations and Electrode Surfaces





Roy SH, De Luca G, Cheng S, Johansson A, Gilmore LD, and De Luca CJ. Electro-mechanical stability of surface EMG sensors. Medical & Biological Engineering & Computing, 45: 447-457, 2007

  05/10/08

Mechanical perturbations and electrode surfaces:

This was a test for establishing the influence of various electrolytes between the electrode and the skin on the generation of a movement artifact. (These are commonly used to improve the electrical conductivity between the electrode and the skin.) We also tested the performance of the sensor with no applied electrolyte.

Mechanical disturbances were applied as a sinusoidal force in the normal and shear direction, and also as an impact in the normal and shear direction.

The disturbance on the skin was monitored with accelerometers and the artifact was monitored by the sensors. See next slide for results.

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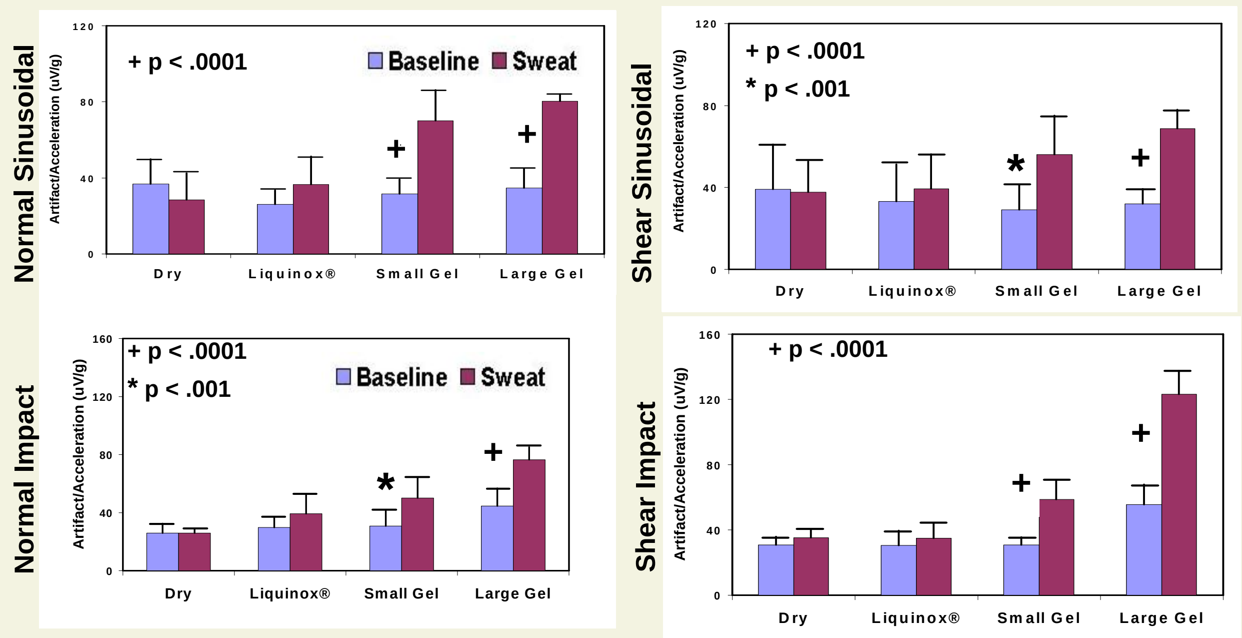
28: Electrode-Skin Interface:
Movement Artifact



Roy SH, De Luca G, Cheng S, Johansson A, Gilmore LD, and De Luca CJ. Electro-mechanical stability of surface EMG sensors. Medical & Biological Engineering & Computing, 45: 447-457, 2007

Movement artifact and the influence of electrolyte contact:

The results of the mechanical perturbations demonstrated that the gel electrolyte performed poorly and worsened in the presence of sweat. The dry electrode (no electrolyte) generally performed the best in the impact test, and the performance was statistically similar to that of the second best (Liquinox) in the shear sinusoidal test.

Note that the impact test represents the disturbance profile on the lower limb that occurs during walking.

FOR MORE INFORMATION ON SENSORS go to the end of the presentation to Appendix A: sEMG Sensor Factors.

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29: Noise in the EMG Signal:

Basic Concepts

- **Concept of Frequency Spectrum**
- **Concept of Filtering**

Noise in the EMG signal:

In the next sequence of slides we will discuss other characteristics of noise components. But in order to do so we need to review the concept of the frequency spectrum of signals, and the concept of filtering. The prior concept shows the frequency range that are common to both the noise signals and the EMG signal. The latter removes unwanted frequency components from the detected signal.

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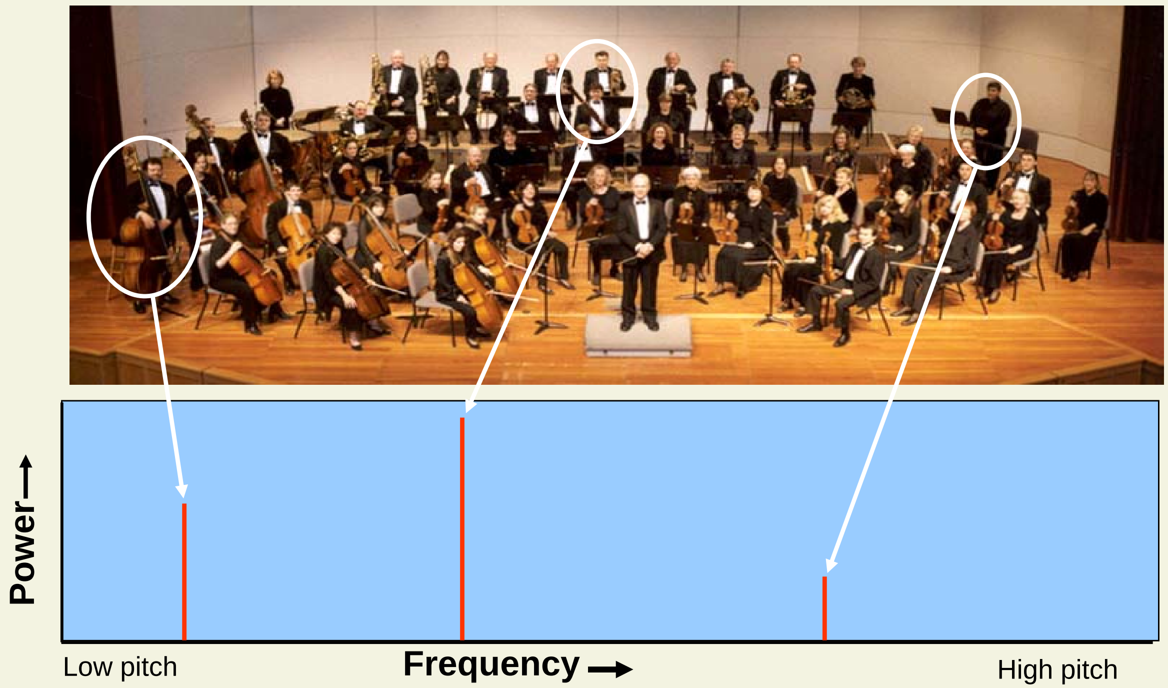
30: Frequency Spectrum



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Frequency spectrum:

The concept of a frequency spectrum can be difficult to grasp for a novice. The frequency spectrum of the EMG signal can be understood by drawing a parallel to the sound emanating from an orchestra. Consider the arrangement of the instruments in an orchestra. (To simplify the comparison the arrangement of instruments in the above figure has been inverted with the base section on the left and the violin section on the right.)

When a single base plays a note it emits a relatively low frequency (pitch) sound. A single frequency contribution to the spectrum is made in the spectrum plot below at the corresponding frequency value. The height of the contribution (the bar) corresponds to the loudness (amplitude) of the note.

A similar operation is performed for a violin having higher pitch (frequency) and for an instrument located in the middle of the orchestra, having an intermediate frequency.

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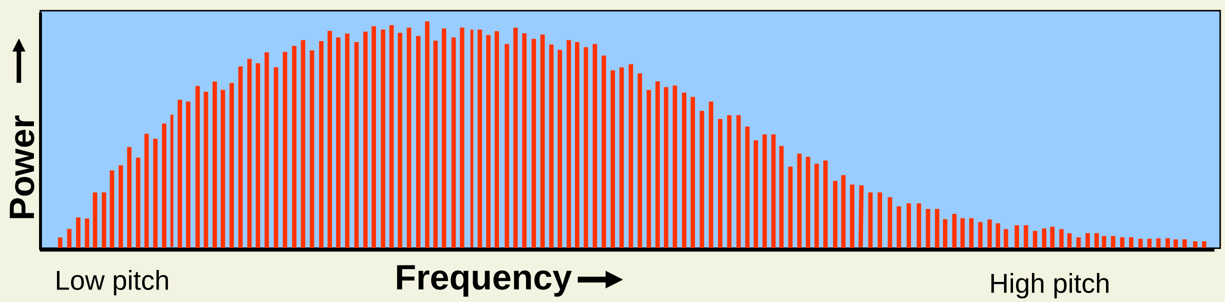
31: Frequency Spectrum



Frequency spectrum:

When all the instruments play, the individual frequency contributions fill the spectrum. And as the orchestra, in unison, modulates the amplitude of all the instruments the envelope of the spectrum modulates correspondingly.

The frequency spectrum of the sEMG signal is constructed in a similar fashion, with a range from 0 to approximately 450 Hz, with a peak in the neighborhood of 80 to 100 Hz.

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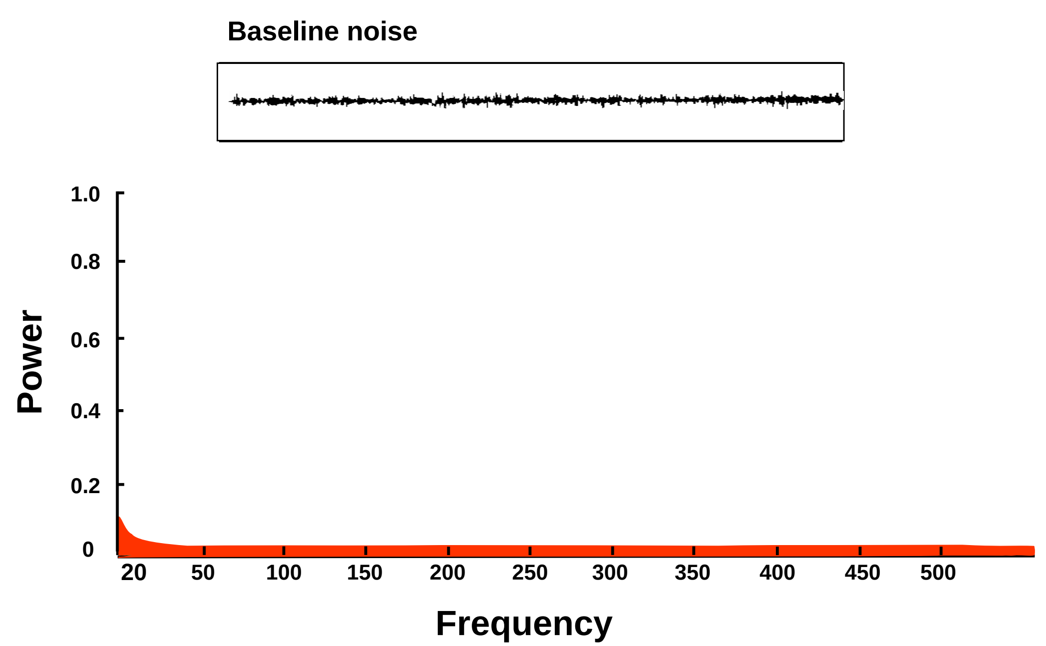
32: Noise Contributions to EMG Signal: Baseline Noise



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Noise contributions to the EMG signal:

The baseline noise of the recording system has a frequency spectrum that ranges from 0 Hz to a frequency range much greater than the sEMG signal (several thousand Hz). The amplitude is greater at the low frequency end and tapers to a near constant amplitude at higher frequencies, still within the bandwidth of the sEMG signal frequency spectrum.

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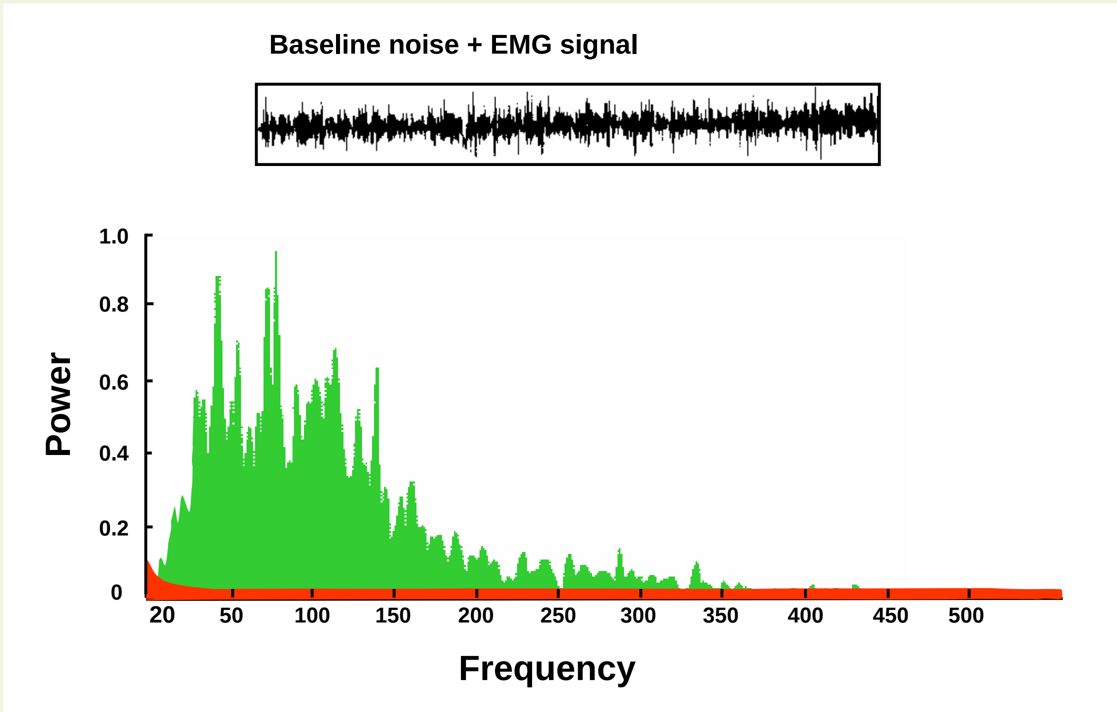
33: Noise Contamination of the EMG Signal



Noise contributions to the EMG signal:

The signal in the box consists of the sEMG signal and the baseline noise. Note that there is no visible indication of the presence of baseline noise. The corresponding spectra of the baseline noise (red) and the sEMG signal (green) can be seen in the plot.

The noise spectrum has the characteristics of 1/f noise, which has its highest amplitude at 0 Hz. It quickly decreases to a near constant level by 10 to 20 Hz. This is an example of the relative amplitudes measured during a weak contraction (say 10% MVC). During higher level contractions, the baseline noise signal remains constant and the sEMG signal amplitude increases. Hence, the baseline noise is obviously a greater concern for sEMG signals acquired during weak contractions.

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34: Movement Artifact

- **Induced by force transmission through the muscle and skin**
- **Caused by relative movement of sensor with respect to skin**
  - Poor electrical contact between electrode and skin
  - The electrolyte material between electrode and skin
- **More dominant in low level EMG signals**
- **Contaminates EMG signal**
  - Frequency components superimpose on those of EMG signal

Movement artifact:

Movement artifact is the most problematic noise in the sEMG signal. In contractions below 10% MVC, it can dominate the amplitude of the signal. It must be addressed when analyzing the sEMG signal. An example is shown in the following slide.

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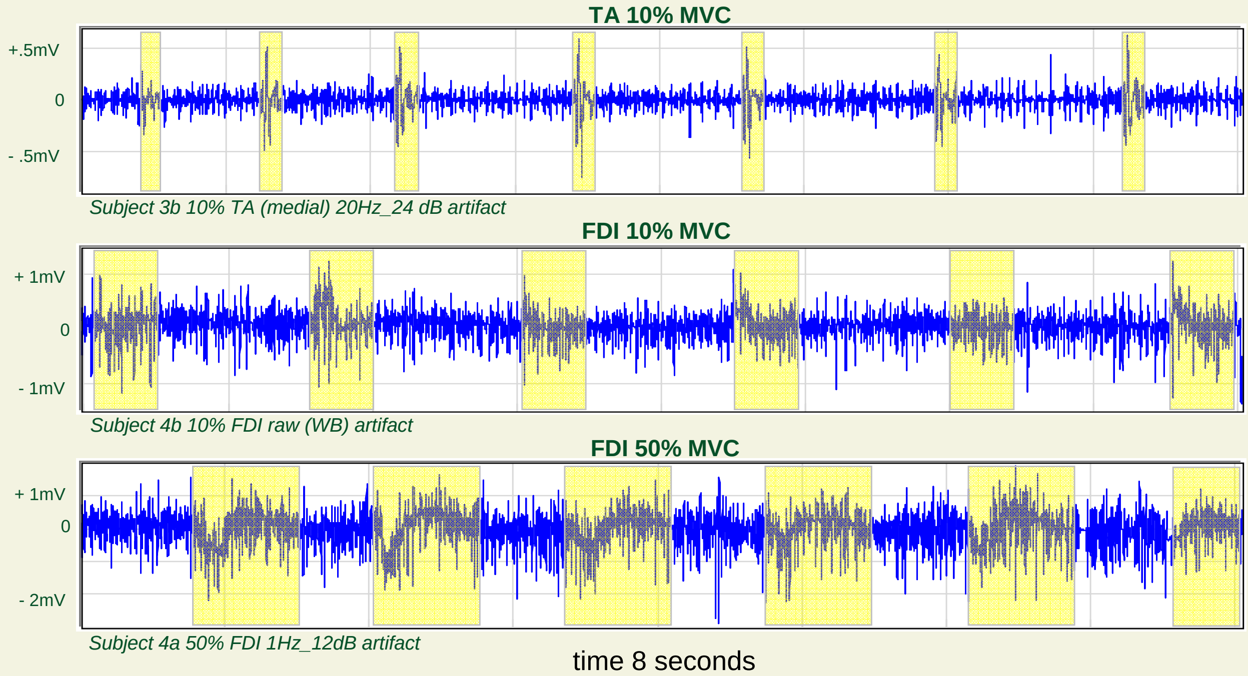
35: Example of Movement Artifact in EMG Signal



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Example of movement artifact in EMG signal:

The movement artifacts are highlighted in yellow in these sample EMG signals. Notice that at low contraction levels, the movement artifact can significantly alter the amplitude of the signal and may cause confusion in the interpretation of the sEMG signal, as the artifact appears to be part of the sEMG signal. At higher contraction levels, the movement artifact may be harder to identify within the EMG signal.

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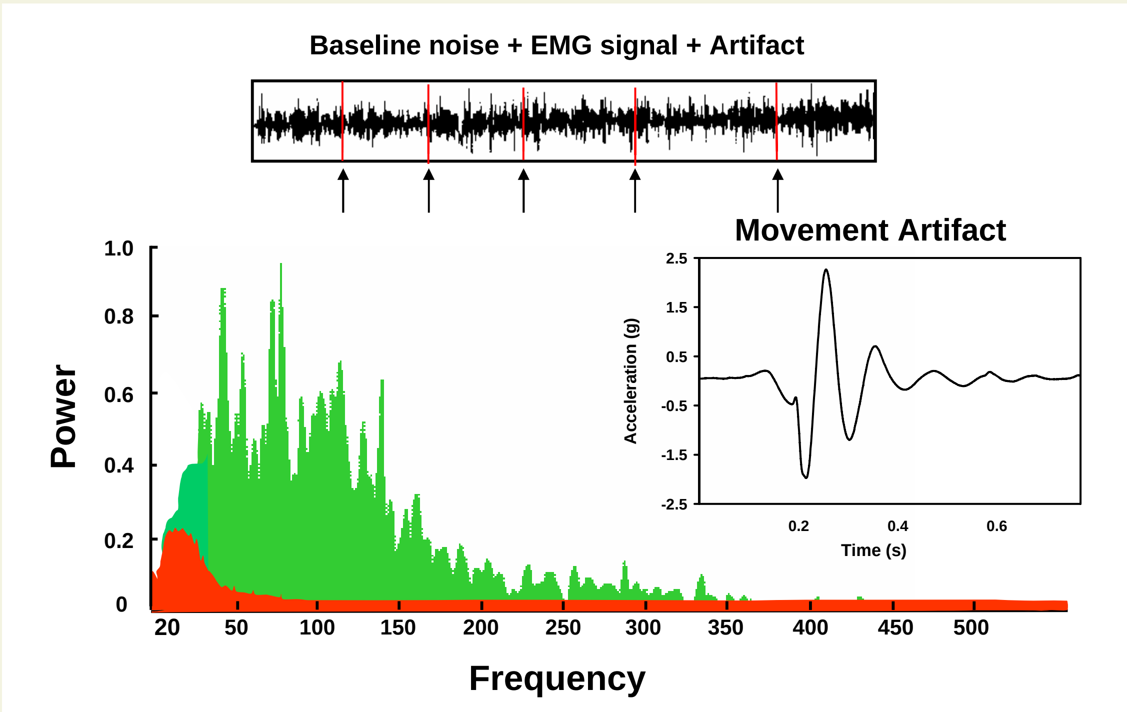
36: Noise Contamination of EMG Signal: Movement Artifact



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Noise contributions to the EMG signal:

The signal in the box at the top of the slide is an sEMG signal acquired during a contraction in which a movement artifact was induced. The location of the movement artifact is indicated by the vertical arrows. An expanded plot of the movement artifact is shown in the lower frame on the right. This motion artifact is comparable in amplitude and shape to that caused during a heel strike while walking. The frequency spectrum of this artifact together with that of the baseline noise is shown in red. Note that it has a considerably greater amplitude than that of the baseline noise (shown in a previous slide) and the bandwidth generally ranges from 0 Hz to 50 Hz, occasionally it may be higher.

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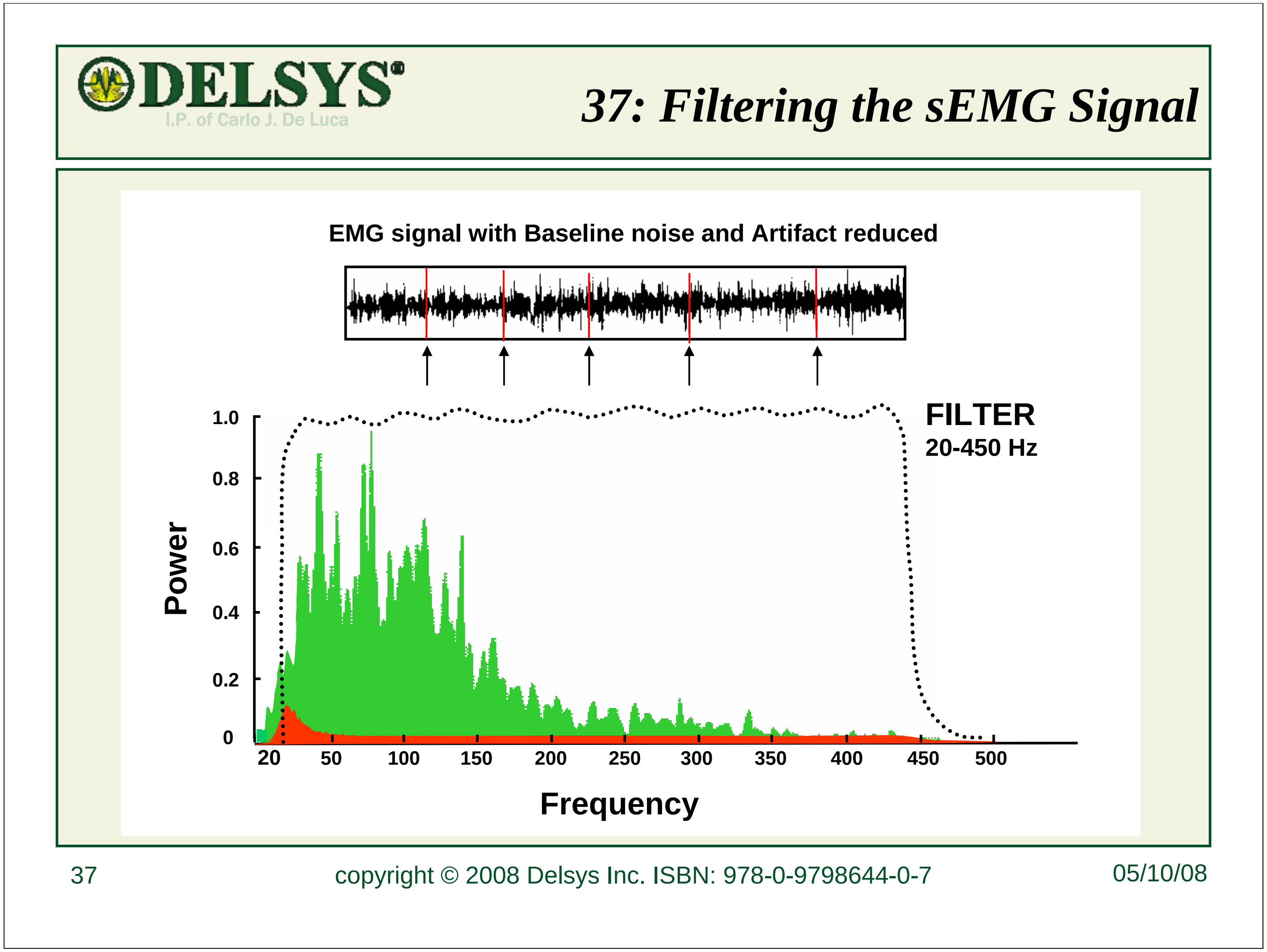

Filtering the EMG signal:

The spectra of both noise sources are shown superimposed on that of the sEMG signal. Much, but not all of their contribution can be removed by judicious filtering. At the high end, a cut-off point at 450 Hz truncates the contribution from the baseline noise without removing any significant contribution from the sEMG signal. At the low-frequency end, a cut-off point at 20 Hz is recommended. This point is contested by other investigators, but the following slide will present evidence in support of this position.

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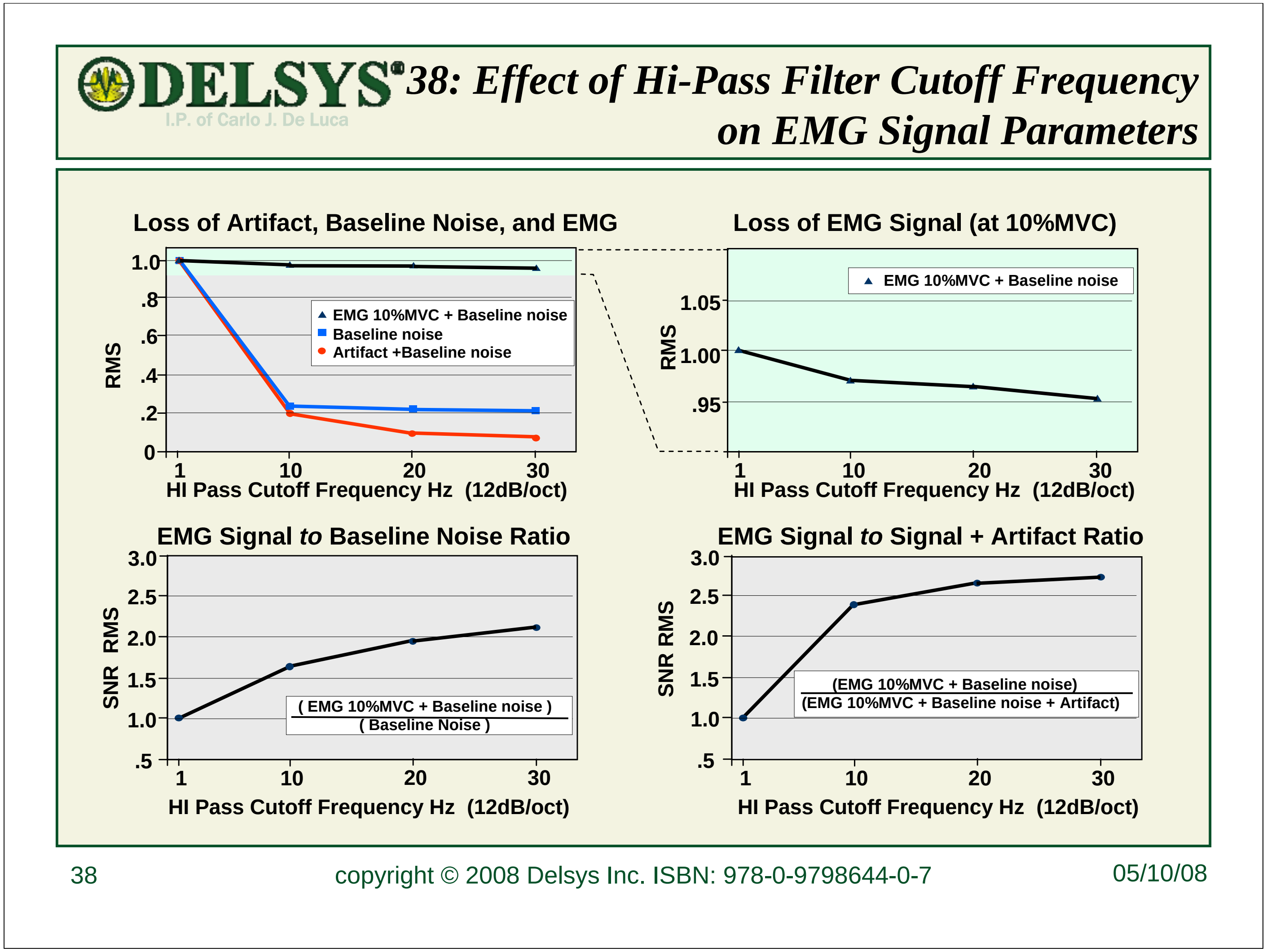

Effect of Hi-Pass filter cutoff frequency on EMG signal parameters:

Top left panel -- Losses in the RMS value of the sEMG signal (black), the Baseline noise (blue), and the movement artifact (red) when the signal is filtered with a high-pass (low-frequency cut-off) at 1, 10, 20 and 30 Hz. Approximately 80% of the noise is removed at 10 Hz, with only 3% loss in the sEMG signal (top right panel). However, an additional 10% of the movement artifact is removed at 20 Hz, with no appreciable additional loss of sEMG signal. Filtering at 30 Hz does not appear to provide any real benefits in noise reduction, while it removes approximately an additional 1% of the sEMG signal.

The benefit of filtering at 20 Hz may be seen in the bottom two panes, where the signal to noise ratio increases only marginally at 30 Hz. It should be noted that for movement artifacts having a wider bandwidth, the cut-off frequency should be greater than 20 Hz.

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39: Effect of Hi-Pass Filtering Compared to Sensor Location

	High Pass -3dB 10Hz → 20Hz	Slope dB/oct 12dB → 24dB	Shift 2cm
RMS Amplitude			
Resting Noise (RMS)	↓10 - 20%	↓<6%	
Resting Noise + Artifact (RMS)	↓10 - 50%	↓<13%	
sEMG signal (10% -100% MVC)	↓ <2%	↓<1%	19 - 38%
sEMG signal + Artifact (10% -50% MVC)	↓ <4%	↓<3%	19 - 38%
Median Frequency (Hz)			
sEMG signal (10% -100%MVC)	↑ <3%	↑<1%	10 - 20%
Signal to Noise Ratio			
Resting Noise + Artifact Signal (artifact reduction)	↑20 - 36%	↑4 -10%	
sEMG signal (10% -100% MVC)	↑11 - 28%	↑<7%	
sEMG signal + Artifact (10% -50% MVC)	↑11 - 28%	↑<7%	

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Effect of hi-pass filtering compared to sensor location:

Note that a 1 cm shift in the location of the sensor introduces a dramatic variation in the amplitude of the sEMG signal, in the range of 10 to 40%. This is far greater than that resulting from filtering. Thus, in terms of amplitude consistency, electrode positioning (inter-subject comparison) and re-positioning (intra-subject comparison) is more important for obtaining a greater signal to noise ratio.

FOR MORE INFORMATION ON SENSORS go to Appendix A: sEMG Sensor Factors.

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40: How to Reduce Movement Artifact

- **Remove excessive hairs. Moderate hair can remain**
- **Clean the skin with alcohol to improve electrical contact with electrode**
- **Use a good adhesive to maintain contact**
- **Do NOT use gel electrolyte**
- **High pass filter the sEMG signal at 20 Hz**

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41: Recommendation:
Detecting the sEMG Signal

- **Active Sensor of High quality signal**
  - Reduces cable artifact
  - Reduces noise contamination
- **Differential detection**
  - Reduces ambient electrical noise
- **Fixed Inter-electrode spacing (Preferably 1 cm)**
  - Maintains constant frequency bandwidth
  - Reduces cross-talk
- **Effective Electrode-Skin preparation for sEMG sensor and Reference electrode**
  - Reduces Noise contamination
  - Reduces ambient electrical noise
  - Reduces movement artifact
- **Locate sensor in the belly of the muscle**
  - Reduces cross-talk
  - Increases signal to noise ratio
  - Do not place sensor on the tendon or on the innervation zone

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Section 3:
Force – sEMG Signal Relationship

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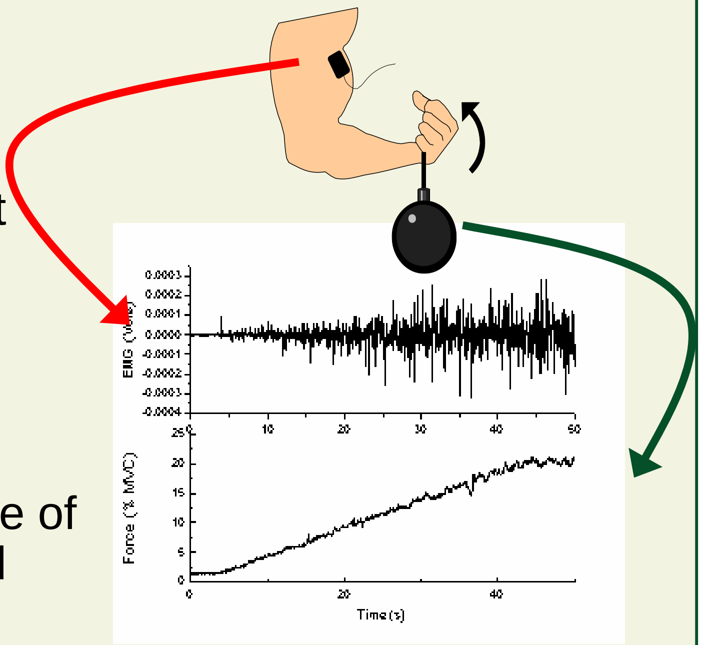
43: The sEMG Signal and Force

- **Where is the sEMG signal originating?**
  – The muscle of interest
  – Cross-talk from other muscles
- **Where is the force originating?**
  – Relation between force of muscle monitored and joint torque



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

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The SEMG signal and the Force:

The panel on the right illustrates the most basic and most used property of the sEMG signal, the relationship between the sEMG signal and the force output of a muscle. Note that as the amplitude of the sEMG signal increases, so does the force. However, the detected force and the sEMG signal are almost always contaminated by contributions from other muscles (this is referred to as cross-talk). Often, investigators use technology and techniques that yield higher amplitude signals believing that they have higher fidelity signals, whereas the quality of the detected signal is likely compromised by contributions from other muscles. For some purposes this contamination may not be problematic, but for finer, more precise work it can be misleading, causing improper interpretations and false conclusions.

The detected sEMG signal and force that are to be analyzed for physiological or biomechanical information will provide incorrect, and perhaps even deceptive information if the two questions posed in the slide cannot be answered with a reasonable degree of assurance. If one intends to relate the force produced by a specific muscle with the sEMG signal detected by a sensor, then the sEMG sensor should be minimally contaminated with information from other muscles (**cross-talk**) and **noise** sources (to be discussed later) and the recorded force should originate from the muscle on which the sEMG sensor is placed. The latter point may be difficult to achieve as externally located force sensors measure the torque at a joint. Nonetheless, all efforts should be made to maintain linearity between the change in the force and the change in the sEMG signal so that the relative comparison remains correct.

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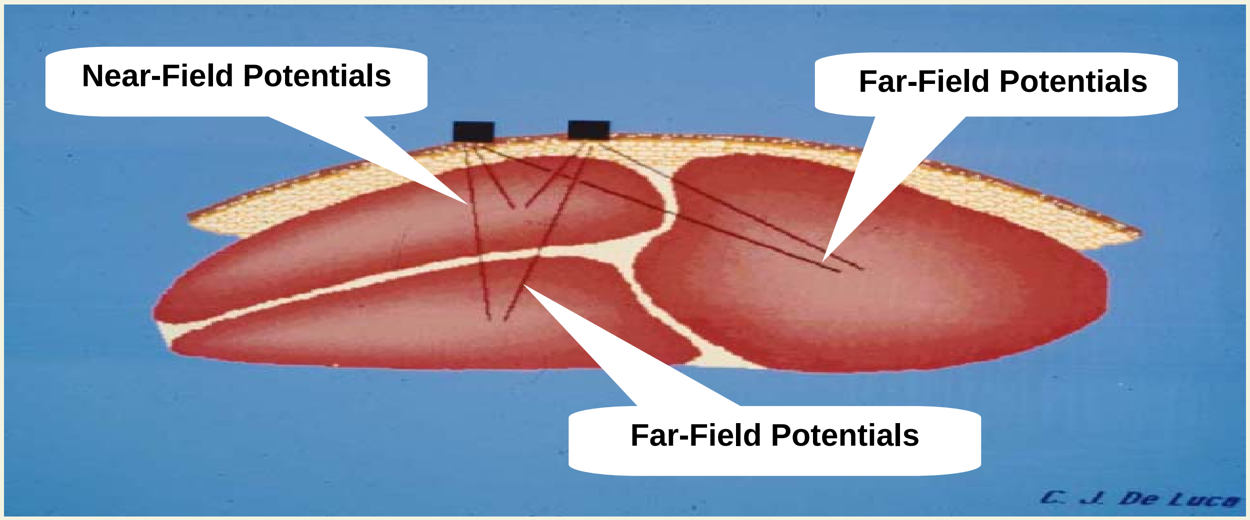
44: Where is the Detected sEMG Signal Originating? Cross-Talk?

- **From the muscle being monitored or elsewhere?**
- **Where is the sensor located?**
- **What are the dimensions of the sensor?**



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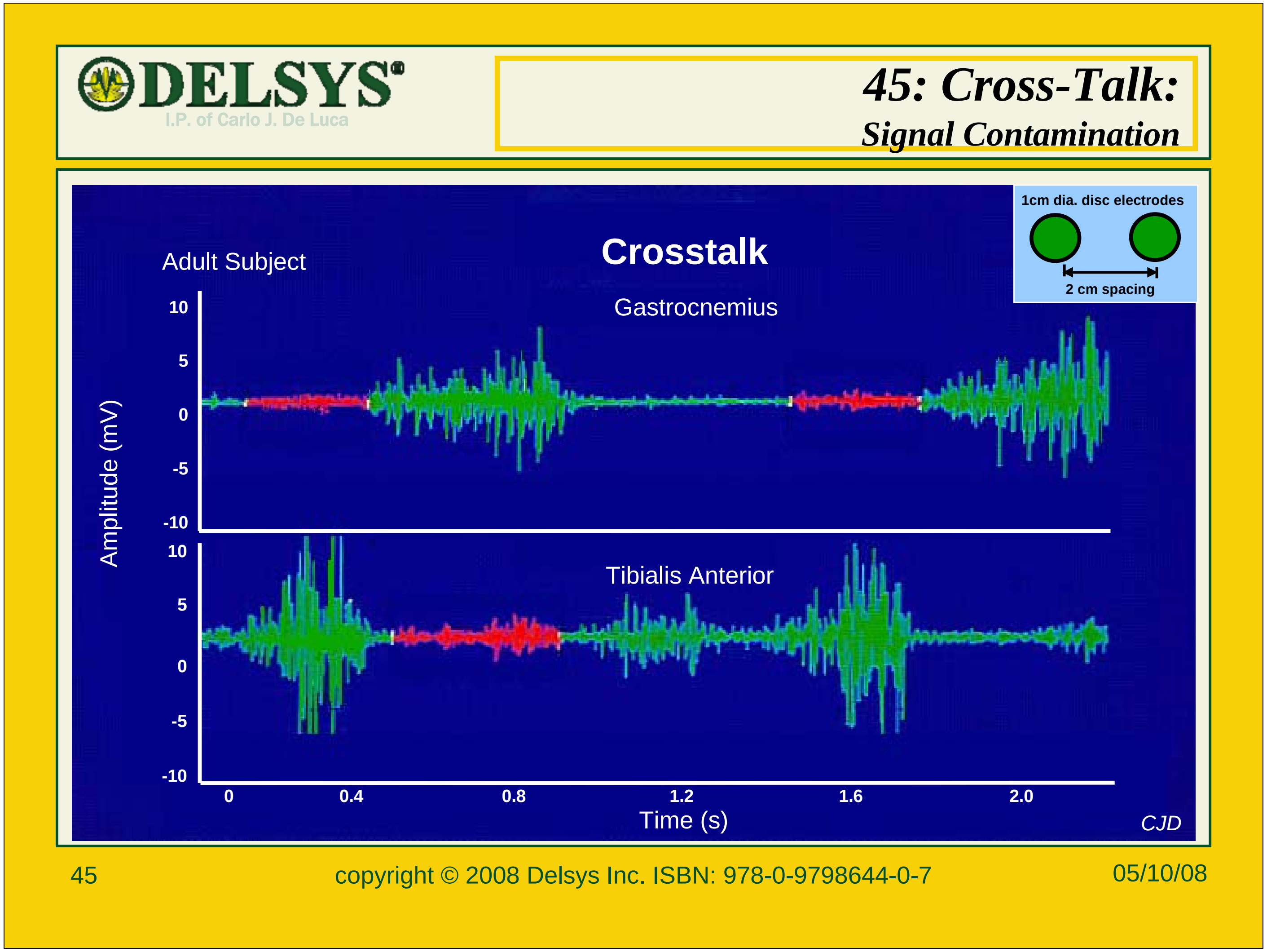
Where is the detected sEMG signal originating? Cross-talk?

For accurate and proper application of sEMG, the user should consider the origin of the signal. If a sensor is placed in a particular location above a group of muscles, then the detected sEMG signal will originate from all the muscles in the proximity. The information in such signals is limited to the activation of the whole group of muscles and to the force contribution of the group of muscles.

If one wishes to perform more precise measurements, then the sensor should be located above individual muscles. If the intent is to compare the performance of a muscle with respect to another or to compare the performance of one muscle performing identical tasks among several subjects than the cross-talk from adjacent muscles becomes problematic.



Cross-talk: Signal Contamination:

The use of sensors with large electrode area and large inter-electrode spacing invariably leads to detection of cross-talk which is often misinterpreted as activity from the monitored muscle. In clinical applications this misunderstanding may lead to false diagnosis. In the research field it may lead to a basic misunderstanding of the performance of the monitored muscle.

The data for this example were collected during a gait cycle of a normal subject with the sensor configuration shown in the top right hand corner. Note that the signal highlighted in red is a cross-talk signal that originates in the other monitored muscle. With sensors having smaller electrodes and shorter inter-electrode spacing, the cross-talk signal would be substantially smaller. Proof will be provided in the following slides.

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46: How is Cross-Talk Measured?

- **Detect sEMG signal from monitored muscle. Detect sEMG signal from detected muscle and nearby muscles. (Explained in next slide.)**
- **Electrically stimulate the muscle of interest and detect signal on adjacent muscles(3 to 10 %)**
  - *De Luca CJ and Merletti R, Surface Myoelectric signal crosstalk among muscles of the leg, EEG and Clin. Neurophysiol., 69: 568-575, 1988*
- **Frequency spectrum of cross-talk EMG has a lower bandwidth than the main EMG signal**
  - *De Luca CJ. The use of surface electromyography in biomechanics. Journal of Applied Biomechanics, 13: 135-163, 1997.*

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How is cross-talk measured?:

The first method will be described in the next two slides as it is the easiest to perform. The third method, dealing with power spectra of the sEMG signal will not be discussed, as it requires knowledge of spectral analysis and spatial filtering.

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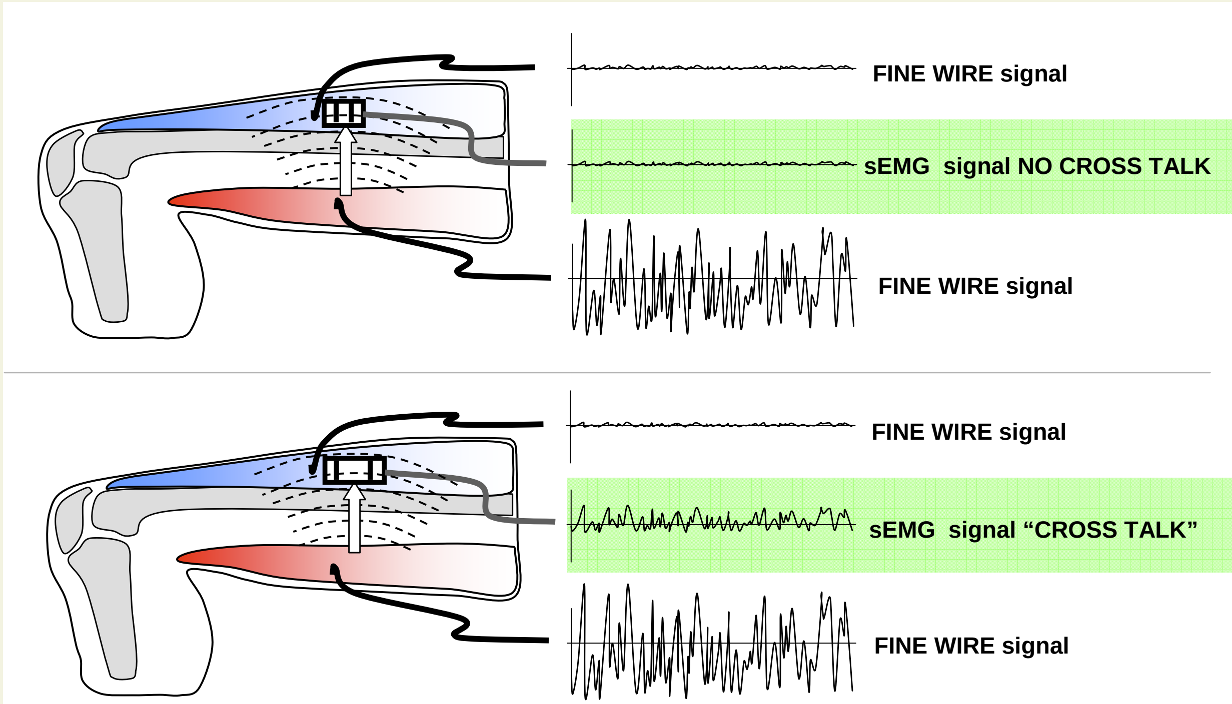
47: Cross-Talk Measurement:

Via the Indwelling Wire Approach



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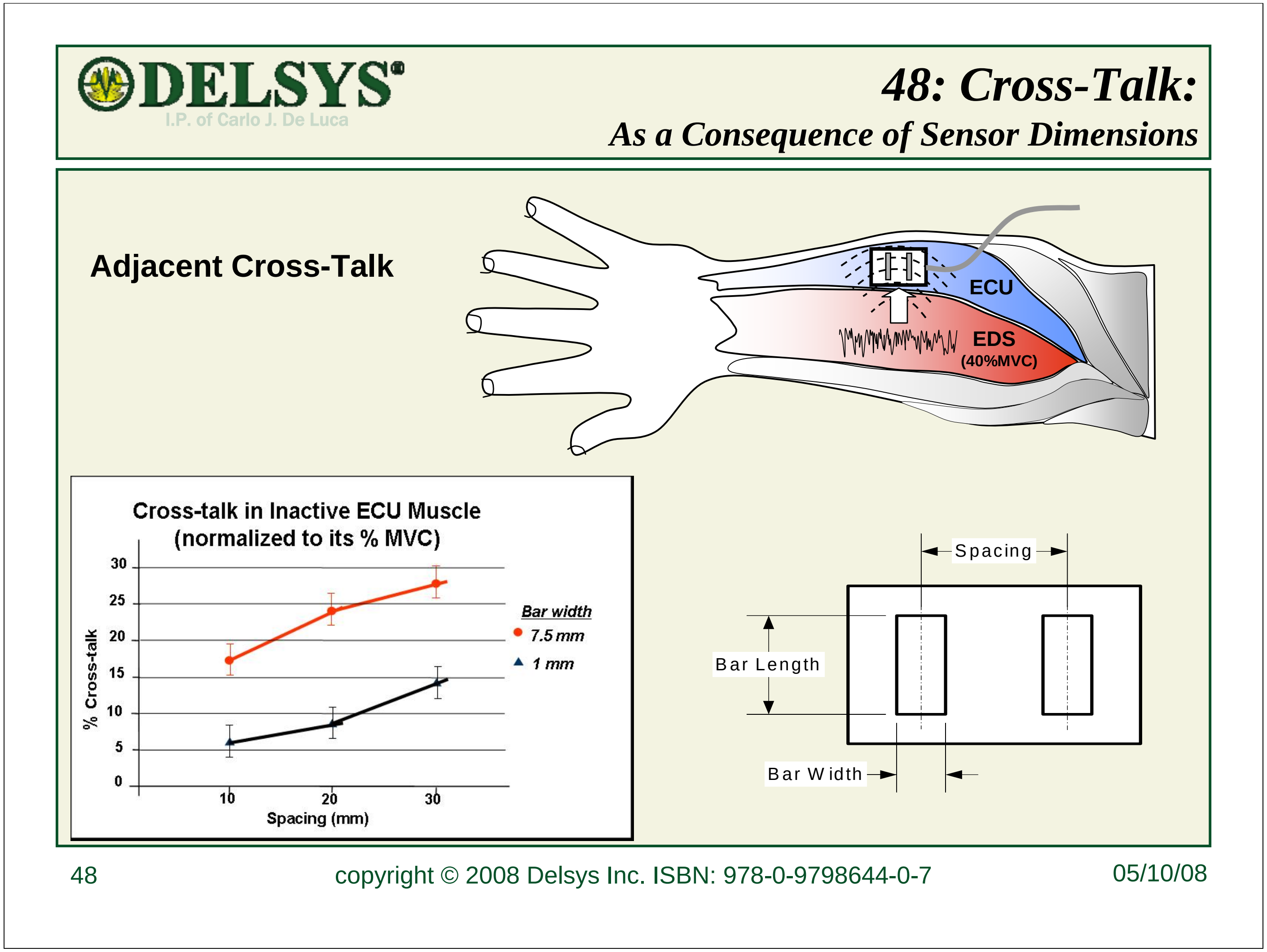
Cross-Talk measurement:

1. Place a fine-wire sensor in the muscle (red) generating a cross-talk signal.
2. Place an sEMG sensor and a fine-wire sensor on and in the muscle (blue) to be monitored.
3. Relax the muscle that is monitored (blue) – verify by lack of activity in both the surface and indwelling sensors. -- <u>Top Panel</u>
4. Contract the muscle (red) that generates cross-talk.
5. If there is no signal from the fine wire and surface sensors, then there is **NO** cross-talk -- <u>Top Panel</u>
6. If there is no signal from the fine wire sensor and there is a signal from the surface sensor, then there **IS** cross-talk. -- <u>Bottom Panel</u>



Cross-Talk and Sensor Dimensions:

The amount of cross-talk detected is greatly affected by the dimensions of the sEMG sensor. Cross-talk measurements were made on the Extensor Carpi Ulnaris with surface sensors whose electrode surface and inter-electrode spacing varied.

Note that as the inter-electrode spacing and the area of the electrode increase, the cross-talk increases. The 1 cm inter-electrode spacing and the 1 mm thick electrode has the lowest cross-talk of all the tested combinations. Note that the commonly used sensor dimensions of 2 cm inter-electrode spacing and the electrode dimensions of 7.5 X 10 mm detects 4 times the amount of cross-talk as the 1mm X 10mm.

It follows that smaller than 1 cm inter-electrode spacing might produce even less cross-talk. However, practical issues such as electrical shorting of the electrodes during sweating and lower signal amplitudes become a concern.

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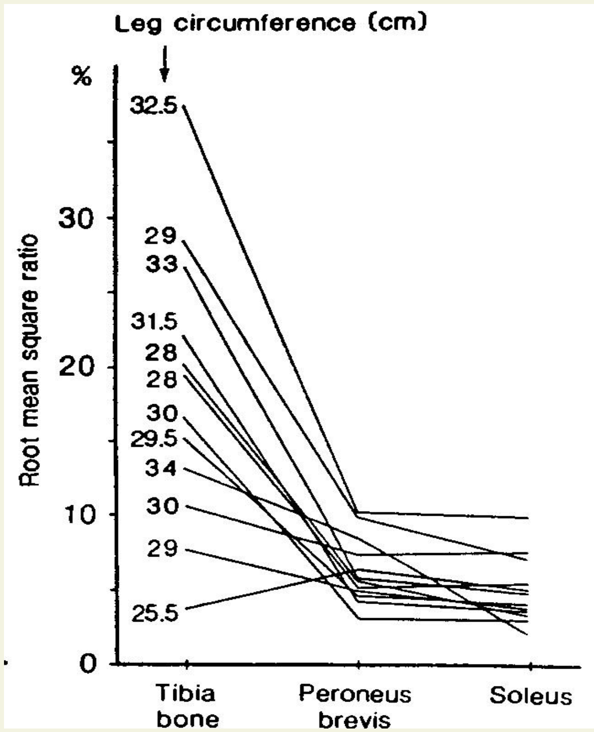
49: Cross-Talk Measurement:

Via Electrical Stimulation



Stimulation applied to the Tibialis Anterior

Cross-talk values range From 3%-10%

De Luca CJ and Merletti R. Surface myoelectric crosstalk among muscles of the leg. Electroencephalography and Clinical Neurophysiology, 69: 568-575, 1988.

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Cross-Talk from Electrical Stimulation:

These are results from the second technique for measuring cross-talk described in slide #47.

The Tibialis Anterior muscle was electrically stimulated and the sEMG signal was detected above the Tibialis Anterior, above adjacent muscles, and above the Tibial bone. Note that in this arrangement an EMG signal is detected on top of a bone, clearly indicating that the signal does not originate below the sensor. The sensor used in this measurement was a Delsys DE2.1 sensor having an inter-electrode spacing of 10 mm and a bar width of 1 mm.

Note that the amplitude of the cross-talk signal does not appear to be correlated to the circumference of the leg, a point that is in agreement with the modeling work of Lowry M. *et al*. (2007) which showed that the EMG signal propagation is influenced by the anisotropy of the surrounding tissue, specifically the ratio of fatty tissue to muscle tissue.

Note that the amount of cross-talk is in the same range as that measured with the technique in the previous slide, if the cross-talk from the 1mm X 10mm bar sensor is compared.

Lowry *et al*. 2007 on pubmed: http://www.ncbi.nlm.nih.gov/sites/entrez?db=pubmed&uid=17482677&cmd=showdetailview&indexed=google

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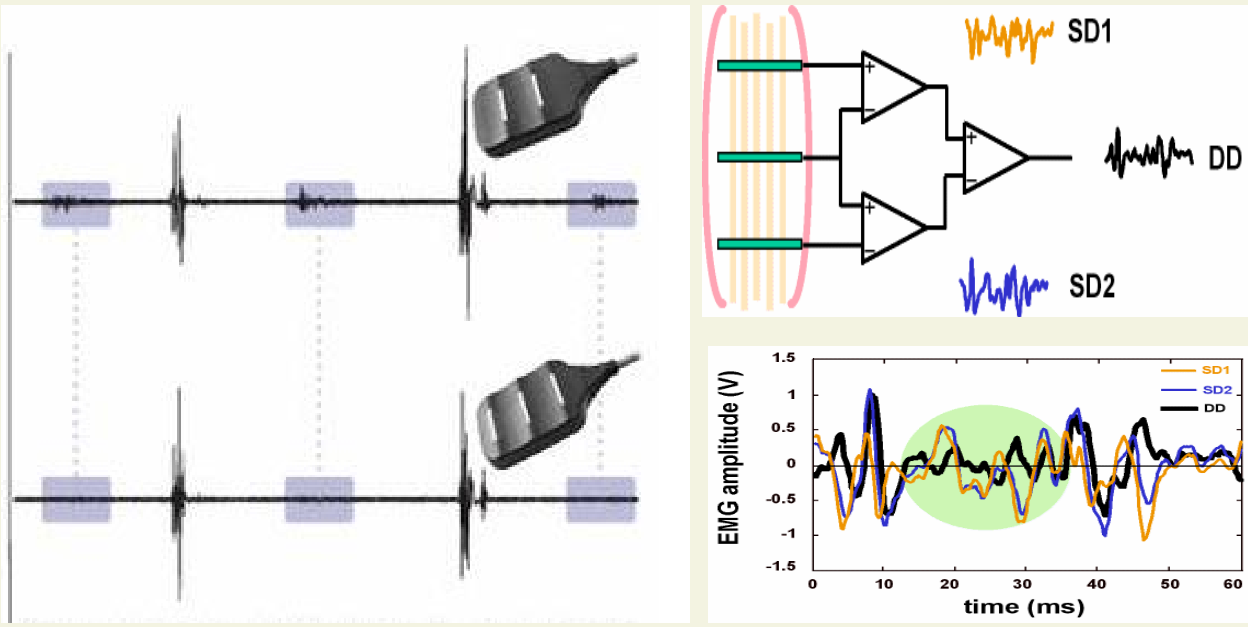
50: Cross-Talk Reduction – 1:
With the Double Differential Sensor



Broman H, Bilotto G, and De Luca CJ. A note on non-invasive estimation of muscle fiber conduction velocity. *IEEE Transactions on Biomedical Engineering*, 32: 341-344, 1985.

Cross-talk elimination with the double differential sensor:

The simplest practical method for reducing cross-talk is to use the double differential (DD) sensor, first described in the above reference. As may be seen in the top right-hand quadrant, the DD sensor consists of two stages of differential amplification. A non-common mode signal such as a cross-talk signal originating from adjacent muscles, will not be removed by the signal differential (SD) amplification. However, at the input of DD amplification, the cross-talk signal appears as a common-mode signal and is, in large part, eliminated by the DD amplification. This point is illuminated in the panel at the bottom right which presents the signals at the output of the SD amplification stage and the signal at the output of the DD stage. The green shaded region shows the DD signal (black) having lower amplitude that the SD signals (orange and blue). In the time interval highlighted by the green region, the amplitude of the DD signal is lower than both the SD signals, indicating that some cross-talk signal has been eliminated.

The performance of the DD sensor may be seen in the panel on the left where the sEMG signal was detected simultaneously from the Flexor Carpi Radialis muscle with a SD sensor and a DD sensor. The shaded areas indicate a crosstalk signal that is eliminated in the signal detected by the DD sensor.

FOR MORE INFORMATION ON SENSORS go to Appendix A: sEMG Sensor Factors.

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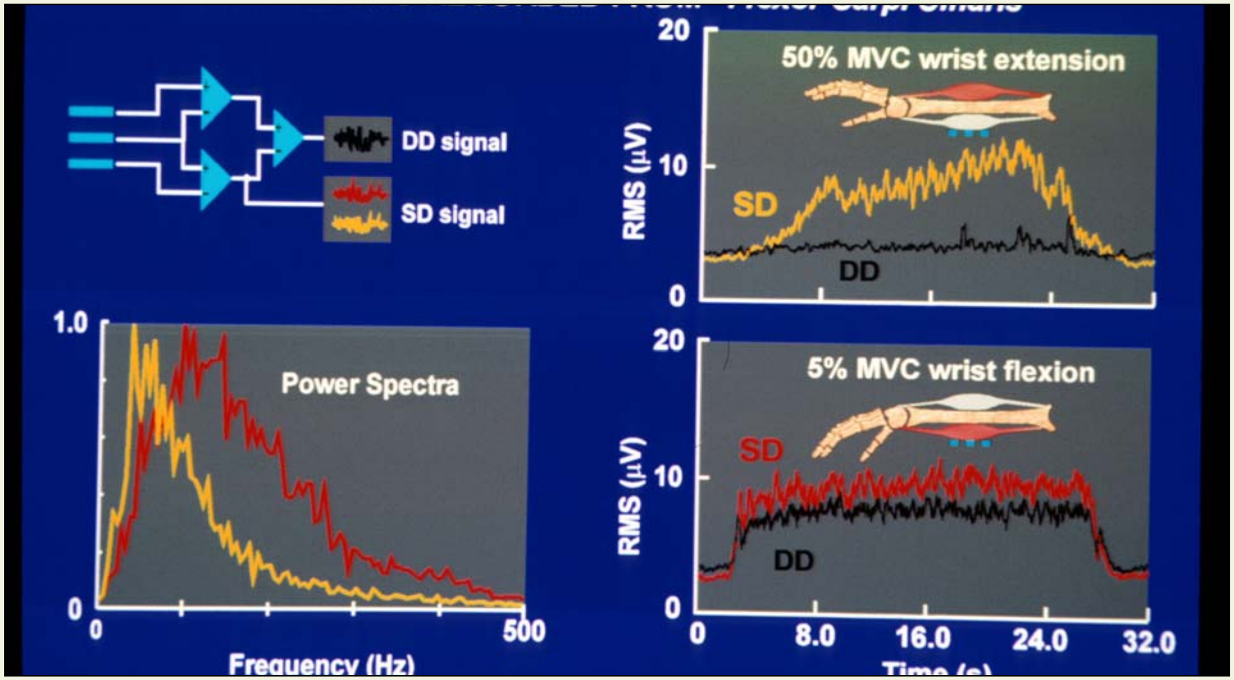
51: Cross-Talk Elimination – 2:
With the Double Differential Sensor



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

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This slide shows how the Double Differential (DD) sensor reduces cross-talk or can be used to reduce the presence of cross-talk (black signal).

.

Another example showing the effectiveness of the Double Differential (DD) sensor for eliminating cross-talk:

The top left panel shows the DD configuration along with a tap on a single differential (SD) configuration. (Note that the SD configuration tap is not available from the commercial version of the DD sensor.) This sensor detects both the SD sEMG signal and the DD sEMG signal.

In the two panels on the right, the sensor is placed on Flexor Carpi Ulnaris. In the top right panel a strong 50% MVC extension contraction is performed; in the bottom right panel a weak 5% MVC flexion contraction is performed.

The top right panel shows during a strong contraction, only a weak (<10 uV) SD sEMG signal (yellow) is detected and virtually no DD sEMG signal (black). Because the signal is weak, it does not originate from the muscle below the sensor, and must originate from the contracting antagonist muscle (Extensor Carpi Ulnaris). Thus it is a cross-talk signal and it is eliminated by the DD detection (black).

The bottom right panel shows that during a weak flexion contraction, a weak SD sEMG signal (red) and a similarly weak DD sEMG signal are detected indicating the signals detected by both configurations originates in the nearby flexor muscle. If the signal had originated elsewhere the SD signal would be small (as seen in the previous panel) and the DD signal would be near zero.

The bottom left panel shows the frequency spectra of the SD sEMG signals during weak flexion (red) and strong extension (yellow). Note that in the spectrum of the SD sEMG signal from the extension contraction (yellow) the higher frequencies are considerably attenuated. This is indicative of “spatial filtering” which acts as a low-pass filter (one that removes higher frequencies) when the signal must travel through the tissues of the body. This observation supports the notion that the SD signal originates at a greater distance, or from some other muscle.

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52: Summary:
How to Reduce Cross-Talk

- **Use sensor with small:**
  - inter-electrode spacing (1 cm)
  - detection surfaces
- **Place sensor in the middle of the muscle surface**
- **Use a double differential sensor**
  - Broman H, Bilotto G, and De Luca CJ. A note on non-invasive estimation of muscle fiber conduction velocity. *IEEE Transactions on Biomedical Engineering*, 32: 341-344, 1985

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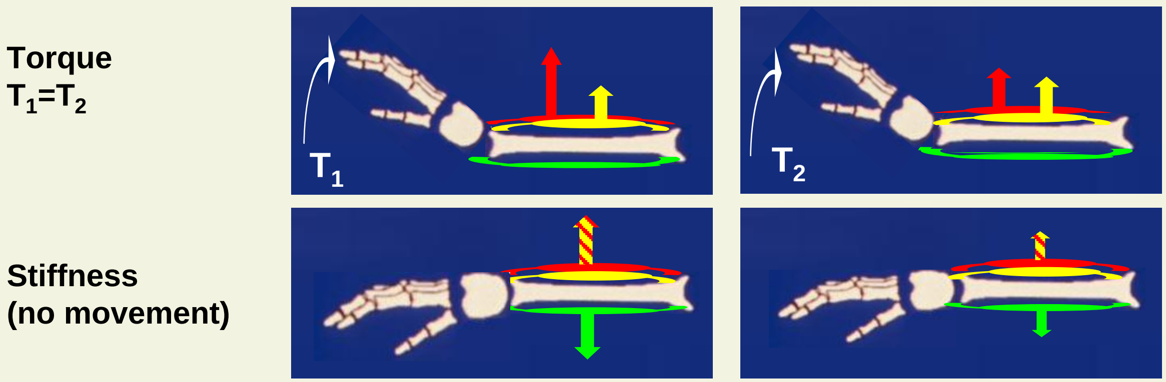
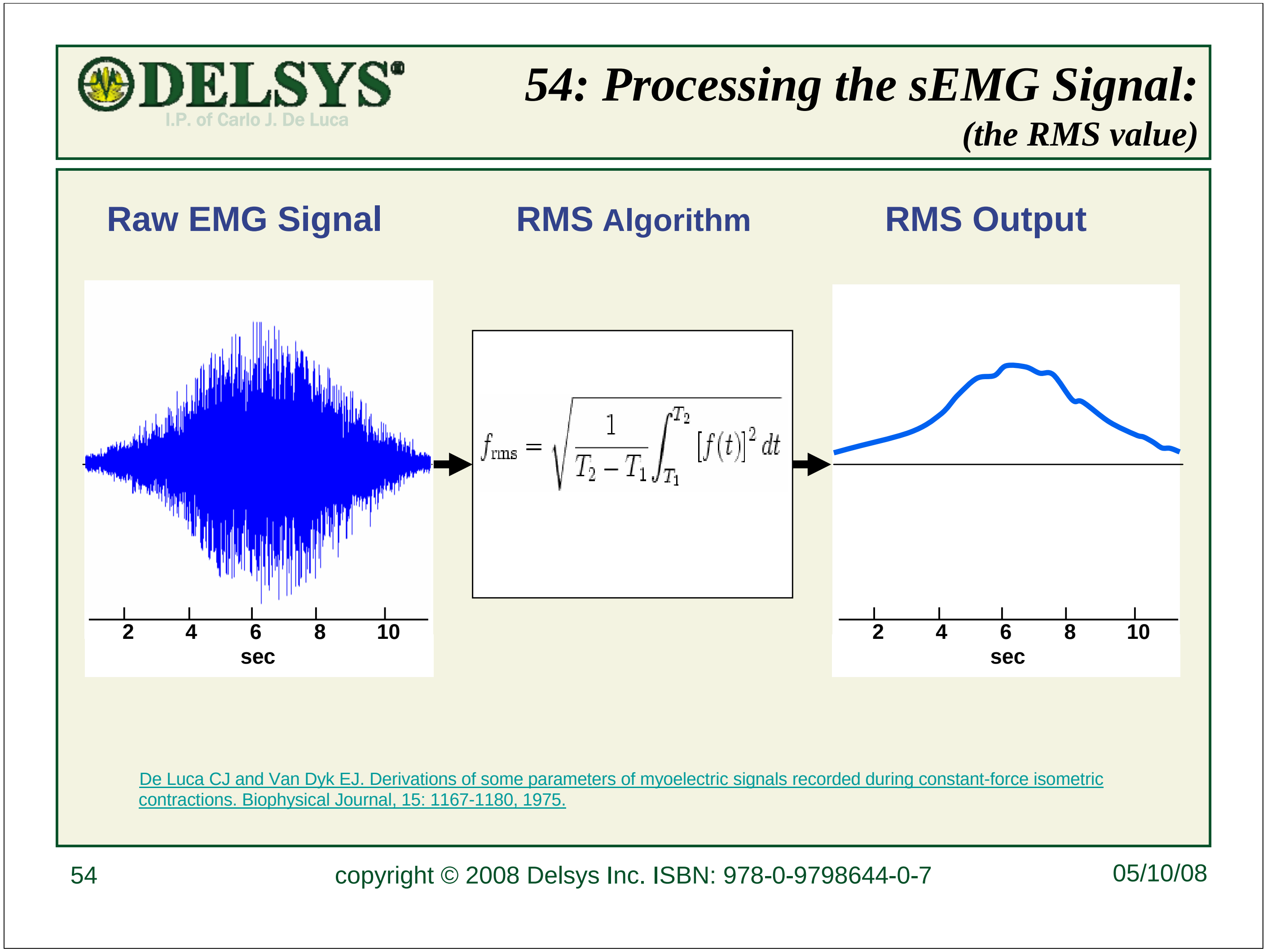
53: Where does the Torque (Force) originate?

- **External force sensors measure the sum of the force about a joint.**
- **The sEMG sensor measures the activity of one muscle**
- **The relative force contribution from each muscle may not remain constant in the presence of pain or injury**



Where does the torque (force) originate?:

When the sEMG signal is related to the force being generated by the muscle, it is important to understand the relationship between the measured force and the force actually being produced by the muscle. As is seen in the diagram, the force or torque measured about a joint is the sum of all the forces acting on that joint. When more than one muscle is active, there are many finite combinations of synergist and antagonist forces that can produce a given torque about the joint.



Processing the sEMG signal (the RMS value):

The raw EMG signal must be processed before it can be used for most scientific purposes. The Root-Mean-Squared (RMS) value provides a measure of a physical property of the EMG signal, that is the energy of the signal. This makes it a more useful way of conceptualizing the EMG signal than other mathematical functions which have been used in the past, such as the mean rectified value and the integrated value.

Let the sEMG signal be represented by f(t). It is known that the amplitude of f(t) is a random value and can be approximated by a Gaussian distribution function (numerous references in the literature). The RMS function processes the signal to render a filtered and thus smooth amplitude. The greater the time interval T2 – T1, the greater the amount of filtering or smoothing.

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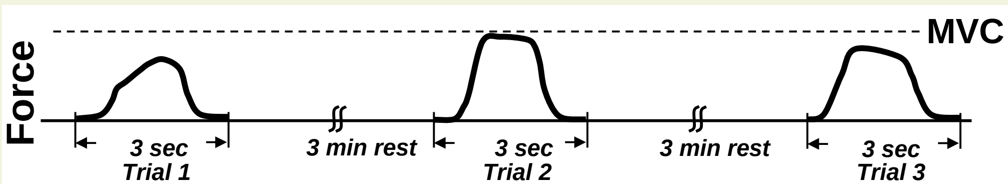
55: Comparing Across Subjects:
Normalization

- **Force: reference to Maximal Voluntary contraction (MVC)**
  - Useful for comparing patterns (amplitude and timing of EMG signals)
    - Choose greatest of the three values



- **EMG signal amplitude: not wise to normalize to maximal level**
  - The amplitude of sEMG signal is unstable above 80% MVC

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Comparing across subjects or comparing among different trials performed at different times (normalization):

In several of the previous slides it has been indicated that the amplitude of the sEMG signal may be influenced by a variety of factors unrelated to the physiological properties of the muscle. Yet sometimes it can be useful to compare the sEMG signal obtained from the same muscle in multiple subjects performing similar tasks, or to compare the sEMG signal from the same muscle of the same subject, but performed during different tests, say on different days. While the absolute value of the sEMG signal varies widely across subjects, we can normalize the signals to some constant value. The point of reference chosen depends on the data of interest. Often, the maximal voluntary contraction (MVC), or strongest contraction the subject can perform with that muscle when asked, is used as a reference point.

Note that even if the contraction is performed at the same force level, as would be the case for holding a weight, the sEMG signal must still be normalized if the sensors are removed between trials, especially if the trials are performed at different times.

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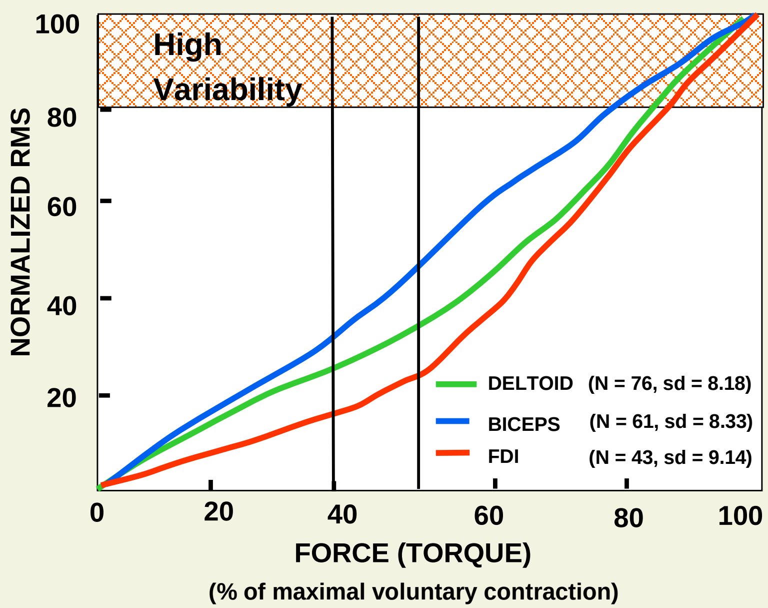
56: RMS of EMG Signal – Force:
Relationship During Isometric Contractions



- **Linear relationship 0 – 40% MVC, 50 – 100% MVC**
- **Non-linearity due to MU recruitment characteristics**
- **Control properties of EMG signal unstable 80 – 100% MVC**

Lawrence JH and De Luca CJ. The myoelectric signal versus force relationship in different human muscles, Journal of Applied Physiology, 54: 1653-1659, 1983.

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RMS of sEMG signal – force relationship during isometric contractions:

At contraction levels above 80% MVC the firings of the high threshold motor units are unstable. Motor unit action potentials from high threshold motor units have relatively higher amplitude, they fire slower, and they are recruited and derecruited as the force level fluctuates. In contrast, low threshold motor units have lower amplitude action potentials, and a greater frequency of firing.

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57: Cautious Use of sEMG – Force Relationship

- **Inter-muscle variation within a subject**
  - **(st. dev. = 4 to 6%) (1 cm spacing)**
  - Different fiber type ratios
  - Cross-talk
- **Intra-subject variation in same muscle**
  - **(st. dev. = 8 to 9%) (1 cm spacing)**
  - Possibly different electrode location (can be eliminated)
  - Different fiber type ratios
- **Intra-test repeatability**
  - Less with sensors not removed than with sensors removed

Lawrence JH and De Luca CJ. The myoelectric signal versus force relationship in different human muscles, Journal of Applied Physiology, 54: 1653-1659, 1983.

Cautious use of sEMG – force relationship:

While the relationship between the sEMG signal and force is often used in movement sciences, it must be remembered that there is a high degree of variation, not only between subjects but between different muscles of the same subject, in how the sEMG signal translates to force output of the muscle. The standard deviations for different types of experiments using the Delsys standard 1cm inter-electrode spacing are shown here.

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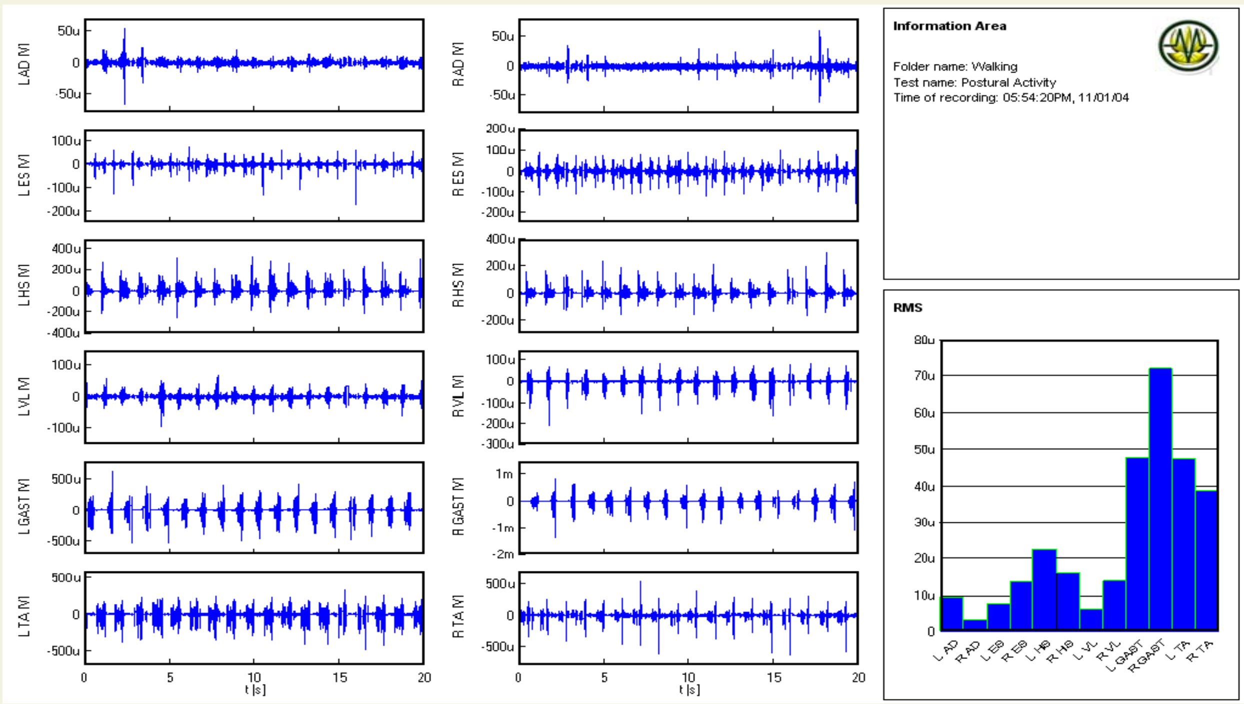
58: Relative Muscle Contribution During Standing: RMS of EMG Signal



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Relative muscle contribution during standing (RMS of EMG signal):

See here an example of the raw EMG signal (in left quadrants) and the corresponding RMS values of the individual muscles (bottom right quadrant). In this case, the RMS value is calculated over the epoch presented in the quadrants.

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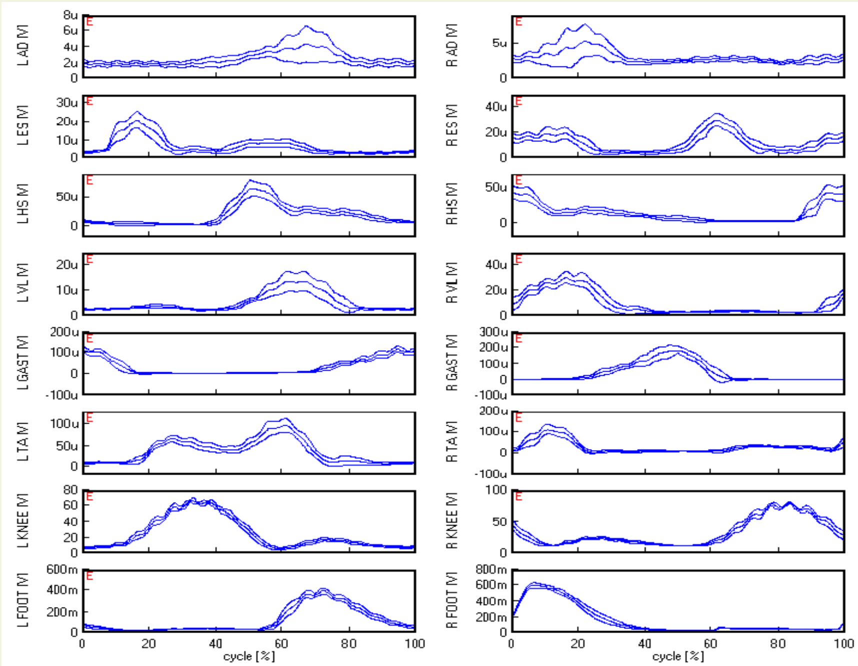
59: Gait Cycle Report (RMS)



Information Area

Folder name: Walking
Test name: Postural Activity
Time of recording: 05:54:20PM, 11/01/04
E = Envelope (RMS)
Window length 0.125000s, Overlap 0.062500s

Calculated parameters

	avgmin	std	time	avgmax	std	time
L AD	1.7	0.3	24%	4.3	2.2	67%
R AD	2.2	0.2	81%	5.3	2.2	22%
L ES	2.3	0.5	86%	20.9	4.3	16%
R ES	3.5	1.1	41%	29.8	4.9	62%
L HS	1.5	0.3	34%	64.0	13.7	51%
R HS	1.4	0.3	81%	43.5	9.7	95%
L VL	1.9	0.3	36%	13.7	3.9	67%
R VL	2.1	0.2	86%	30.3	4.6	16%
L GAST	-0.1	4.1	18%	113.5	13.8	0%
R GAST	0.2	7.2	68%	183.8	22.5	50%
L TA	5.3	3.1	91%	96.3	16.4	61%
R TA	2.2	8.7	25%	111.8	22.8	11%
L KNEE	5.0	1.4	59%	65.5	2.9	33%
R KNEE	11.5	1.0	53%	78.6	1.5	84%
L FOOT	14.3	0.6	18%	394.5	25.5	72%
R FOOT	0.0	0.0	59%	0.6	0.0	6%

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An example of Intra-test variability:

The mean (center trace) and the standard deviation (upper and lower trace) of the cyclic behavior of muscles in the back and lower limb (first six panels) and the joint angles of the knee and ankle during a gait step. These values were calculated by averaging over 12 steps whose time duration was normalized to 100%. In each step, the initiation of EMG activity had to be identified in order to synchronize the epochs.

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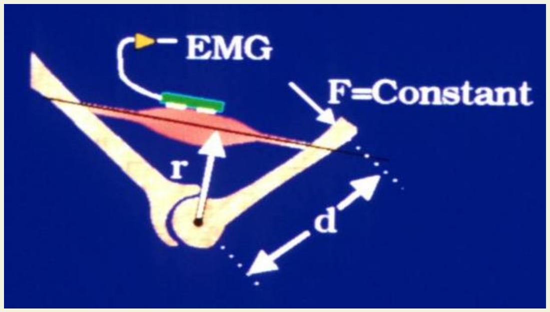
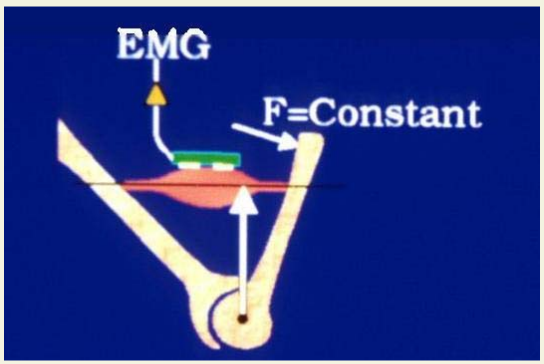
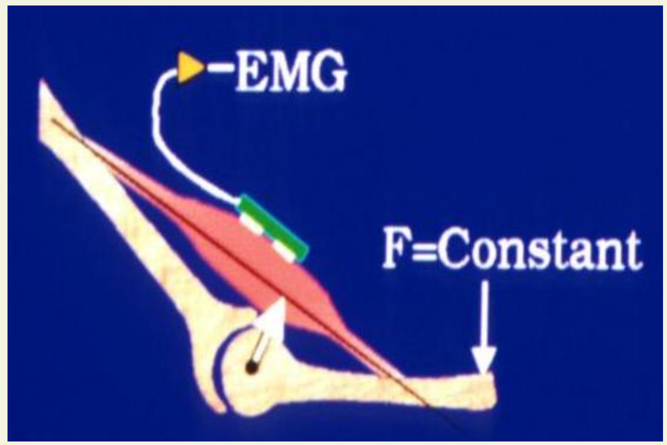
60: The Relationship Between Force and sEMG is NOT Linear in Dynamic Contraction



$$F(t) = (K)\left(\frac{r(t)}{d}\right)EMG_{RMS}(t)$$





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The relationship between force and sEMG is NOT linear in dynamic contraction:

Consider the case of a single muscle acting on a joint. When the muscle contracts over a period of time - *t* -, the length of the muscle shortens, the joint angle decreases, and the moment arm of the muscle (the distance from the muscle to the center of rotation of the joint) increases. The time course of this distance is defined as *r(t).* The monitored torque is equal to the force - *F* - times the distance - *d* -, where *d* is the moment arm of the measured force to the center of rotation. Thus we can write the equation in the top right quadrant where K is the factor that relates the RMS value of the monitored sEMG signal to the force produced by the contracting muscle.

Now consider the case where the monitored force - *F* - remains constant during the shortening contraction. From the equation and from the pictorial of the other quadrants it follows that the relationship between The RMS value of the monitored sEMG signal and the monitored force changes. As the moment arm *r(t)* decreases the force produced by the lengthening muscle must increase.

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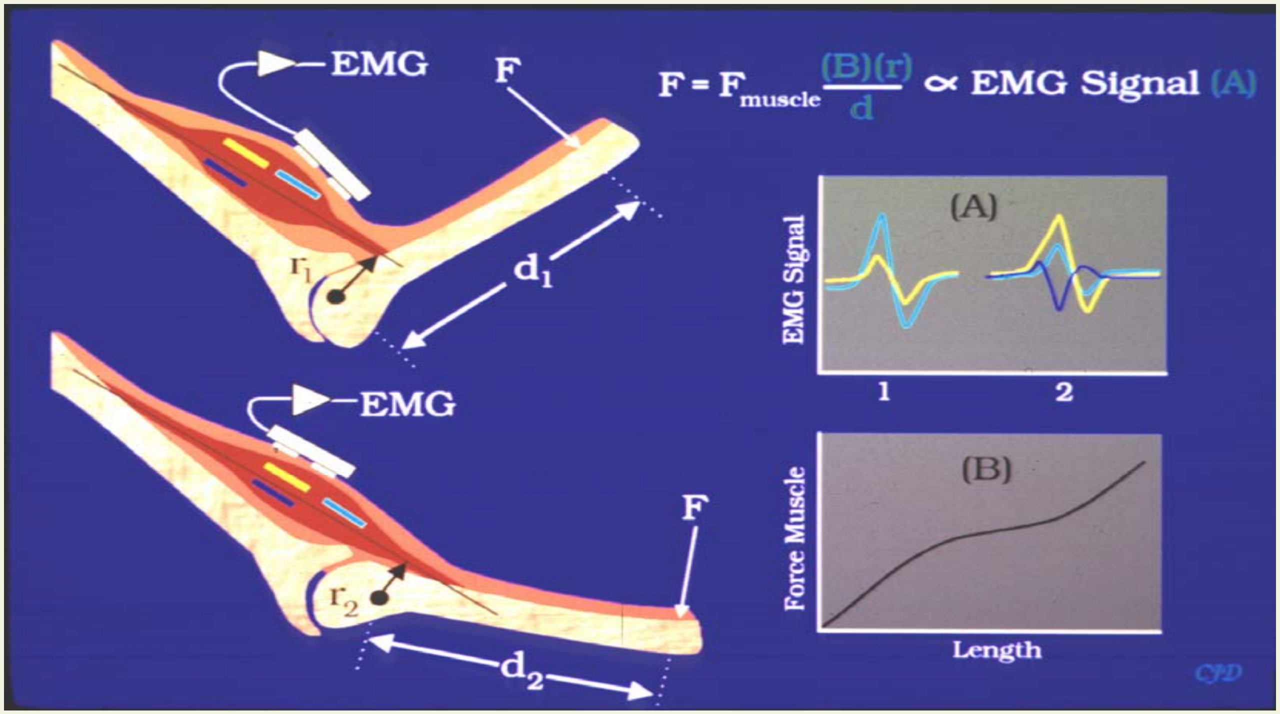
61: Effect of Electrode Displacement During Dynamic Contractions



Effect of electrode Displacement during dynamic contractions:

During a dynamic contraction, in addition to the change in the moment arm, there are two other factors that add to the nonlinearity between the force output and the EMG signal amplitude. The first factor is the change in the relative position of the source of the EMG signal and the sensor which remains attached to the skin as the muscle moves below the skin. This factor changes the spatial filter between the signal origin and the sensor, rendering a change in the amplitude and frequency spectrum of the signal. (See top panel on the right.) The second factor is the non-linear relationship of the force produced by the muscle and the length of the muscle. (See bottom panel on the right.)

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62: Summary:
Relationship between EMG Signal and Force

- **Isometric Contraction**
  - Linear between 0 to 40%, and 50 to 100% MVC
  - EMG signal Unstable between 80 and 100 % MVC
  - Valid if the relative contribution from agonist and synergist muscle remains constant
- **Anisometric Contraction**
  - Monotonic, but not linear
- **Force output is the sum of forces from all the contributing muscles**
  - Co-contraction (Stiffness) reduces monitored force

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Summary – Relationship between EMG signal and Force:

Isometric contractions are those in which the muscle produces force, but does not change length. In anisometric contractions, the muscle is allowed to lengthen or contract.

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63: Proper Use of sEMG:
Within a Subject

- **Monitor variation in performance of a muscle in a subject during;**
  - different tasks
    - Sensor not removed
  - different times
    - Sensors not removed
    - Sensor removed, but replaced in same location
- **Compare the relative contribution of individual muscles during a task**

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64: Proper Use of sEMG:

Across Subjects

Compare the contribution of a specific muscle across subjects during static or dynamic contractions

Compare the relative contribution of various muscles across subjects during static or dynamic contractions.

This operation is valid because the absolute value of the force is not obtained. The comparison is performed by normalization.

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Section 4: Activation Timing

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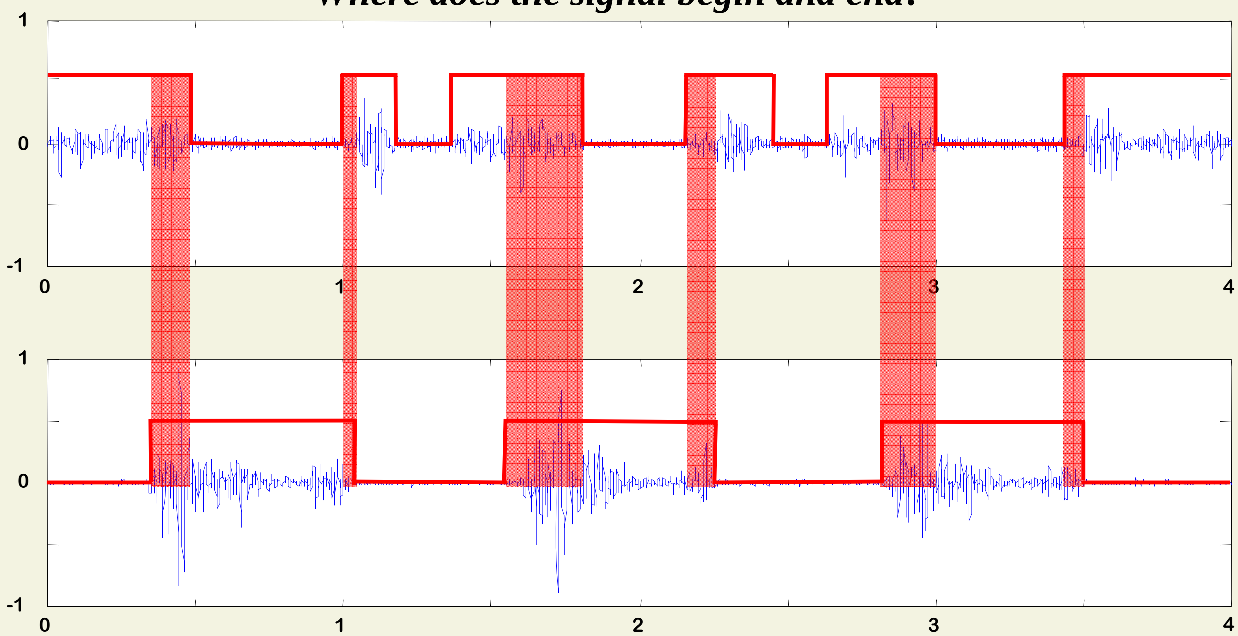
66: Activation Timing



Activation Timing:

One of the most common use of the sEMG signal is to determine when the muscle contraction begins and ends. That information establishes when muscles are acting as synergists and/or antagonists. In the example above, the top trace has a red line that indicates when the contraction begins and ends. The red shaded region indicates when the muscle in the top trace is co-activated with the muscle in the bottom trace.

The designation of the begin and end time is made difficult by the presence of noise and cross-talk. Of the two, the more damaging is the cross-talk. The noise is mostly constant, with the exception of the movement artifact, whereas the cross-talk varies in a fashion similar to the sEMG signal of interest.

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67: Activation Timing

- **Cross-talk and Noise blur the beginning and end of the EMG activation**

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Activation timing:

The presence of cross-talk and noise in the EMG signal contaminates the information concerning the behavior of the muscle being monitored. Some of the noise is inevitable, some can be reduced, and the cross-talk can be reduced or removed.

The following slides will describe procedures for dealing with noise when measuring the activation timing. Note that the example does not deal with cross-talk, which can be even more difficult to deal with, especially if it is not constant as would be the case during force varying contractions. In such cases, the sEMG signal should be recorded with the double differential sensor.

68: Resolution of Activation Timing:

Influence of Noise Level: Off-line Method

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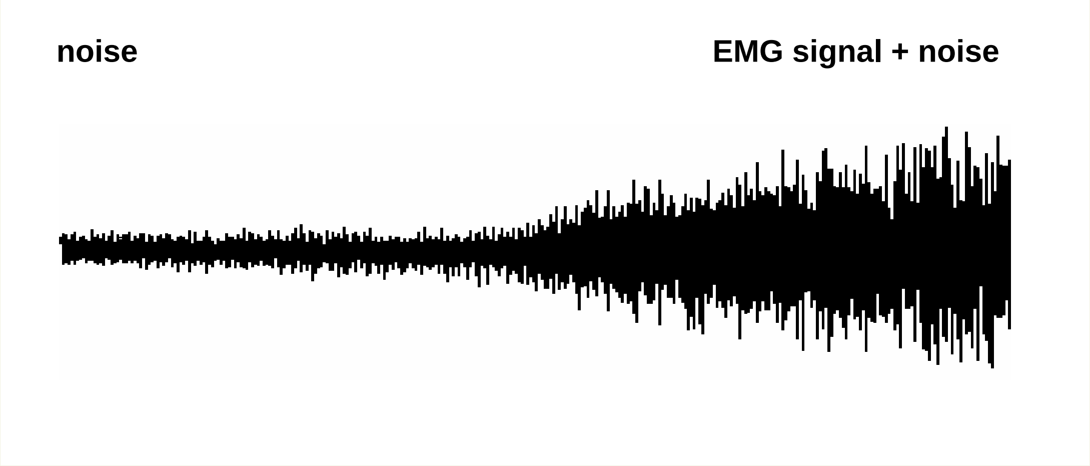

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Resolution of activation timing – influence of noise level: off-line method:

With baseline noise and the often erratic appearance of the EMG signal, finding the beginning of the signal, or activation timing, is not a trivial matter. Here we will see one method which is independent of the noise level. This is a sample of baseline noise and an sEMG signal at the beginning of a weak contraction, for which we will find the activation timing.

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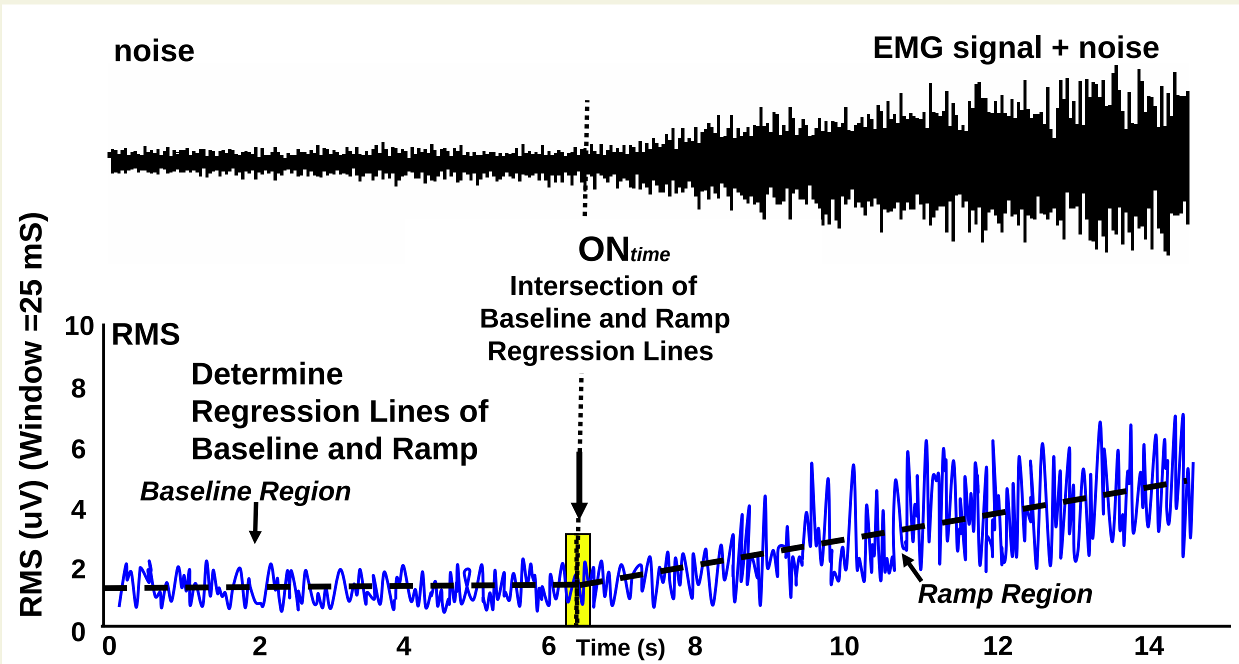
69: Resolution of Activation Timing:

Influence of Noise Level: Off-line Method



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

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Resolution of activation timing – influence of noise level: off-line method:

This method of determining where the sEMG signal begins is as follows:

- Find a segment of the signal that has a constant lowest level value.
- Calculate the RMS value with a window of 50 ms or less.
- Calculate the regression line for this segment.
- Follow the signal until it begins to increase, and calculate the regression for the segment with the increased signal.
- The point where the regression lines meet is the ON time.
- Perform reverse calculation for finding the OFF time.

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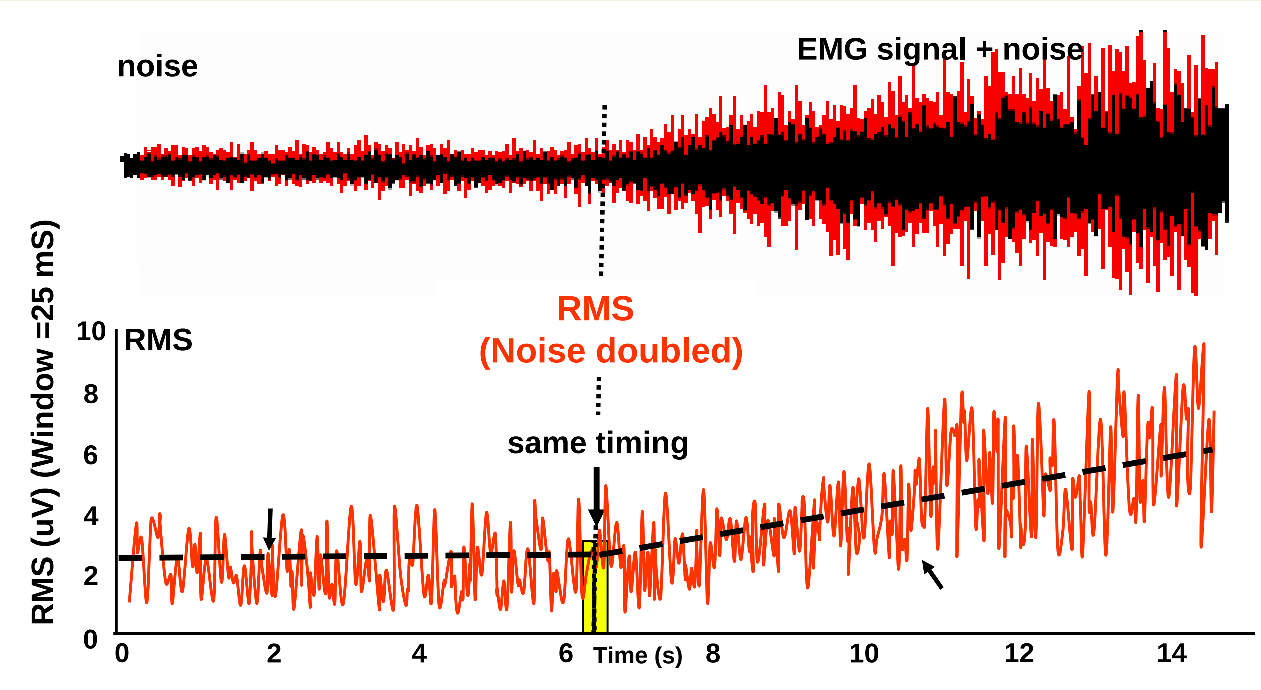
70: Resolution of Activation Timing:
Influence of Noise Level: Off-line Method



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

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Resolution of activation timing – influence of noise level: off-line method:

The procedure described in the previous slide is independent of the noise amplitude, as long as it is lower that that of the sEMG signal. This can be seen in this slide, where the noise level is doubled, but the activation timing found is the same.

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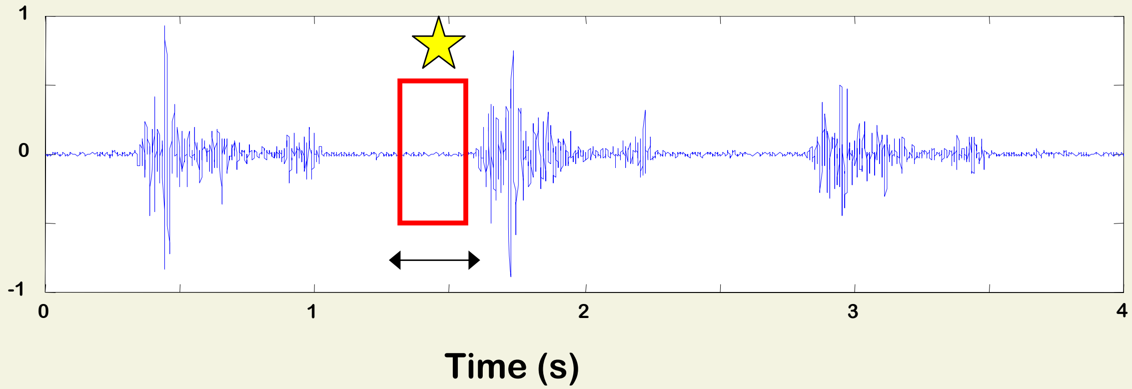
71: Detection of ON - OFF:

Where Does the EMG Signal Begin and End?



1. Sweep the time file with a window.

2. Calculate RMS value in window.

3. Set lowest value to noise level.

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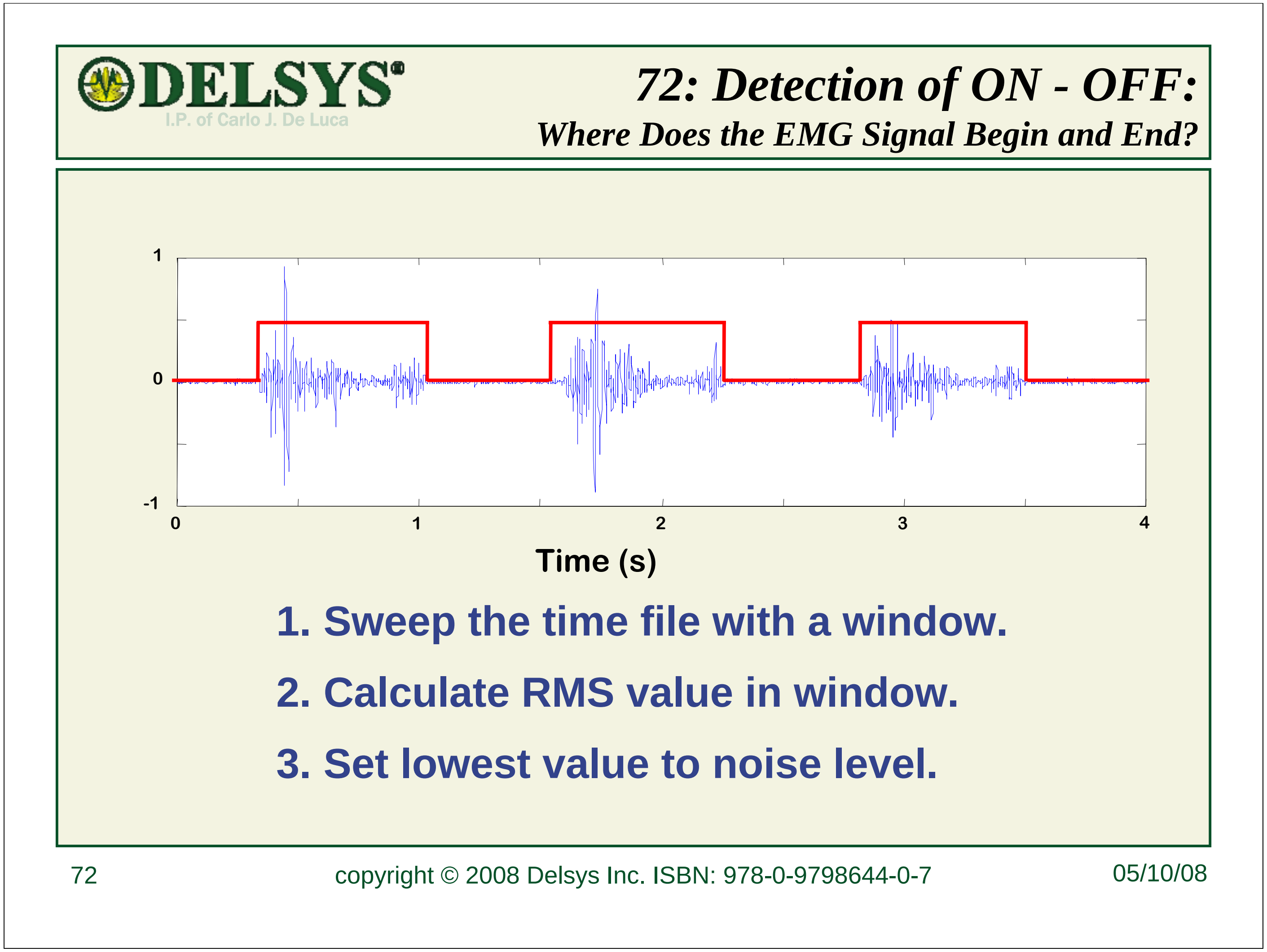
Detection of ON – OFF: where does the EMG signal begin and end?:

This is an alternative method of resolving baseline noise from the signal of interest. Begin with a window size of 50 ms. Gradually expand the window size as necessary to obtain consistent and realistic results. The lowest value of RMS calculated in the window is set to the noise level. The advantage of this method is that it does not require regression calculations and in some cases may be performed in real time.

Click here to animate slide



Detection of ON – OFF: where does the EMG signal begin and end?:

Anything with an RMS greater than that of the noise is considered to be part of the signal of interest, shown on this slide in the raised red rectangles.

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Section 5:
Peripheral Muscle Fatigue

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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**

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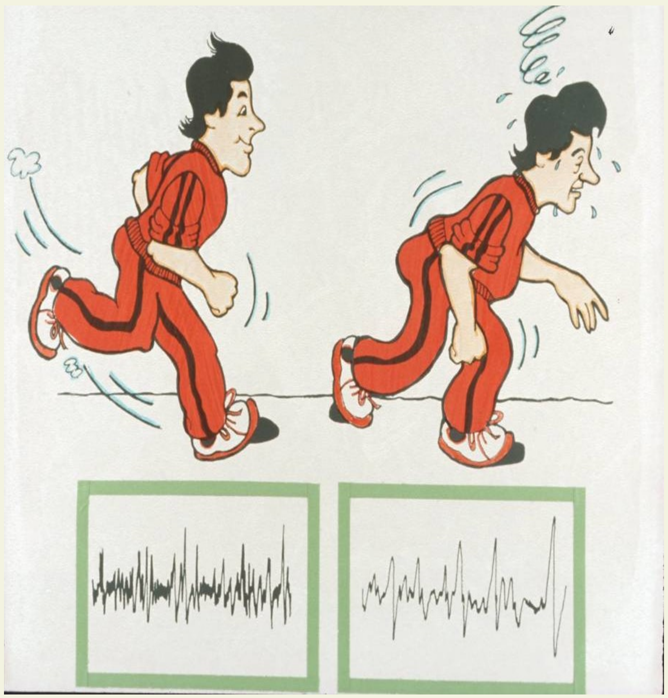
75: Fatigue and sEMG Signal Characteristics



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

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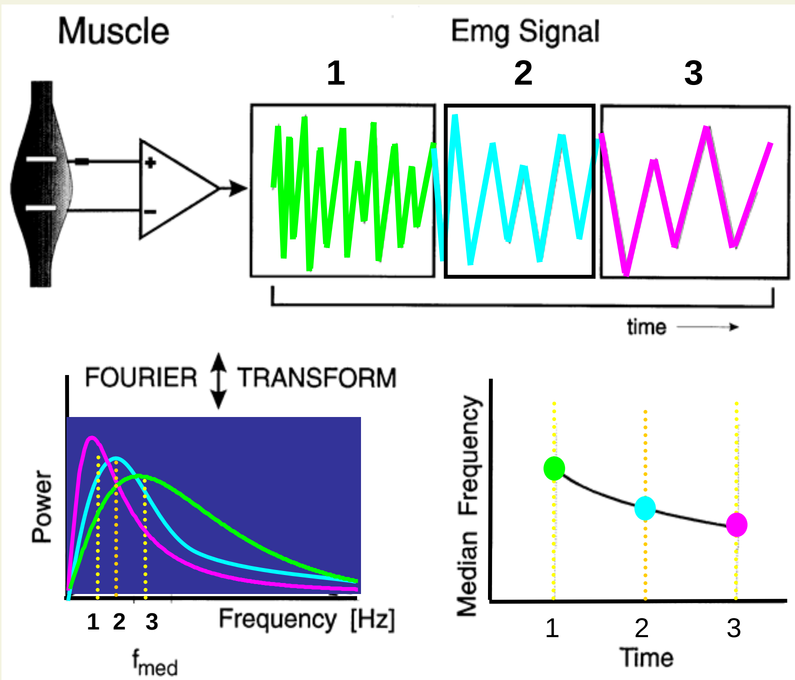
76: Effect of Fatigue on sEMG Signal



- **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.

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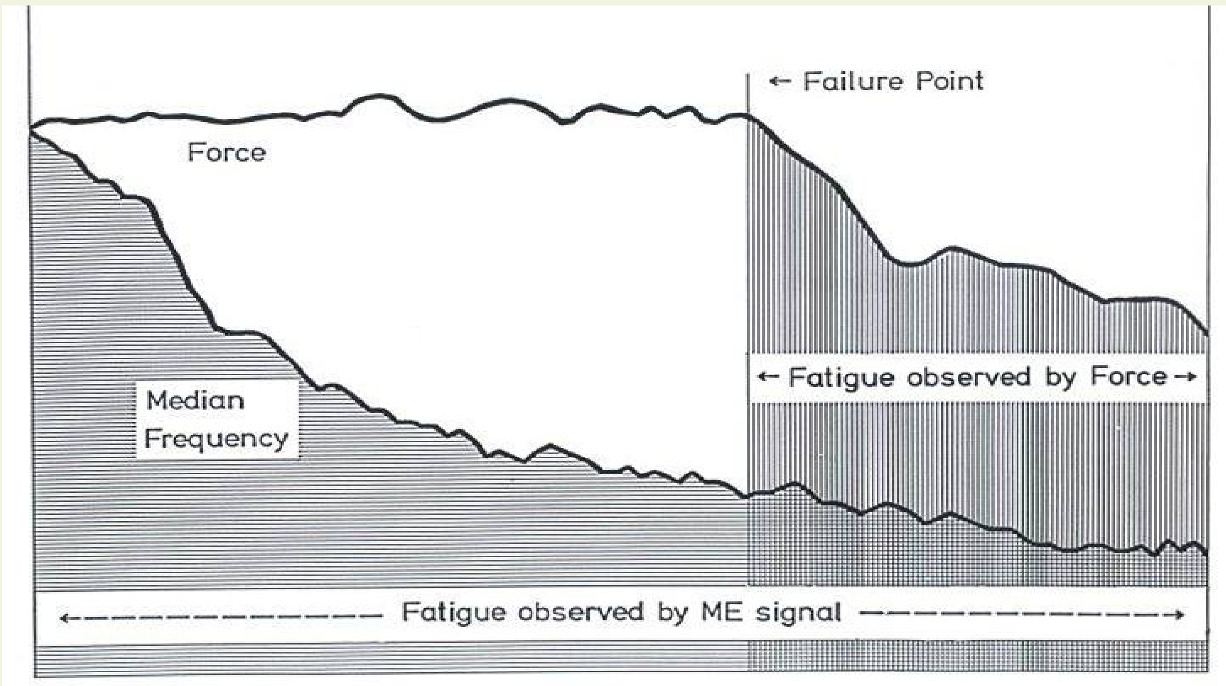
77: Why use the sEMG Fatigue Index?



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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 loosing 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.

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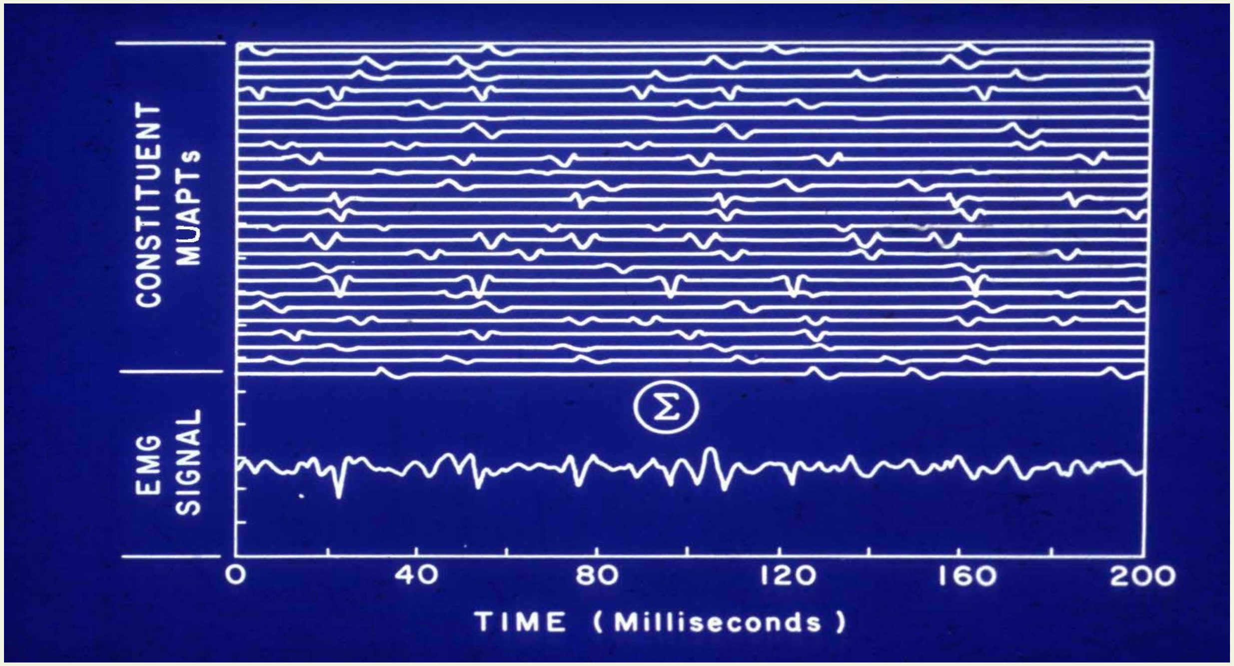
78: What Causes Spectral Compression?: Consider the Synthesized EMG Signal



Basmajian JV and De Luca CJ. *Muscles Alive (5th 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.

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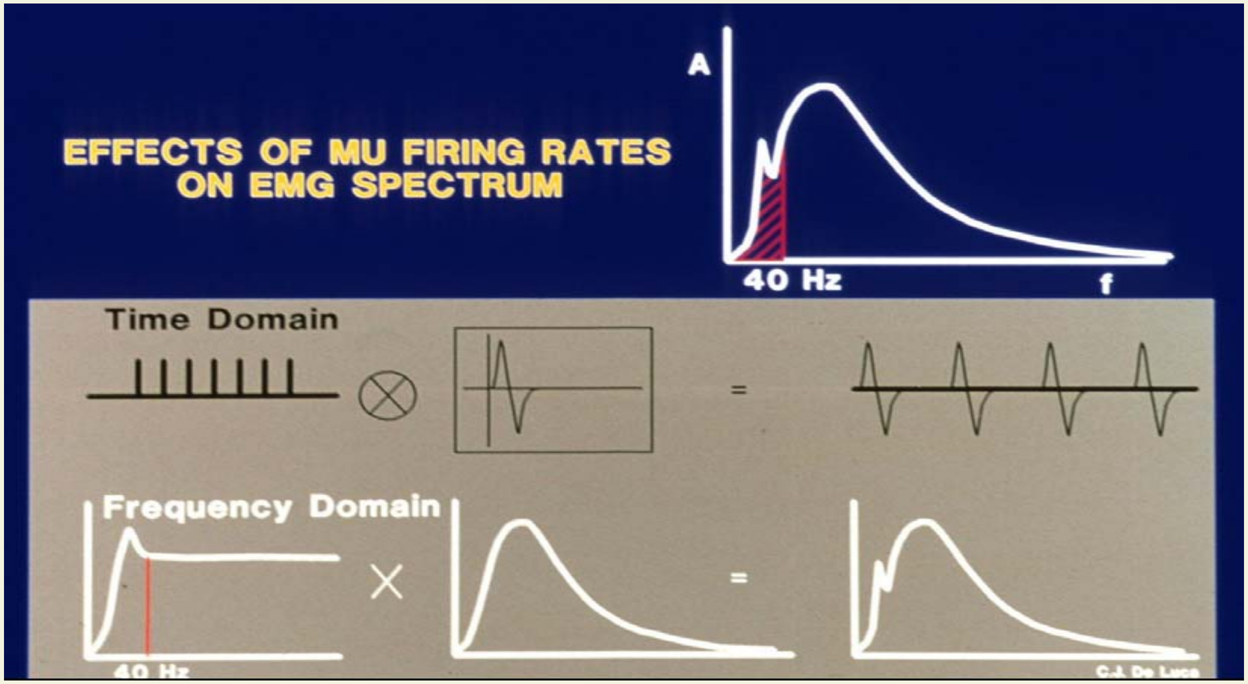
79: Contribution of Motor Unit Firing Rates on EMG Frequency Spectrum



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

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.

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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**

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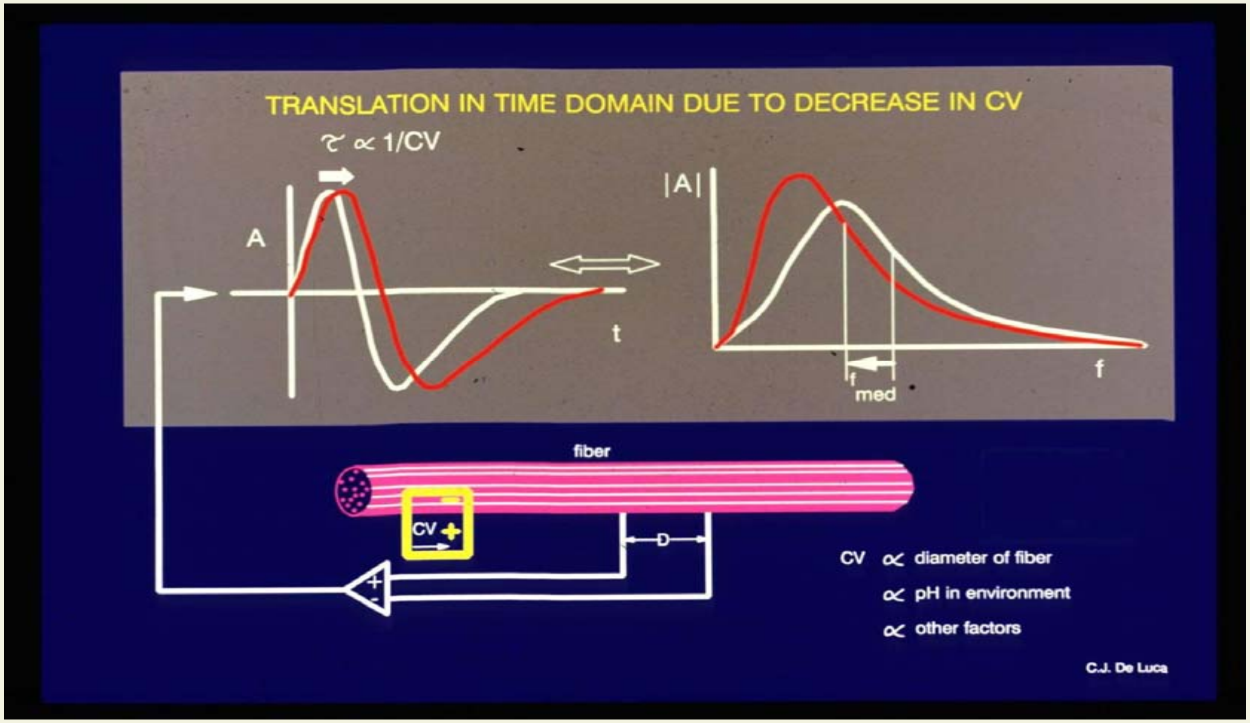
81: Dominant Factor:
Influence of Conduction Velocity



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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.

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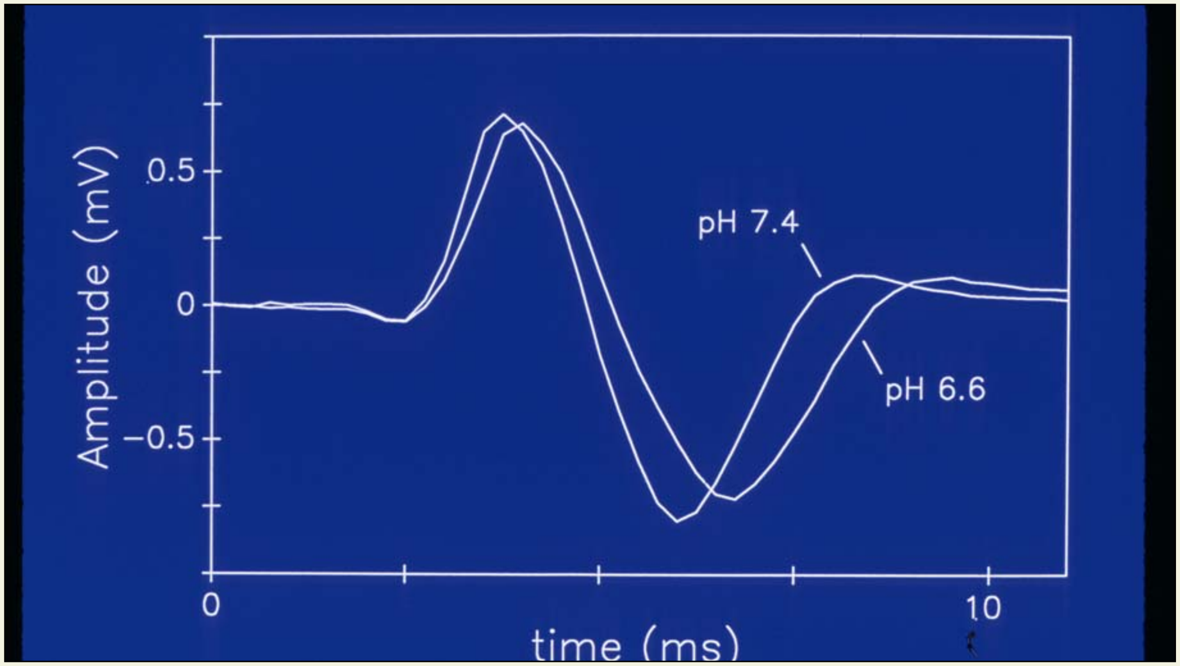
82: Effect of pH on the Action Potential



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.

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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.

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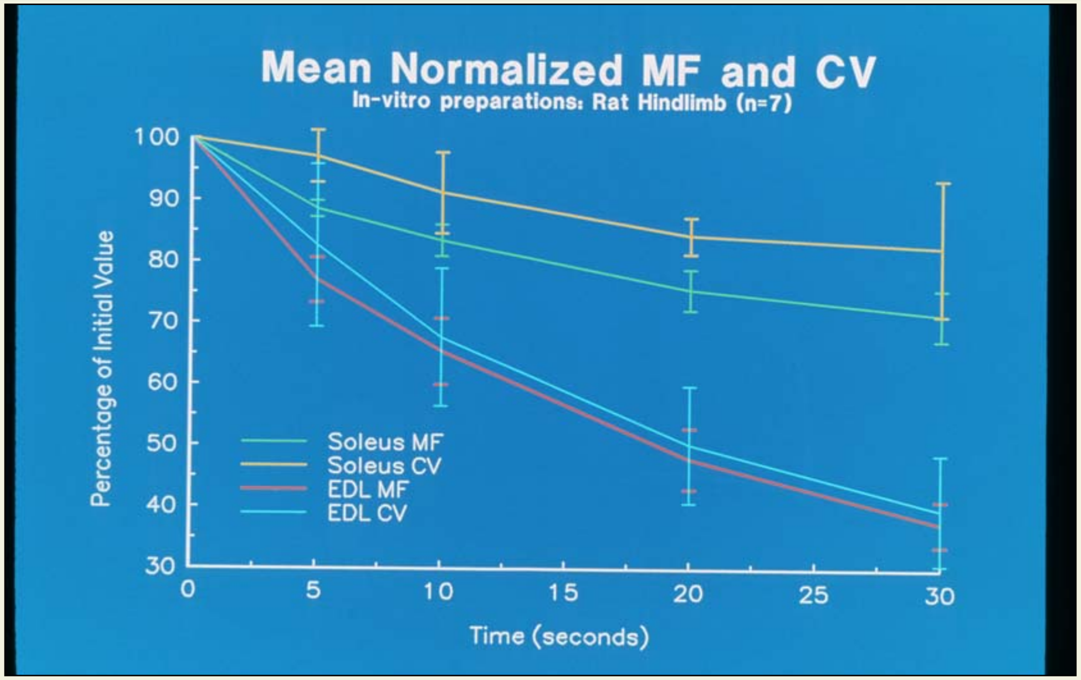
83: pH Induced Effect:

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.

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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.

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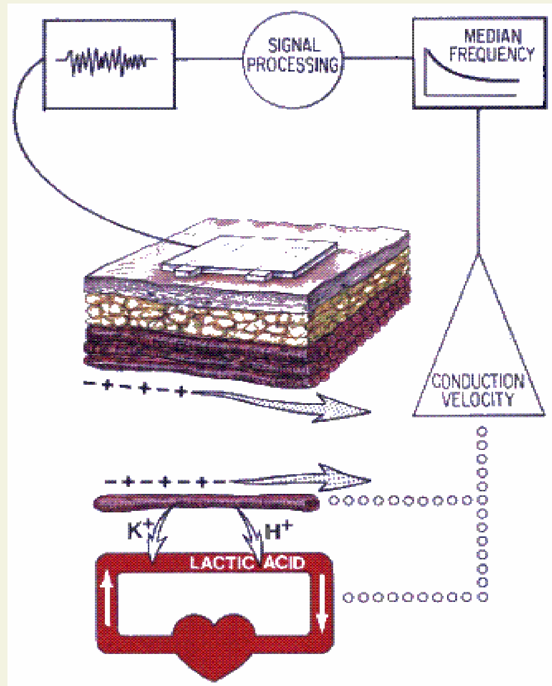
84: Fatigue:

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



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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+ concentration which increases the positive charge outside the cell. The K+ inside the cell now needs to move against a stronger repelling electro-chemical gradient slowing down the K+ / Na+ exchange that produces 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.

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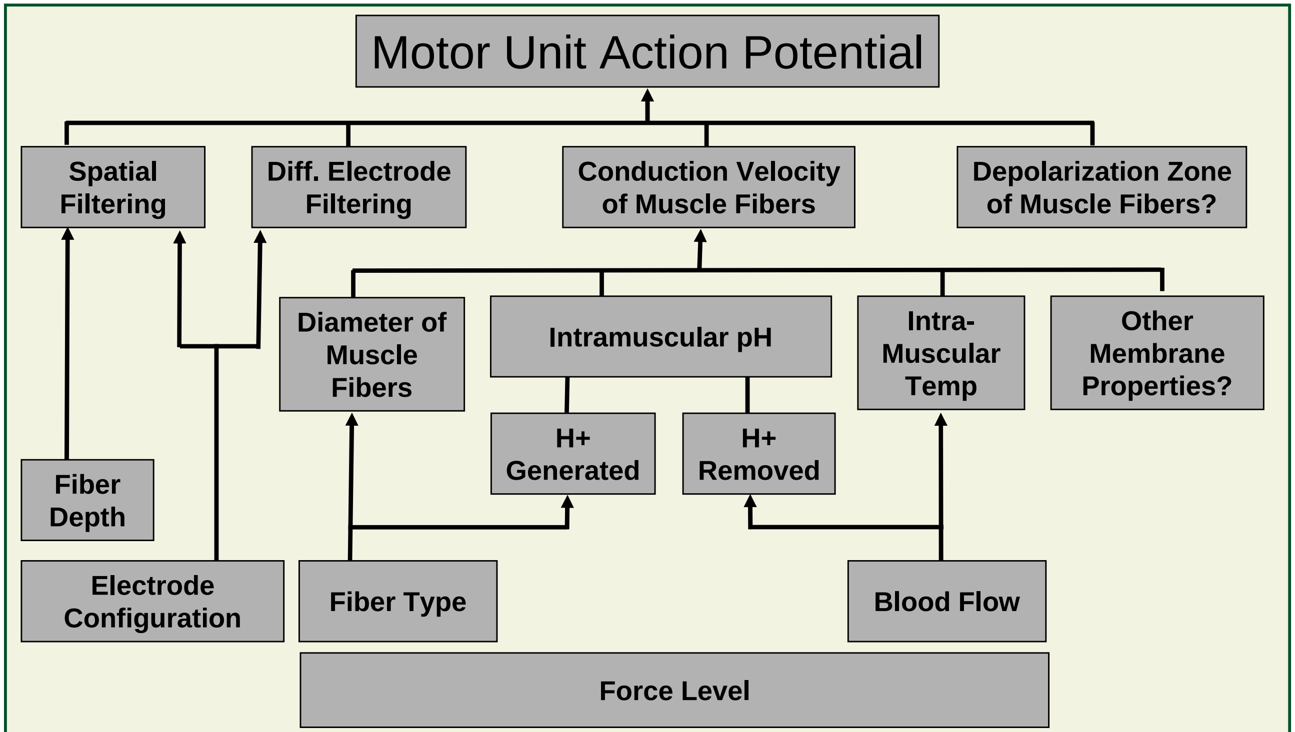
85: Factors that affect the sEMG Signal



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

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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.

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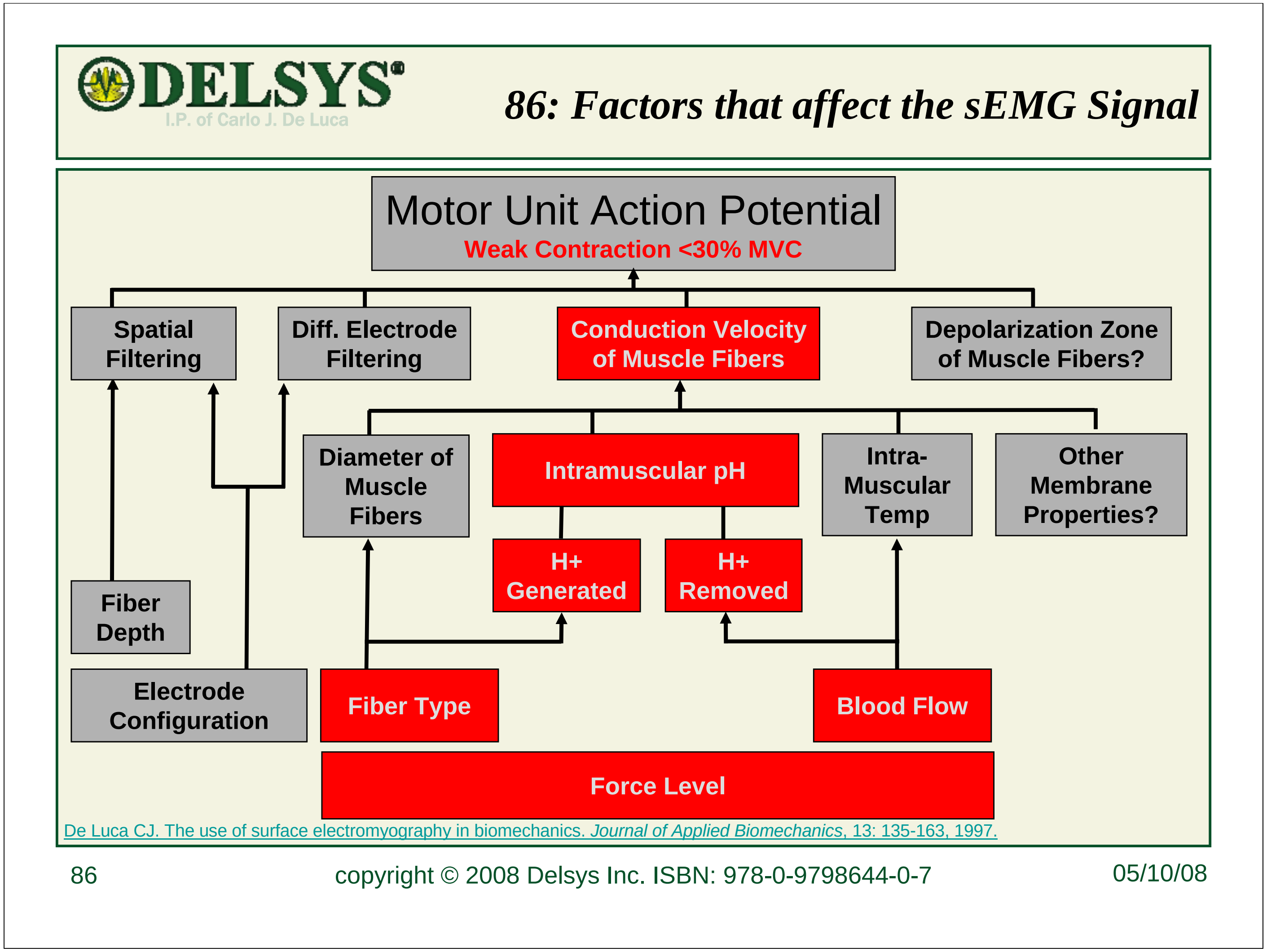
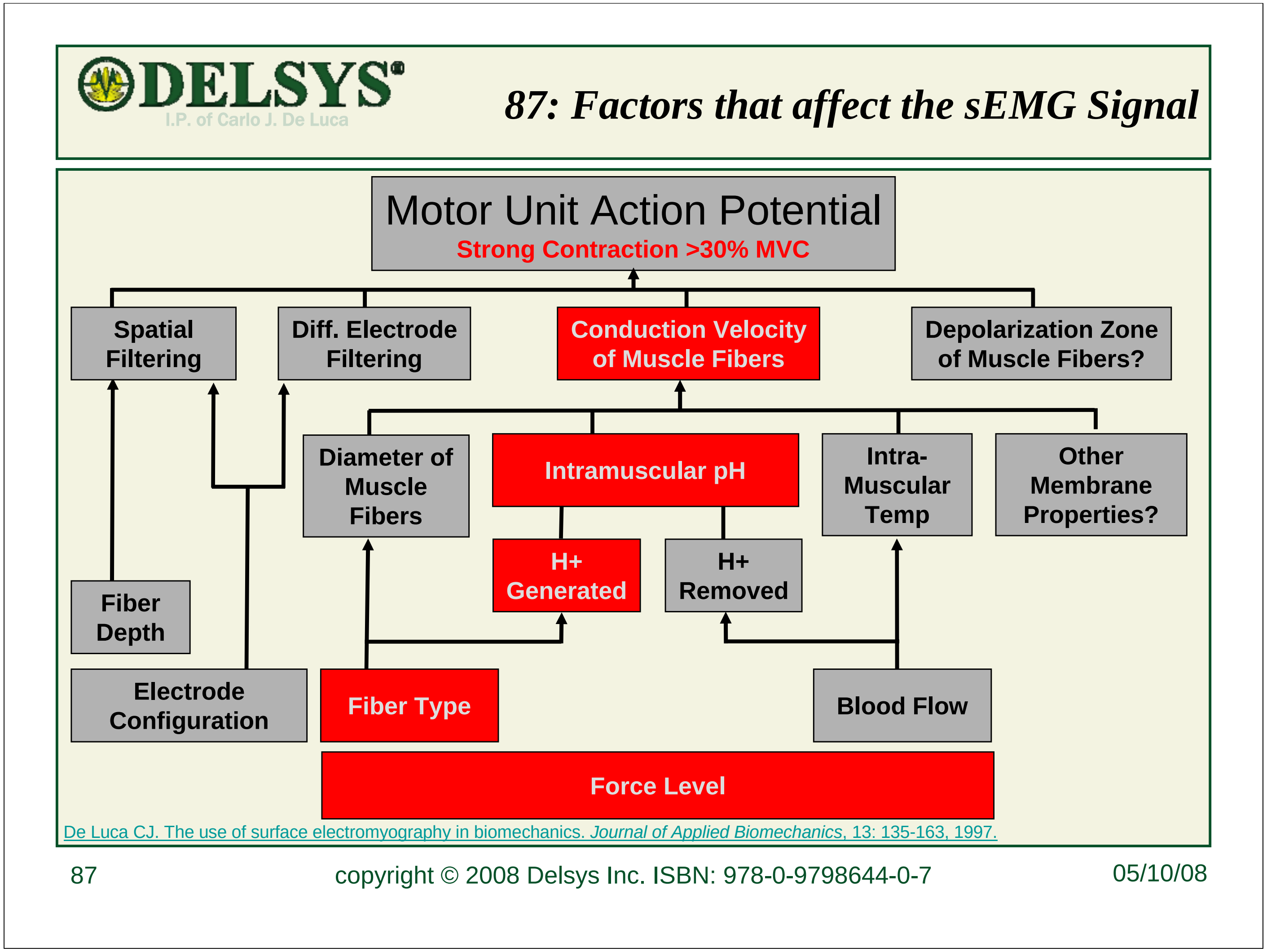


Factors that affect the sEMG signal:

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



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.

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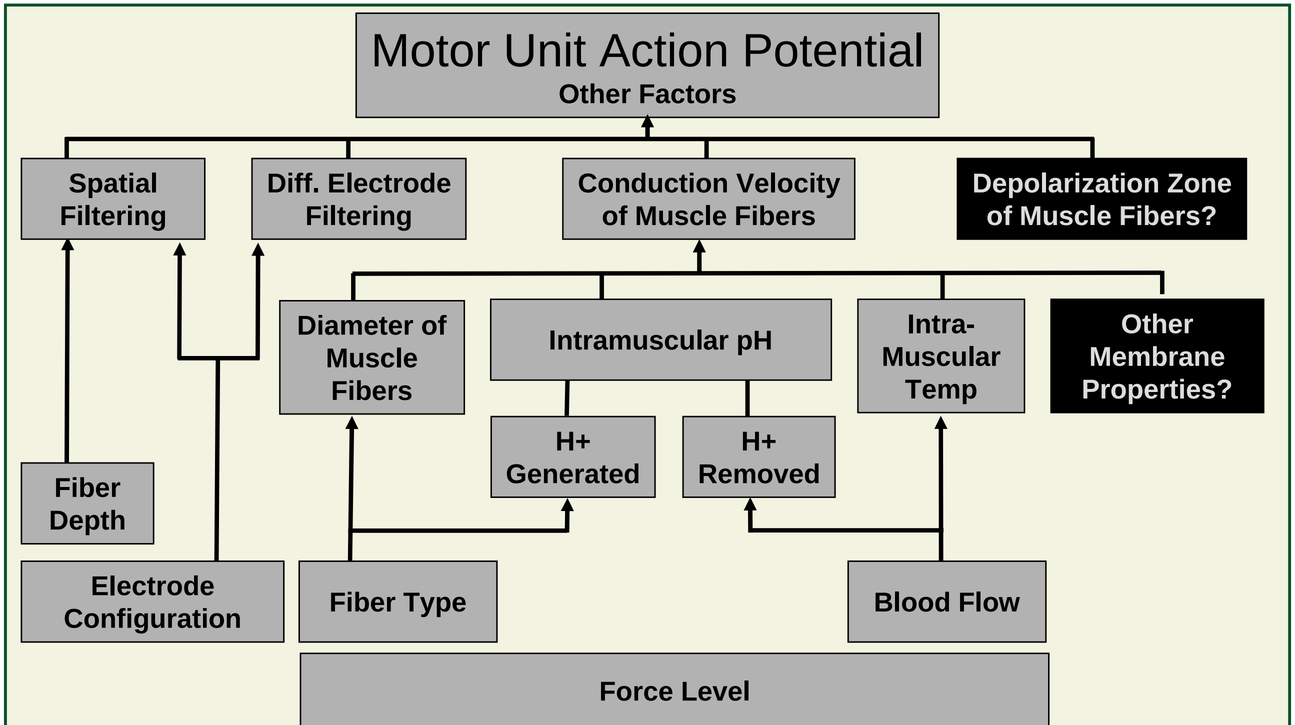
88: Factors that affect the sEMG Signal



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

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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.

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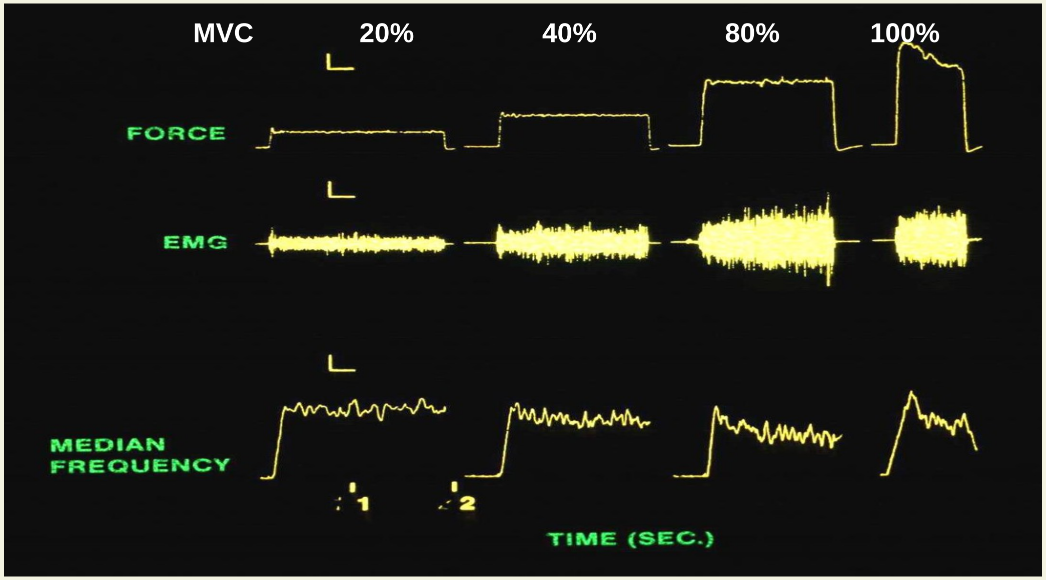
89: Median Frequency: *the Influence of Force*



De Luca CJ, Sabbahi MA, Stulen FB, and BilottoG. 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.

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Median frequency – the influence of force:

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

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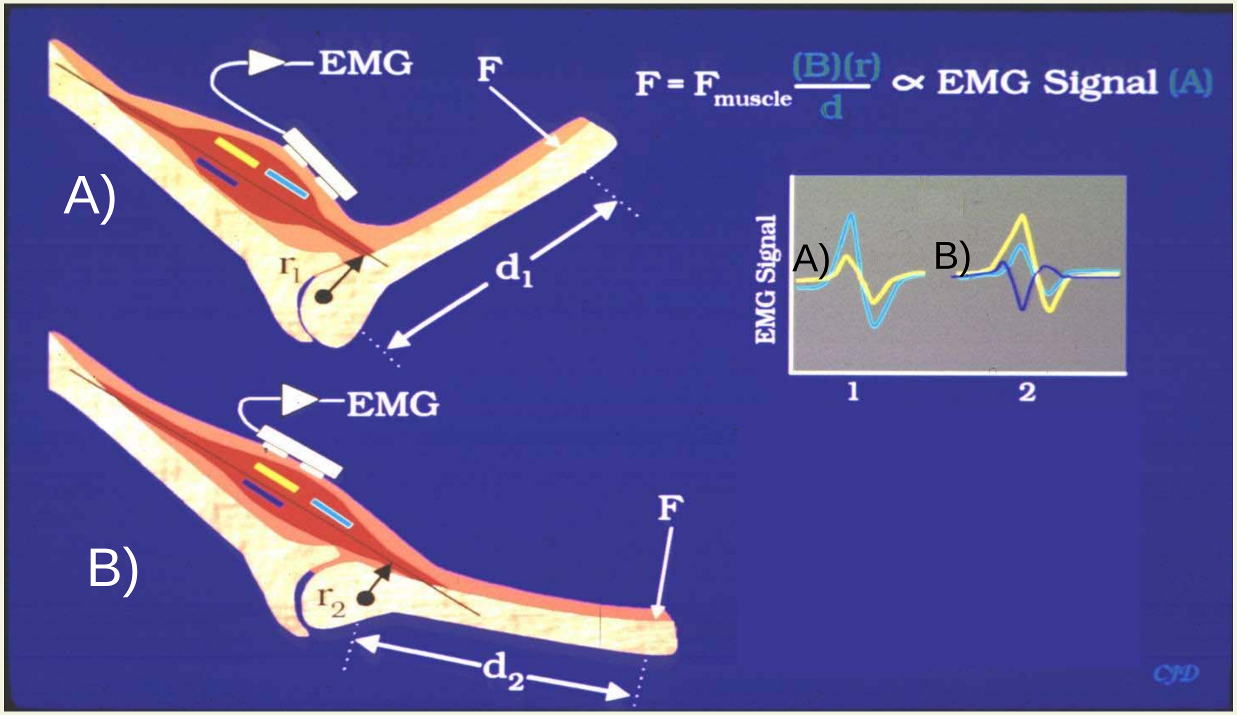
90: Effect of Electrode Displacement During Movement



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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.

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91: Confounding Factors for Fatigue Measurements

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

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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

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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

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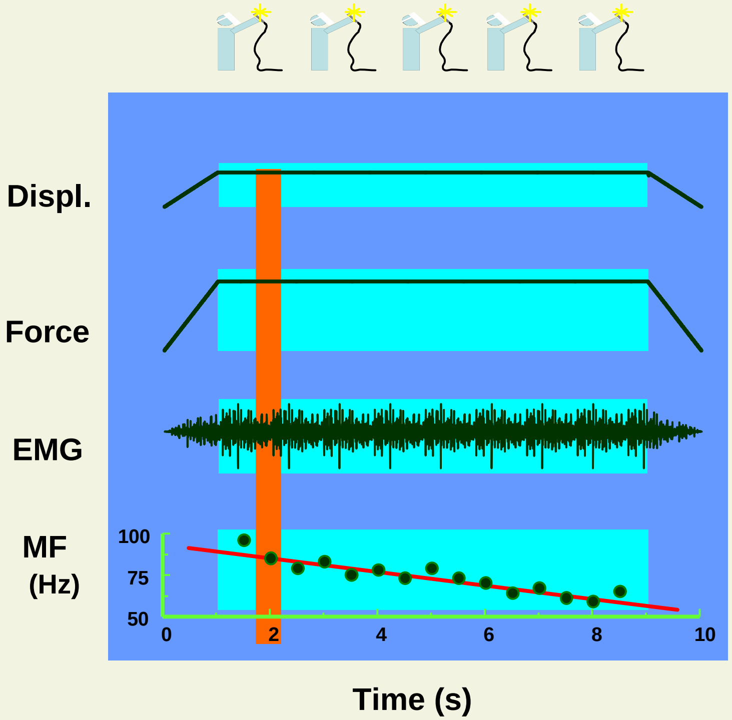
94: Static Contractions



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.

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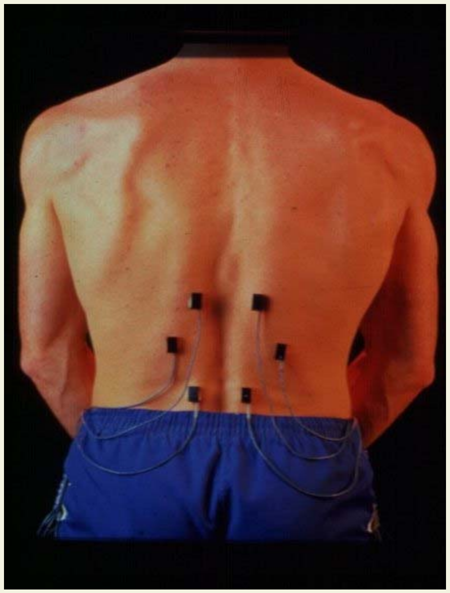
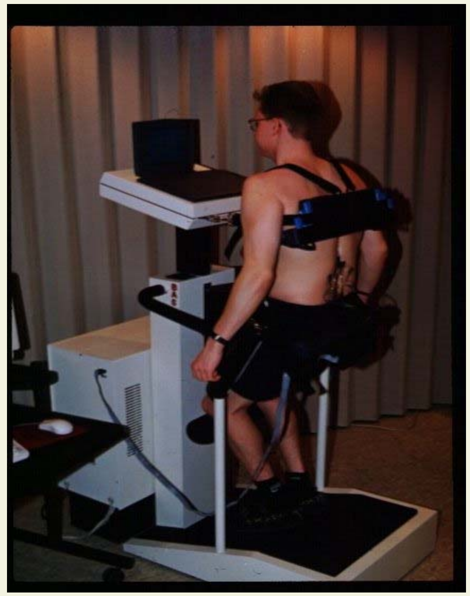
95: Back Analysis System





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.

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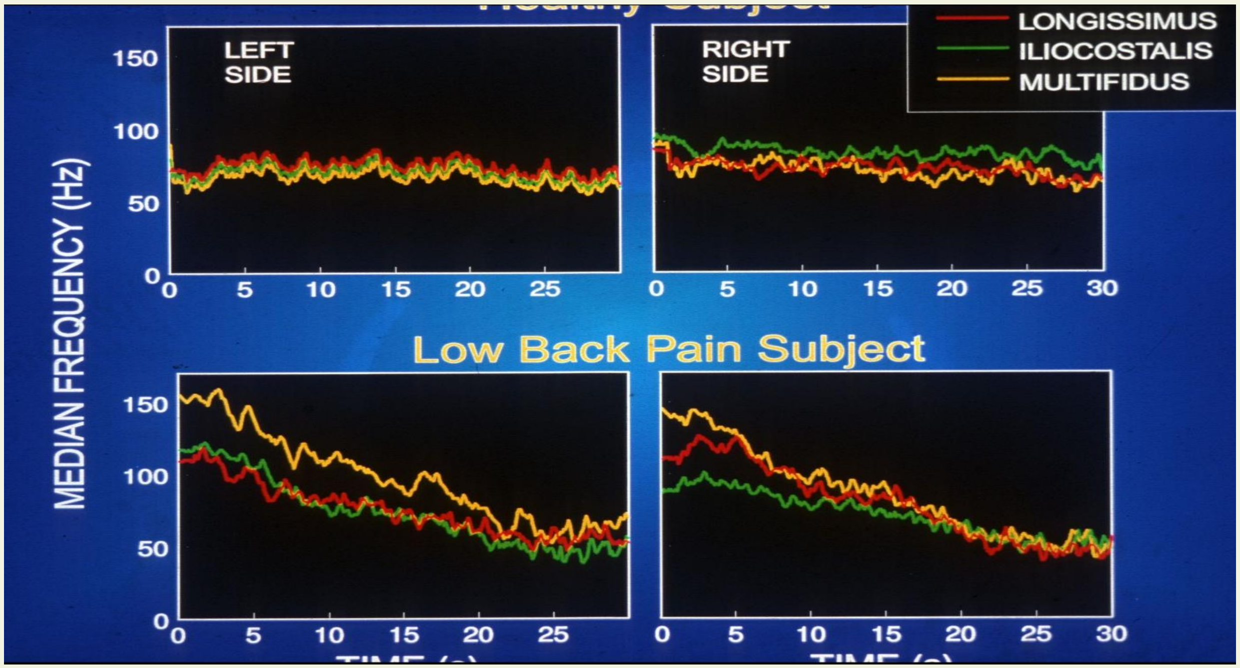
96: Back Analysis



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

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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.

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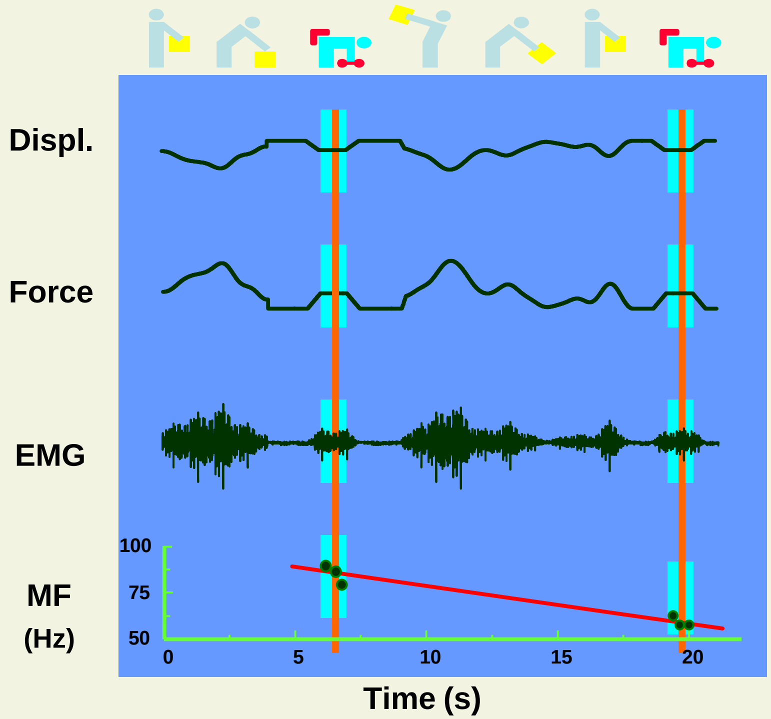
97: Dynamic Contractions: with Static Sampling



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**

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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.

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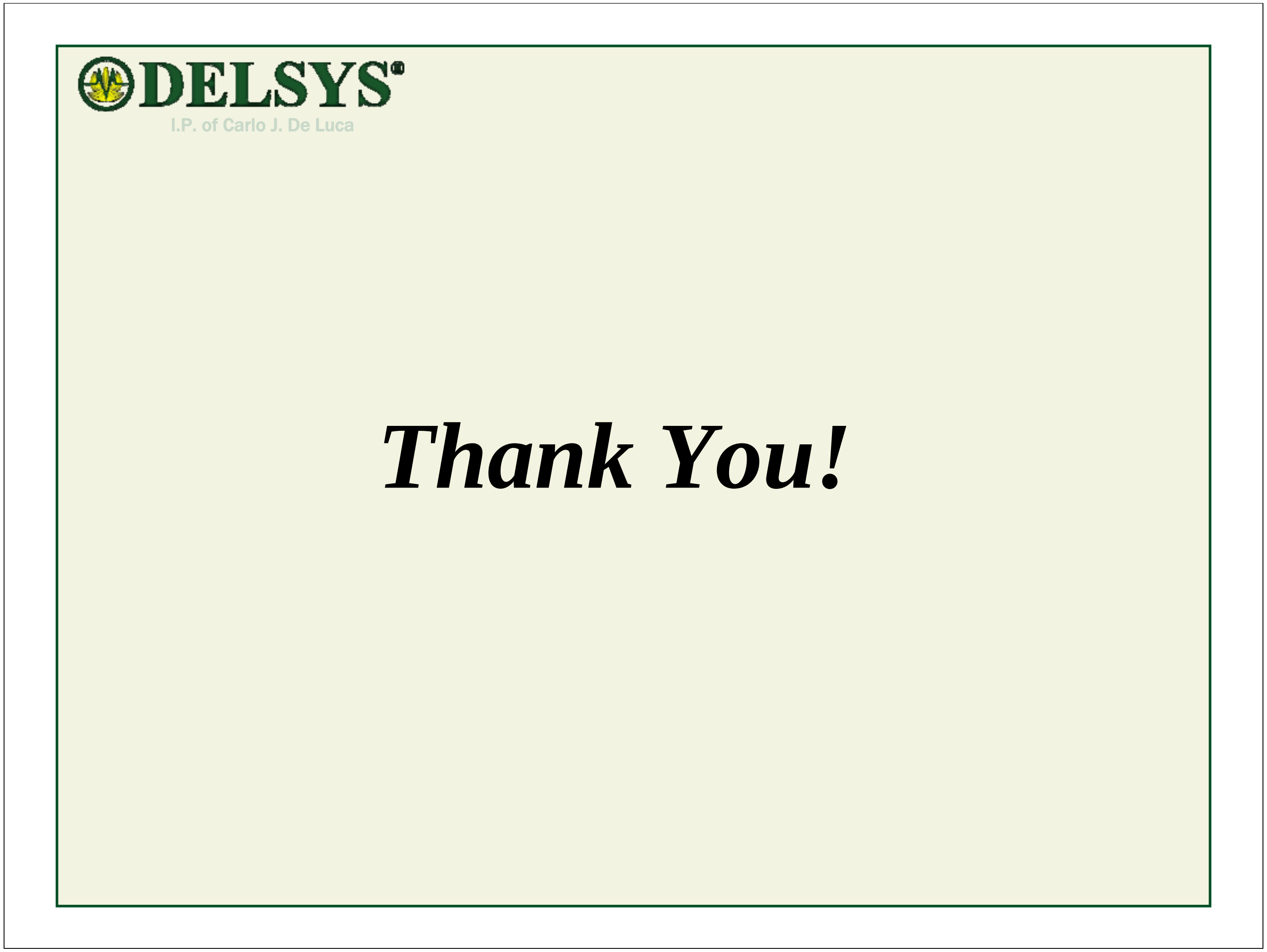
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Thank You!

<u>Sensor Related Factors and Fidelity of the sEMG Signal©</u>

ISBN: 978-0-9798644-1-4

Carlo J De Luca

29 July, 2007

<u>Electrode</u> – The metal surface of the sensor which makes electrical contact with the skin.

<u>Sensor</u> – The unit that contains the electrodes and the electronic circuitry for differential amplification of the EMG signal and reduces the contribution of various noise sources.

<u>Noise</u> – Those electrical signals which are detected by the electrodes and the remainder of the sensor, but do not originate in the muscle below the sensor.

The following table outlines the relationship between sensor design, user preparation, sEMG signal, and various noise sources. Note that the sensor application and the skin preparation play important parts in detecting an sEMG signal of high fidelity. The dominant factor in the User Preparation is the location on the muscle where the sensor is attached. The proper sensor location can enhance the amplitude of the sEMG signal and reduce the crosstalk much more dramatically than the design of the sensor. Thus, the signal fidelity is in large part influenced by proper choice of sensor location – a decision that is left to the user.

Key to table - independent variable -- Sensor Design and User Preparation
dependent variable -- Signal and Noise Source

▲ dependent variable increases as the independent variable increases
▼ dependent variable decreases as the independent variable increases
▲▼ the dependent variable either increases or decreases

(The larger arrows indicate a more dominant factor.)
(Green indicates a favorable occurrence, red indicates an unfavorable occurrence.)

ACTIVE DIFFERENTIAL SENSOR	**SIGNAL**	**NOISE SOURCES**				
		Cross-Talk	Movement Artifact	Baseline	Line radiation (50, 60 Hz)	EKG
Sensor Design						
Inter-electrode spacing	▲	▲				▲
Electrode area		▲		▼		
Electronics quality				▼	▼	
Sensor construction				▼	▼	
User Preparation						
Location on muscle	▲▼	▲▼				
Skin preparation	▲					
Liquid electrolyte				▲▼		
Hydrophilic-gel electrolyte			▲			
Sensor orientation with fibers	▲▼					▼
Location and size of reference electrode					▲▼	▲
Proximity to heart						▲

EXPLANATION

Inter-electrode spacing – The distance between the electrodes renders an increase in the amplitude [1] of the signal (which is beneficial) as well as an increase in the cross-talk sensitivity (which is detrimental) [unpublished work]. Between the two, it is advisable to reduce the cross-talk sensitivity, because cross-talk is virtually indistinguishable from the EMG signal. With greater inter-electrode spacing, there is a greater chance of detecting the EKG signal if the sensor is placed on the chest or upper back muscles.

Thus, smaller inter-electrode spacing is preferable. Also, the electrodes should have a fixed spacing in order to provide consistent and repeatable measurements of signal amplitude. Delsys uses a spacing fixed at 1.0 cm for this and other reasons.

Electrode area – The larger the area the greater the amplitude of the cross-talk signal. This occurs partially due to the encroachment of the electrodes on the nearby muscles. The baseline noise decreases with increasing electrode area [2].

Electronics quality – Electronics components with higher tolerances generate less baseline noise and are better able to reduce (possibly eliminate) the line radiation noise (50 or 60 Hz) enabling a more accurate performance.

Sensor construction – Features such as surface shielding, component layout, and ground-plane geometry can reduce the baseline noise and the line radiation noise.

Location on muscle – If the sensor is placed:

1) Near the innervation zone – the amplitude of the sEMG signal will decrease because cancellation occurs among the action potentials which propagate in opposite directions. The bandwidth of the signal will increase because the subtraction of action potentials moving in opposite directions yields residuals that have sharper transition in the time course of the signal.

In most large muscles, the innervation zones are located at the perimeter of the muscle or near the tendon- muscle interface [3].

2) Near the tendon – The amplitude of the sEMG signal will be relatively lower because the number of muscle fibers and the diameter of the muscle fibers are reduced in this region. Consequently the there are fewer action potentials that contribute to the sEMG signal and those have lower amplitudes.

3) Near the perimeter of the muscle – In most muscles, especially in the larger muscles, the amplitude of the sEMG signal will be relatively lower because there are fewer fibers in this region. Sensors located in this region detect an increased amount of cross-talk from adjacent muscles when they are active, which is likely to be so during most contractions.

PLACE sensor in the MIDDLE of the muscle surface – This location lies between the innervation zones (near the perimeter of the muscle) and the tendon- muscle interface. It satisfies the above considerations in most large muscles. In smaller muscles, such as those in the hand, there is no choice as to where to locate the sensor.

Skin preparation – The oils and debris that normally accumulate on the skin must be removed in order for the ionic exchange to occur effectively between the salts in the skin and the metal of the electrode. Removal of the oils and debris decreases the impedance of the electrical contact and increases the effectiveness of the sensor which renders increased sEMG signal amplitude, a decreased baseline noise, and, at times, a reduced line radiation noise.

Liquid electrolyte – Delsys EMG sensors do not normally require an electrolyte to make proper electrical contact with the skin when the skin is cleaned properly. These are referred to as “dry’ sensors. They were first introduced by Delsys personnel in 1979 [4]. If the signal quality requires improvement, then a liquid electrolyte should be applied to the surface of the electrodes only. Be very careful not to apply electrolyte on the skin as this would cause an electrical short between the two electrodes and would worsen the signal quality.

Hydrophilic-gel electrolytes – Do not use hydrophilic gel electrolyte if it is likely that a force impulse will be transmitted through the limb to which the senor is attached, as it will enable the occurrence of movement artifact [5]. The viscosity of the hydrophilic-gel causes relative movement of the electrode with respect to the skin, both in the normal (perpendicular) as well as the shear (parallel) direction.

Sensor orientation with fibers – The orientation of the sensor, hence the electrodes, with respect to the direction of the muscle fibers can influence the amplitude of the sEMG signal. The greatest amplitude is obtained when the electrode is perpendicular to the fibers. Also, changing the sensor orientation with respect to the heart will reduce the EKG signal, if one is detected. The sensor is a differential amplifier, thus if both electrodes are arranged so that they are equidistant in the EKG current path the EKG signal will be common mode (similar in amplitude and phase at both electrodes) and it will be removed. If the electrodes are placed along the path of the EKG current, then a differential voltage will be amplified and the EKG signal may be detected.

Location and size of reference electrode – It is advisable to place the reference electrode as far away from the sEMG sensor as is convenient, and not near sources of line radiation such as power cables or lights. Clean the skin with alcohol. Use large (4 to 5 cm) electrodes with strong adhesives that make an effective electrical contact. Placing the reference electrode close to the sensor may disturb the sEMG signal, especially if multiple sensors are attached to the body. An effective reference electrode contact is important. Choose a location that decreases noise interference and prepare the skin accordingly.

Proximity to heart – When recording sEMG signals from muscles in the chest and upper back it is possible to detect the unwanted EKG signal while detecting the sEMG signal. This interference can be reduced and at times eliminated by using sensors with small inter-electrode spacing and by rotating the alignment of the sensor with respect to the heart.

Reference

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RECOMMENDED PRACTICE
(in order of importance)

1) Use a sensor with a 1 cm inter-electrode spacing.

2) Place sensor in the middle of the muscle surface.

3) Orient the electrodes along the length of the muscle fibers. If using the Delsys sensors, align the arrow along the muscle fibers.

4) Carefully attach sensor to skin.
    a. clean skin with 70% Isopropynol alcohol and
    b. remove excessive hair – in most individuals this is not necessary
    c. use effective adhesive and apply it forcefully
    d. do not use hydrophilic gel electrolyte if movement artifact is a concern

5) Filter signal from 20 to 450 Hz.

6) Use high-quality equipment.