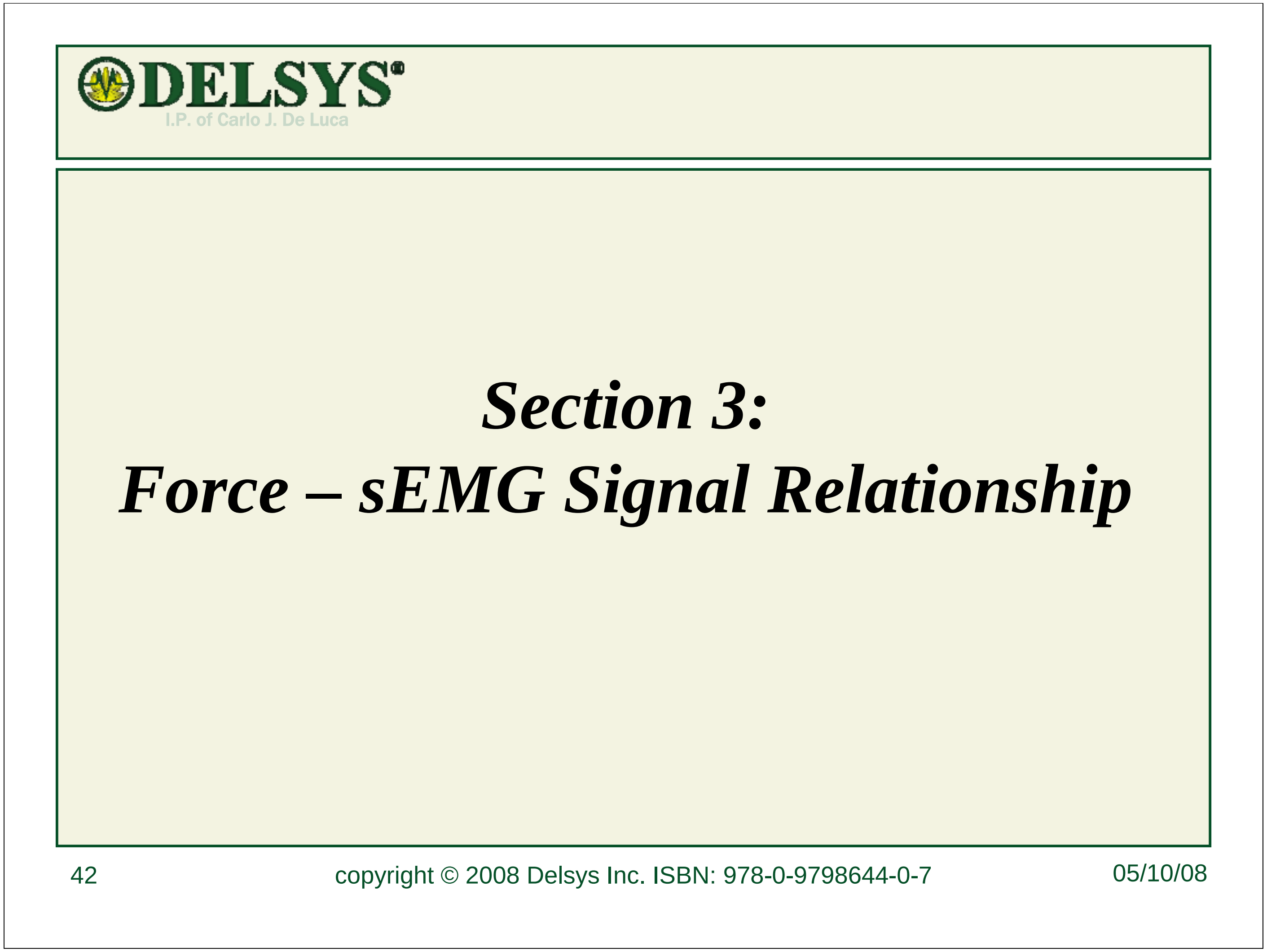
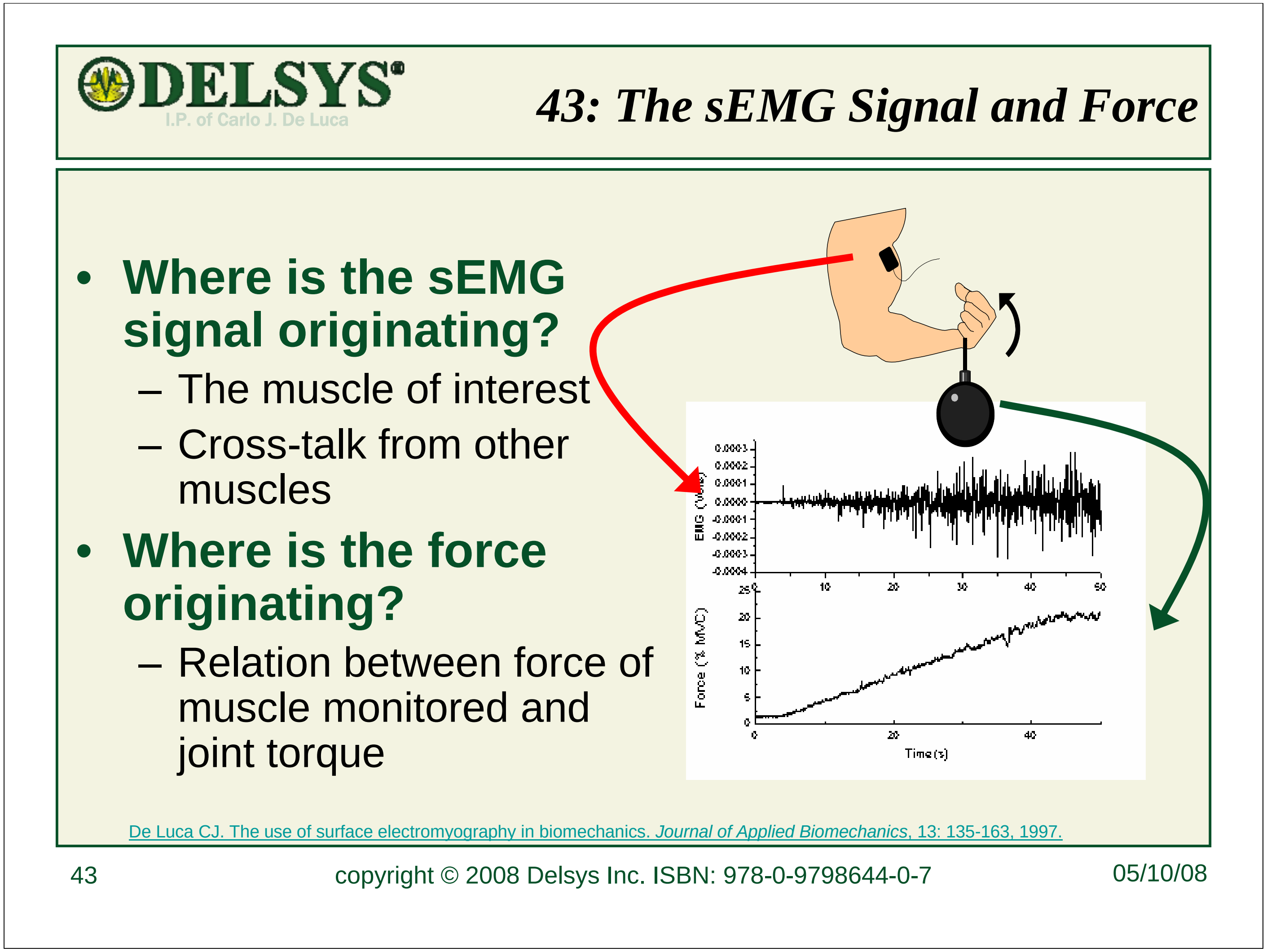


Section 3:
Force – sEMG Signal Relationship



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43: The sEMG Signal and Force

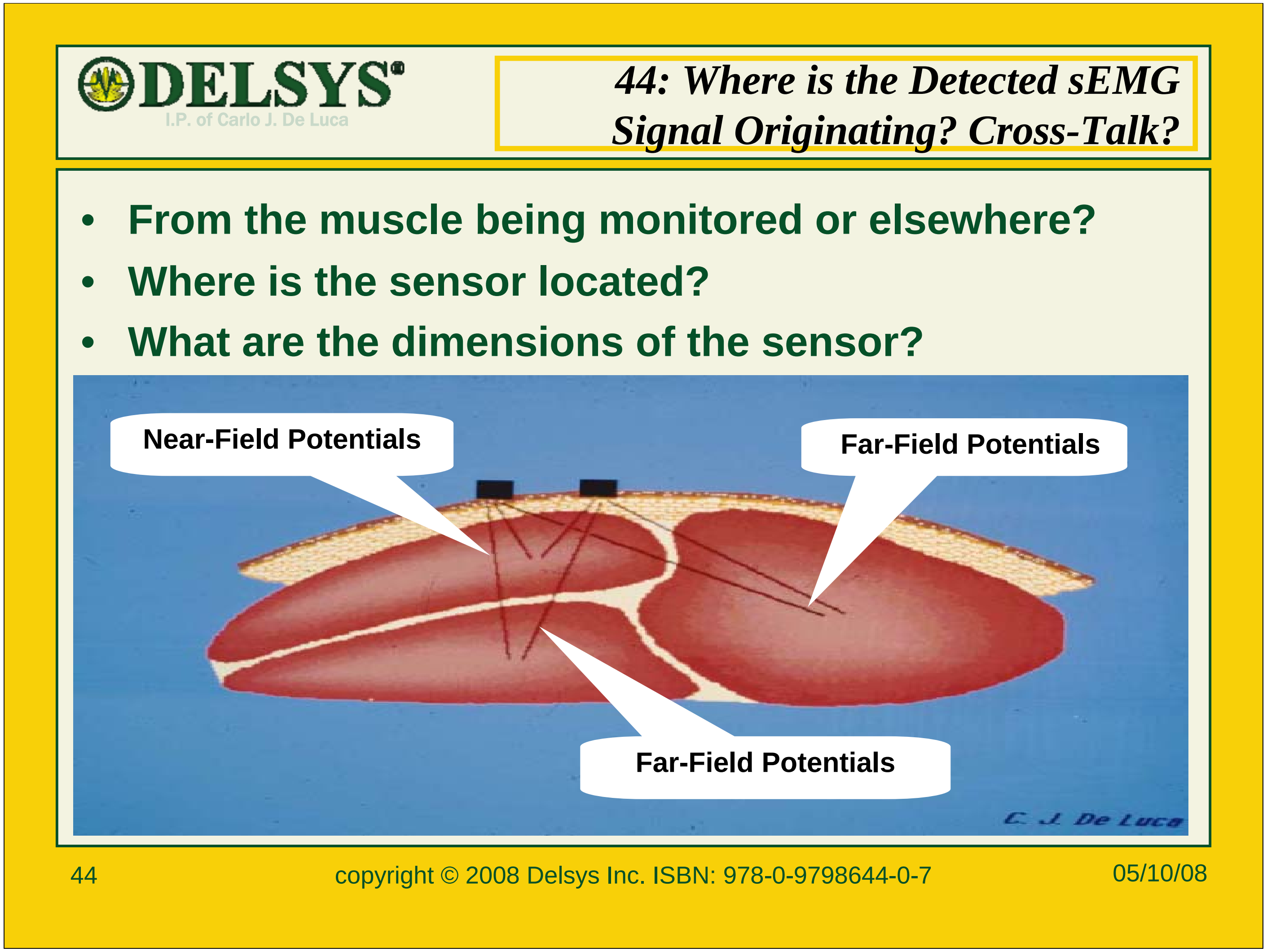
- **Where is the sEMG signal originating?**
  - The muscle of interest
  - Cross-talk from other muscles
- **Where is the force originating?**
  - Relation between force of muscle monitored and joint torque

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

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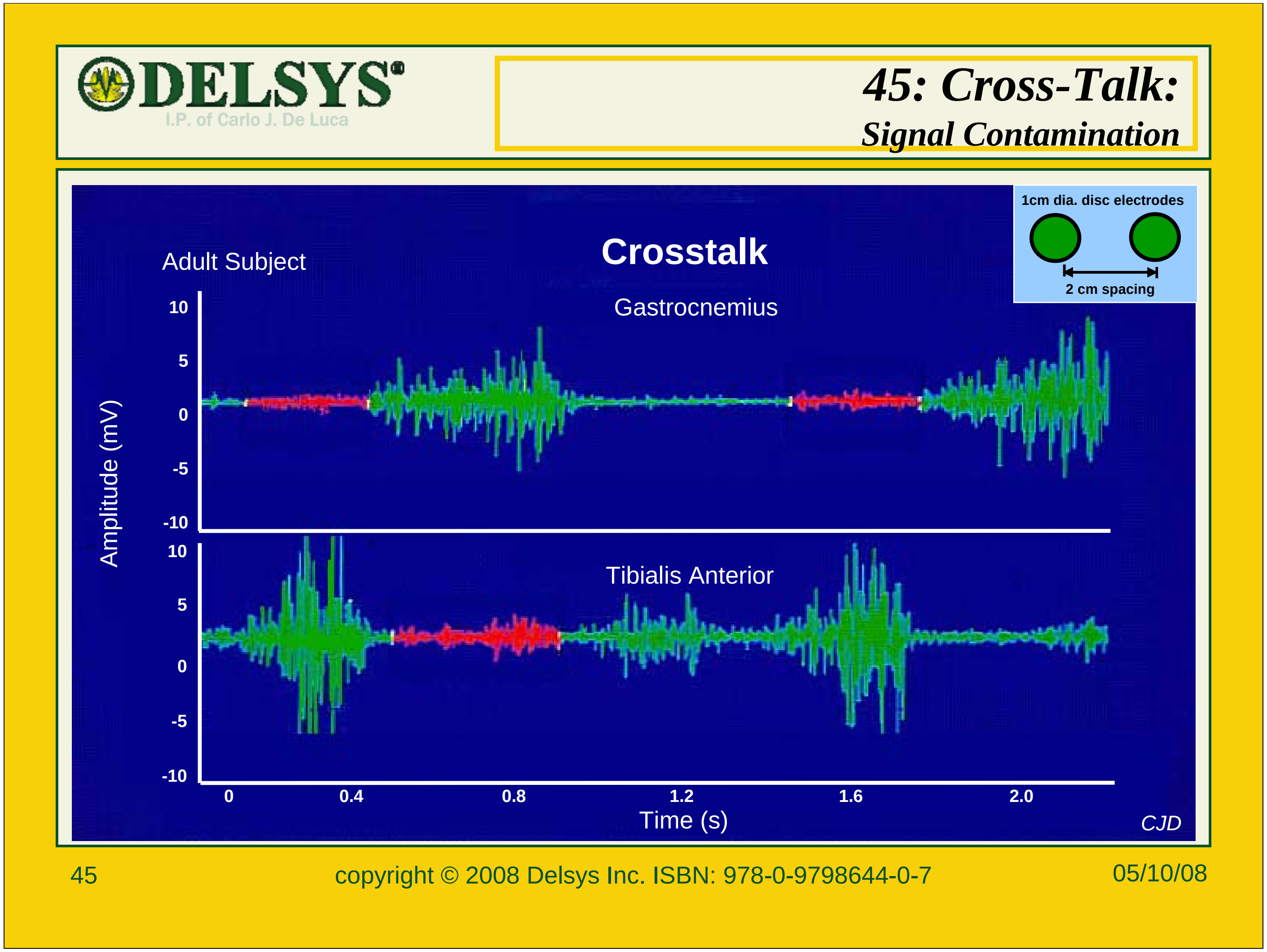
Where is the detected sEMG signal originating? Cross-talk?

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.



45: Cross-Talk:
Signal Contamination

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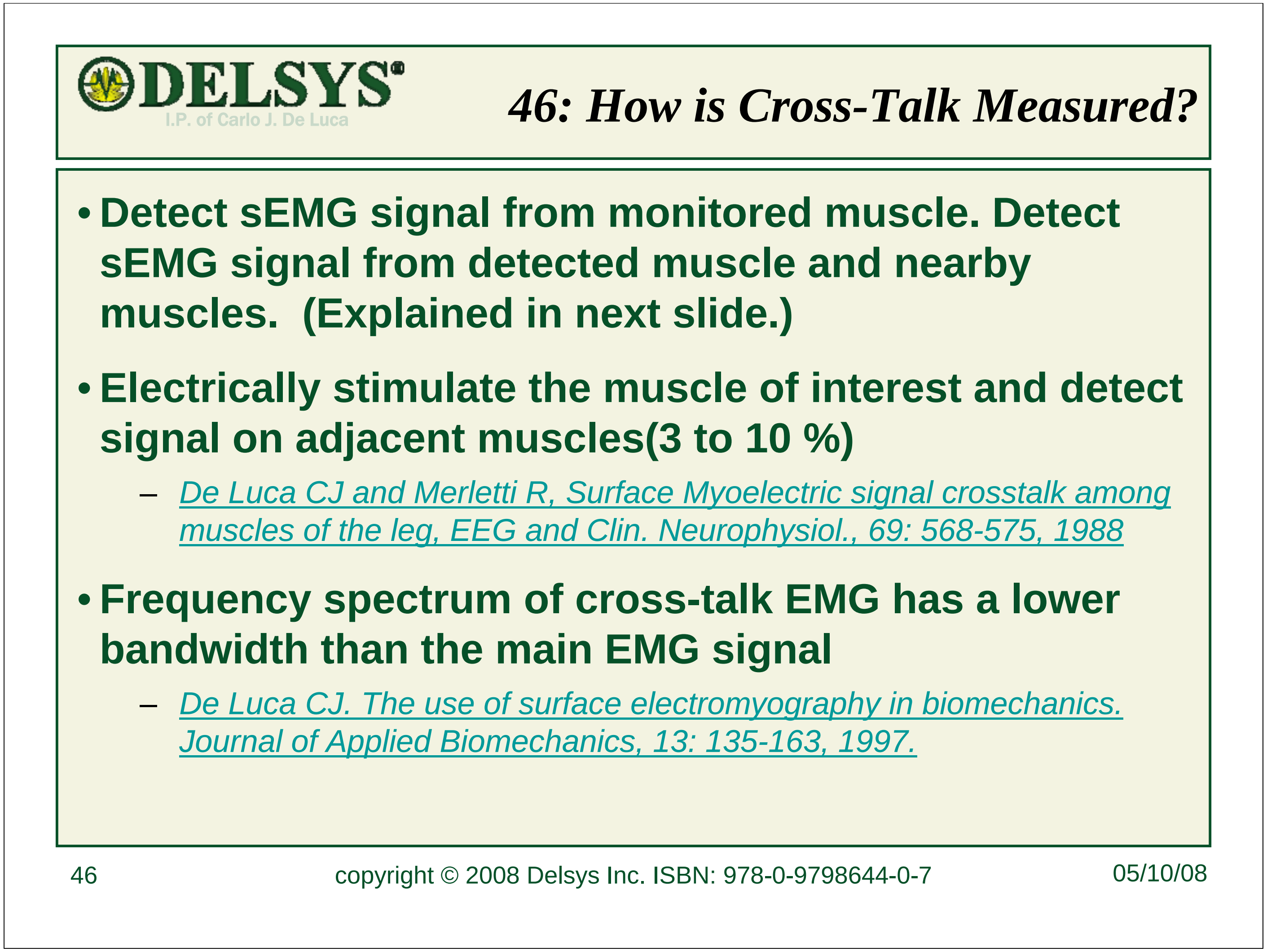
Cross-talk: Signal Contamination:

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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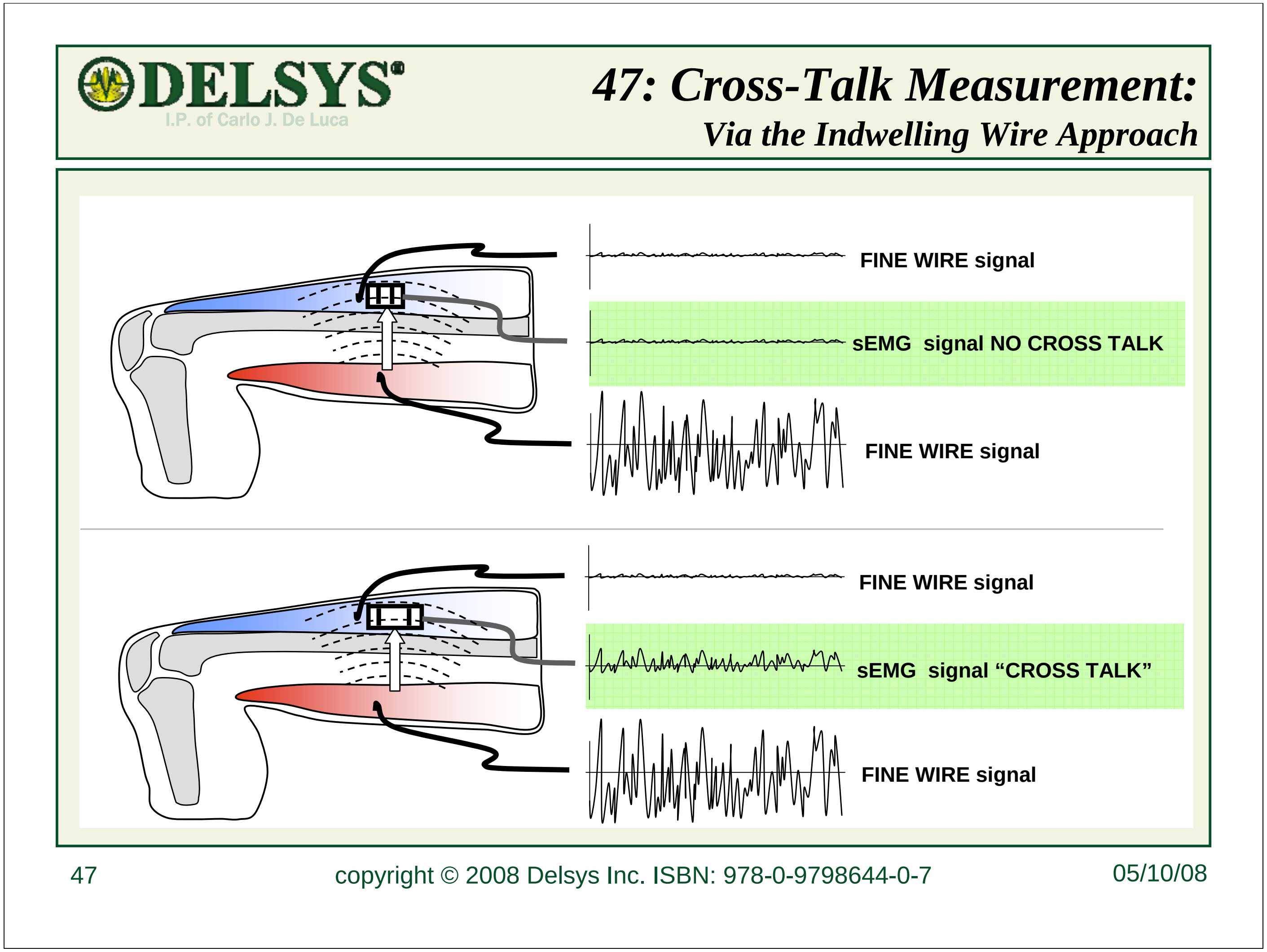
46: How is Cross-Talk Measured?

- **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.*

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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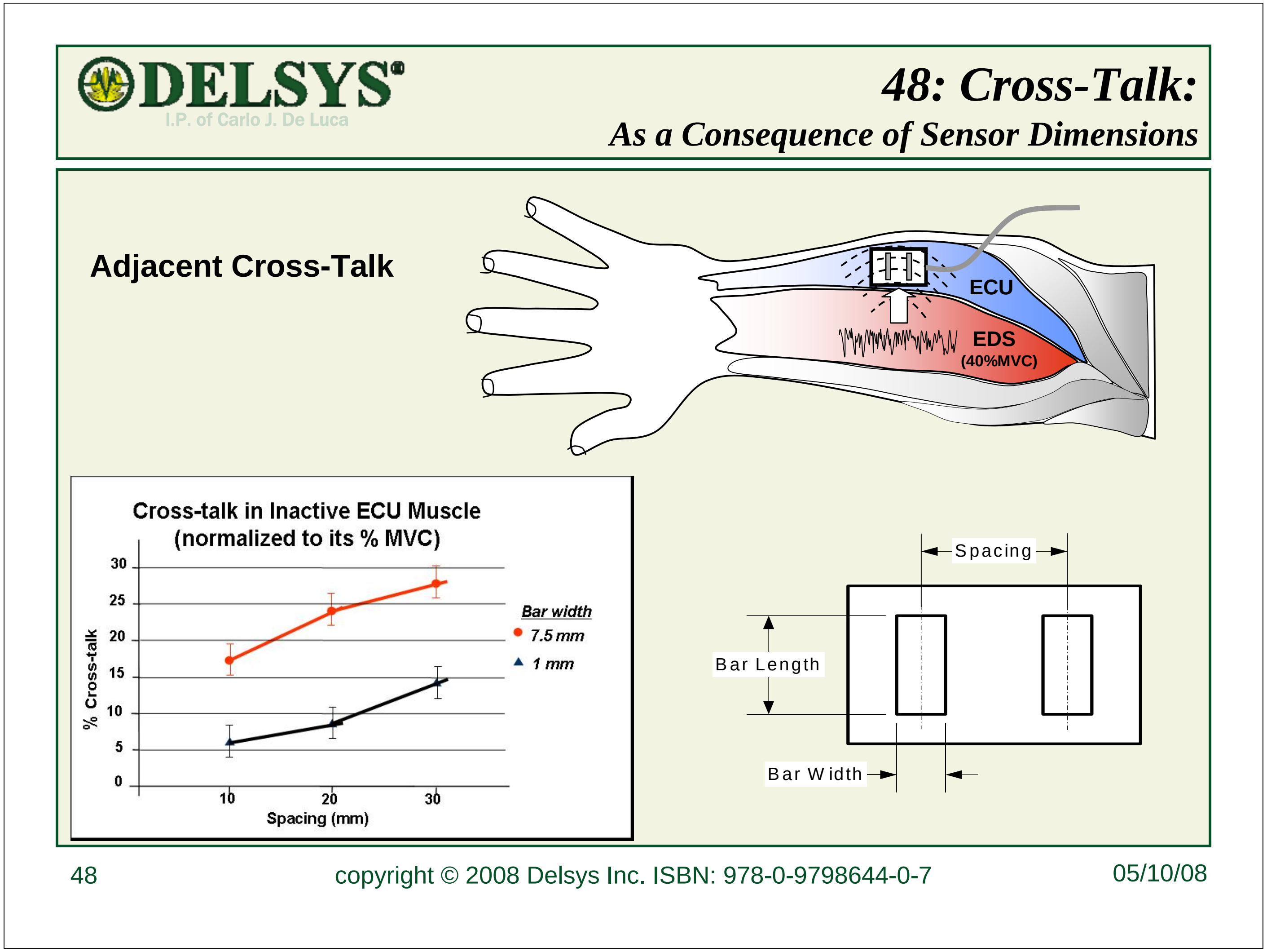
Cross-Talk measurement:

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. -- Top Panel
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 -- Top Panel
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. -- Bottom Panel



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48: Cross-Talk:

As a Consequence of Sensor Dimensions

Adjacent Cross-Talk

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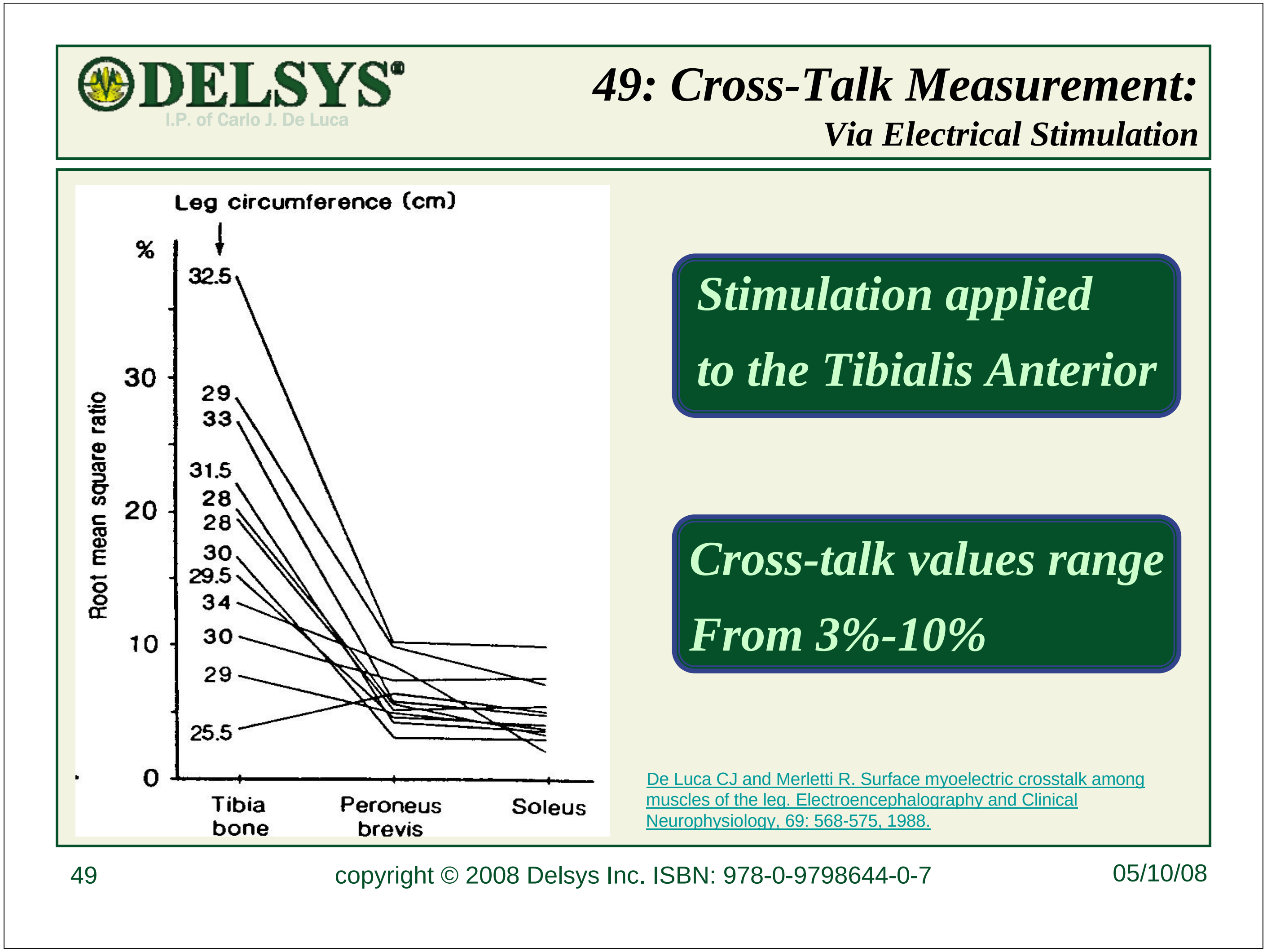
Cross-Talk and Sensor Dimensions:

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.

Cross-Talk from Electrical Stimulation:

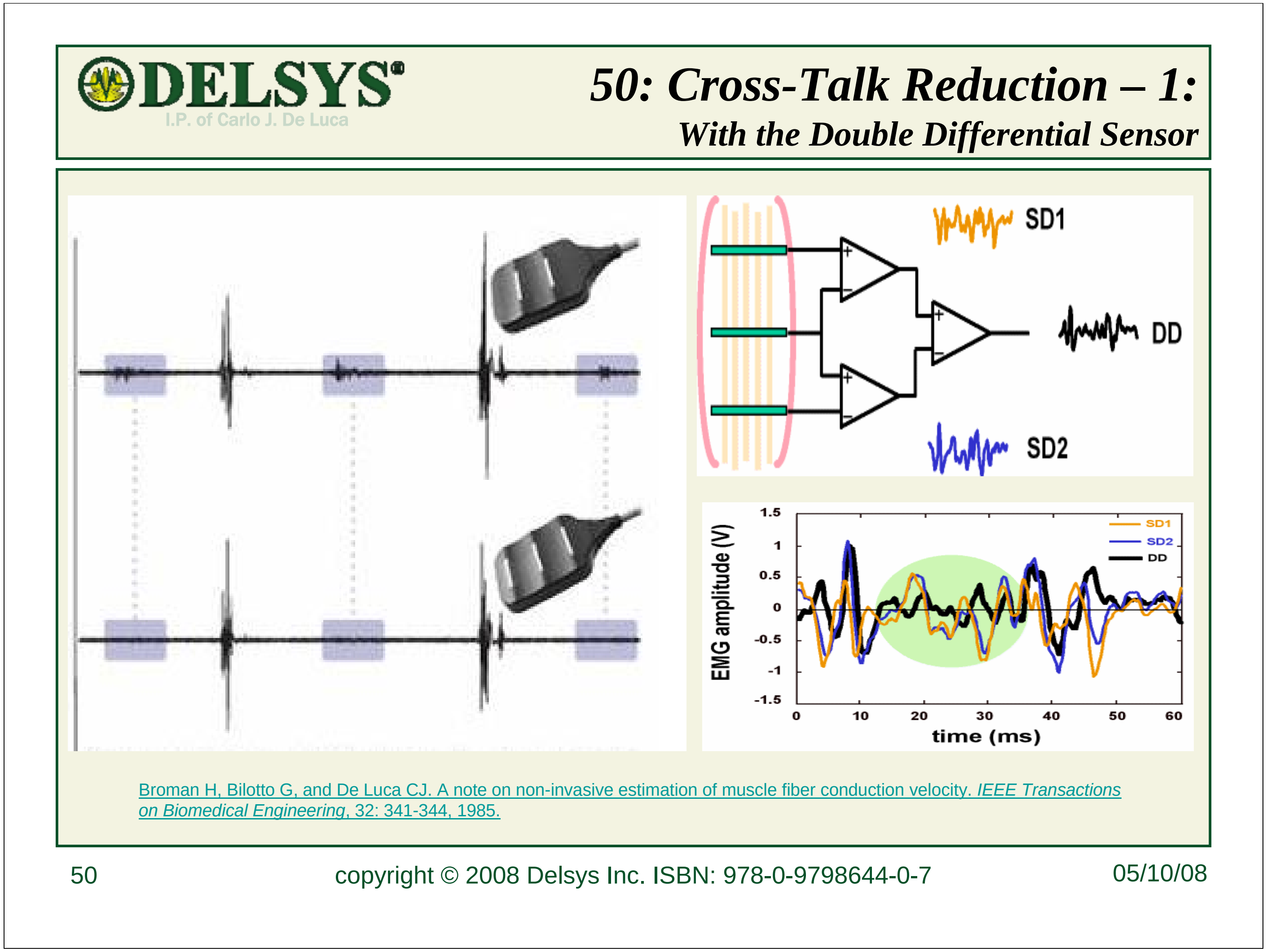
These are results from the second technique for measuring cross-talk described in slide #47.

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.

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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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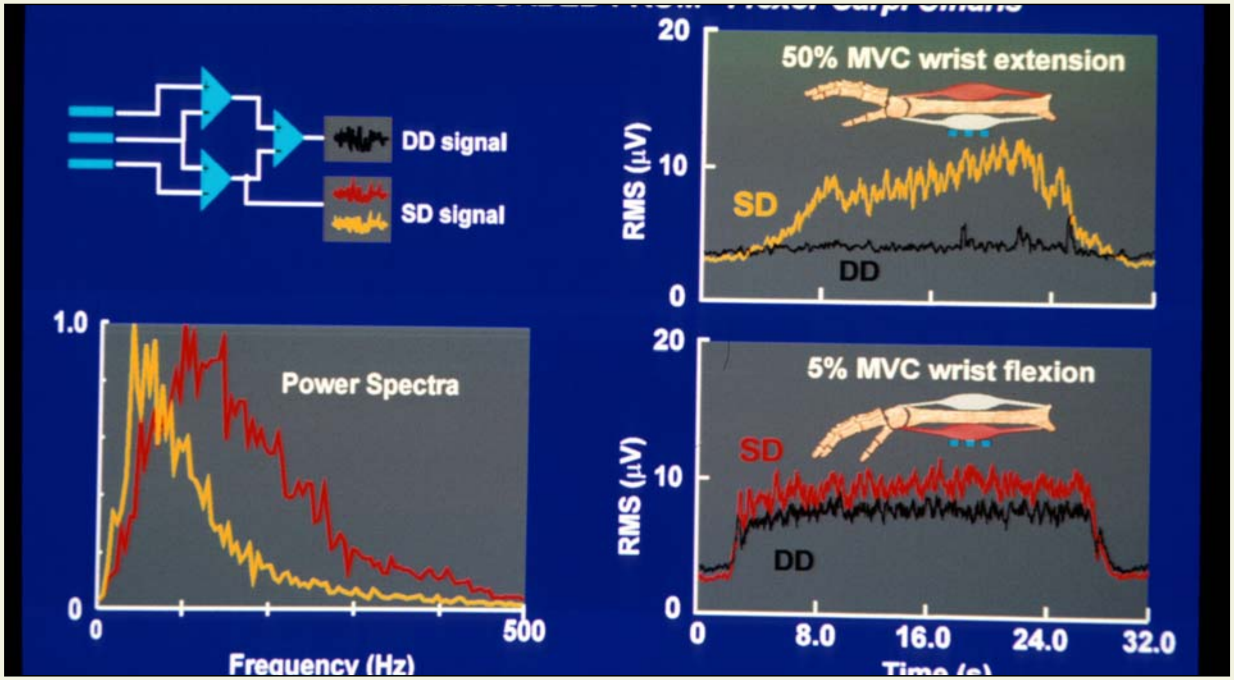
51: Cross-Talk Elimination – 2:

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:

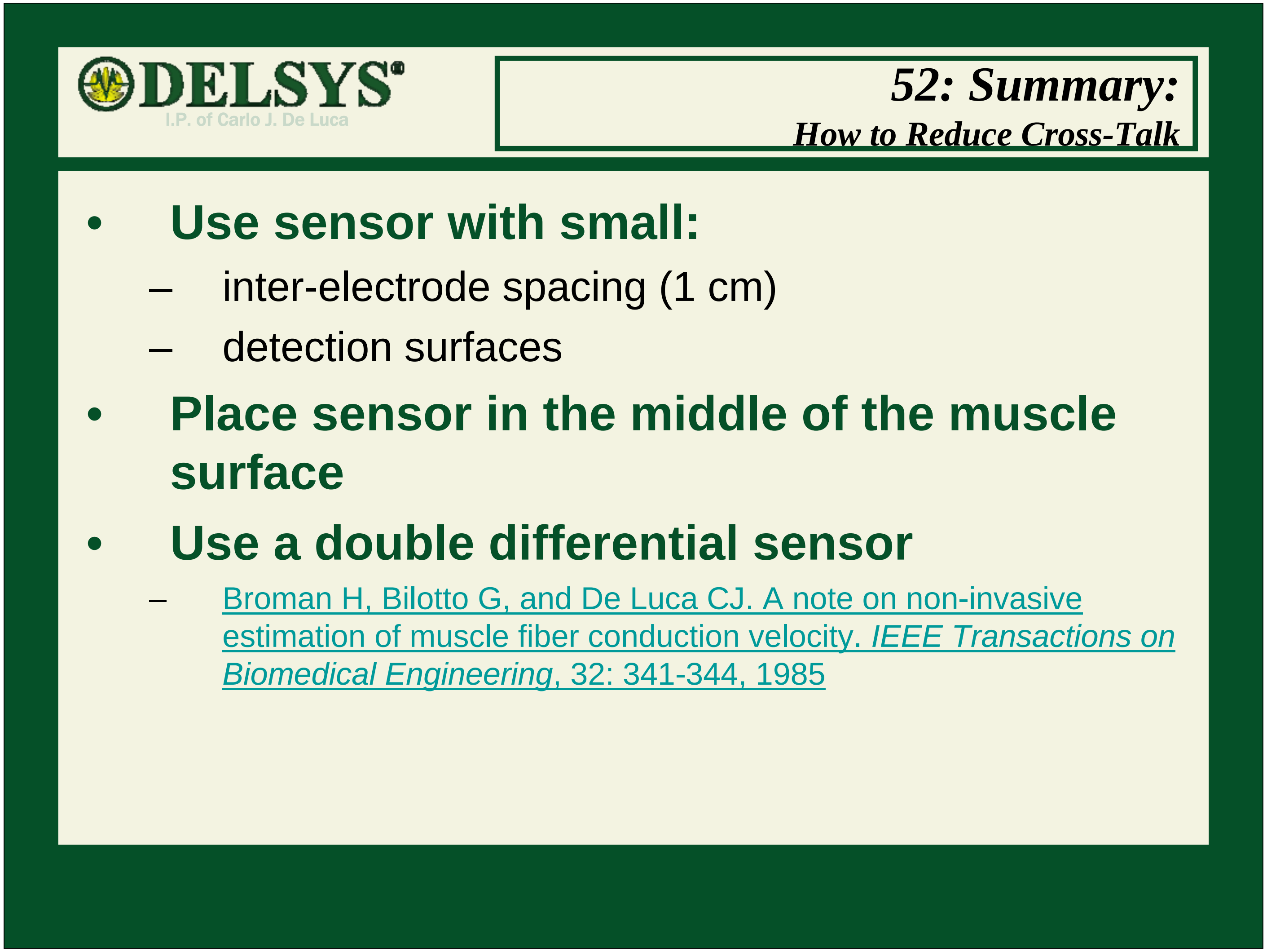
The top left panel shows the DD configuration along with a tap on a single differential (SD) configuration. (Note that the SD configuration tap is not available from the commercial version of the DD sensor.) This sensor detects both the SD sEMG signal and the DD sEMG signal.

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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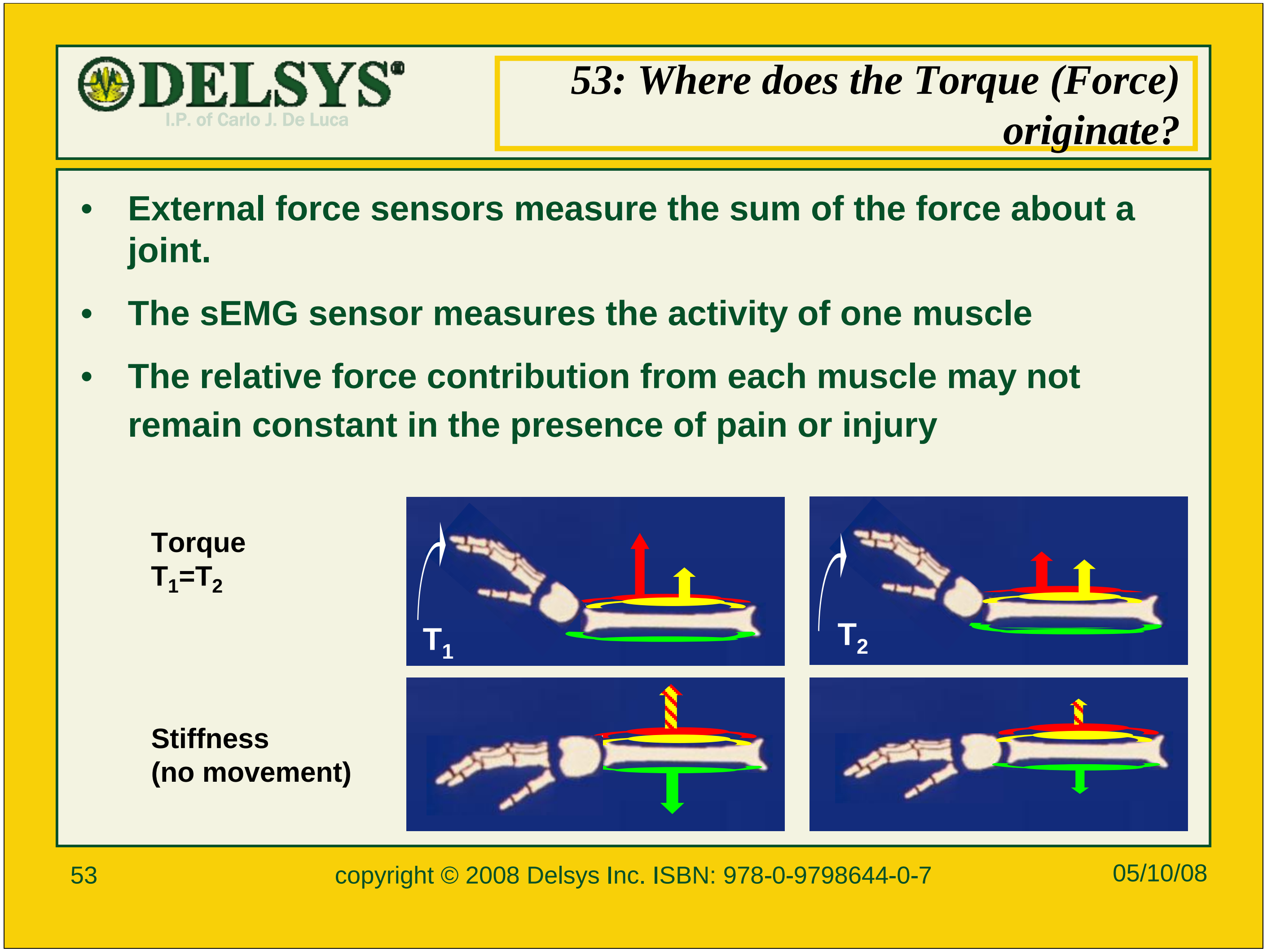
52: Summary:

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



53: Where does the Torque (Force) originate?

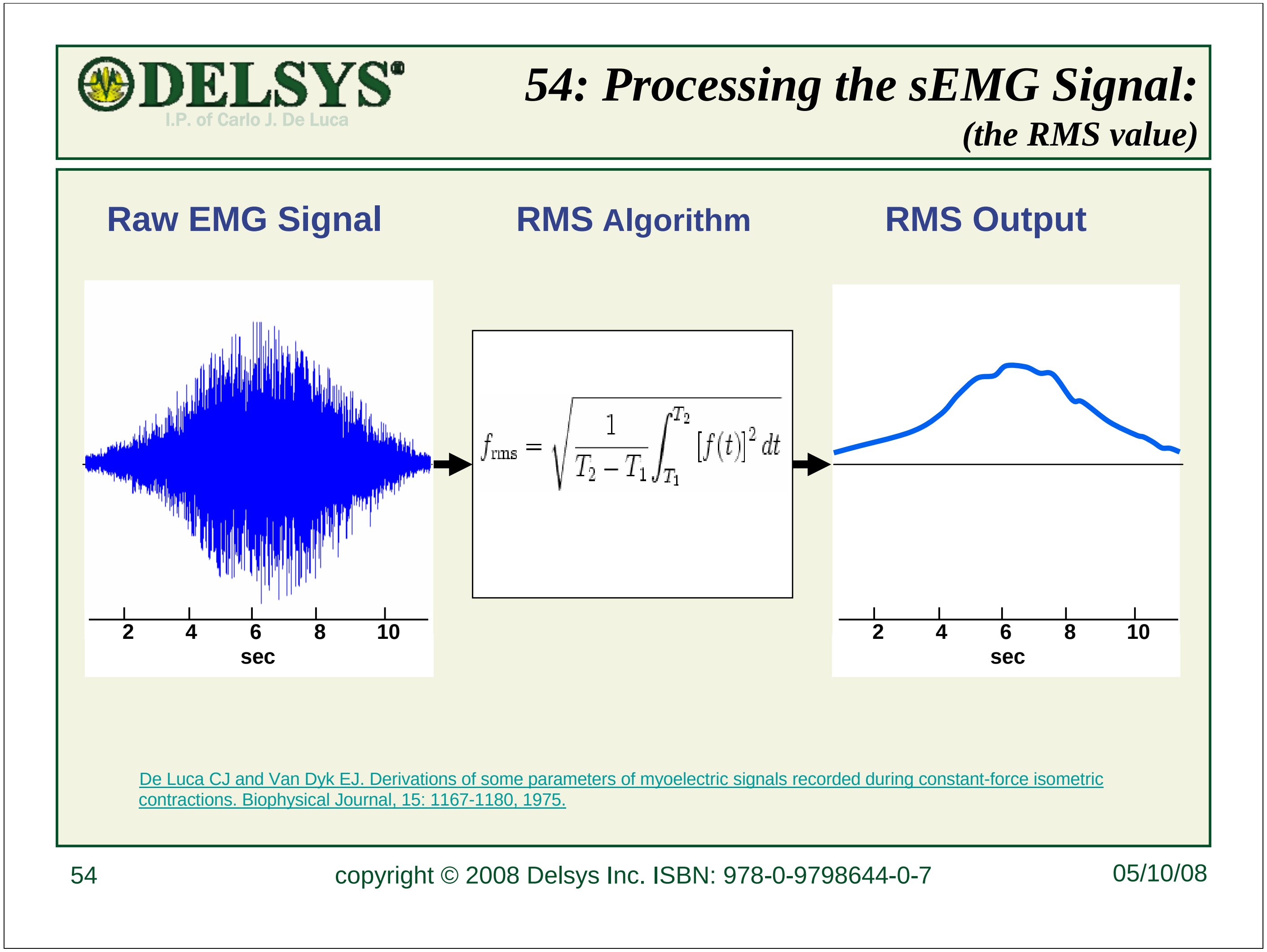
- **External force sensors measure the sum of the force about a joint.**
- **The sEMG sensor measures the activity of one muscle**
- **The relative force contribution from each muscle may not remain constant in the presence of pain or injury**

Torque
$T_1=T_2$

Stiffness
(no movement)

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.



54: Processing the sEMG Signal:

(the RMS value)

Raw EMG Signal **RMS Algorithm** **RMS Output**

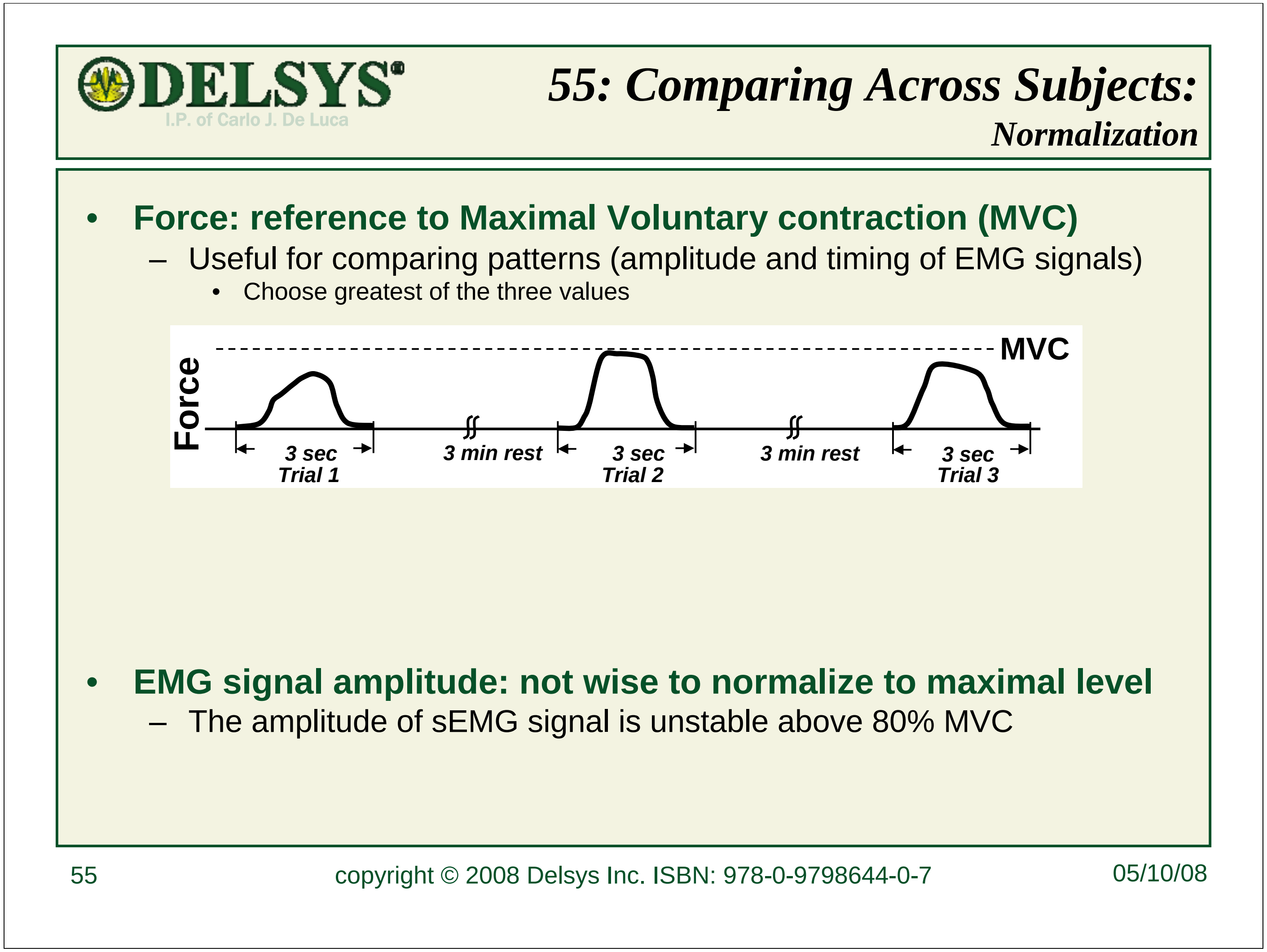
$$f_{\mathrm{rms}} = \sqrt{\frac{1}{T_2 - T_1}\int_{T_1}^{T_2} [f(t)]^2\, dt}$$

De Luca CJ and Van Dyk EJ. Derivations of some parameters of myoelectric signals recorded during constant-force isometric contractions. Biophysical Journal, 15: 1167-1180, 1975.

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

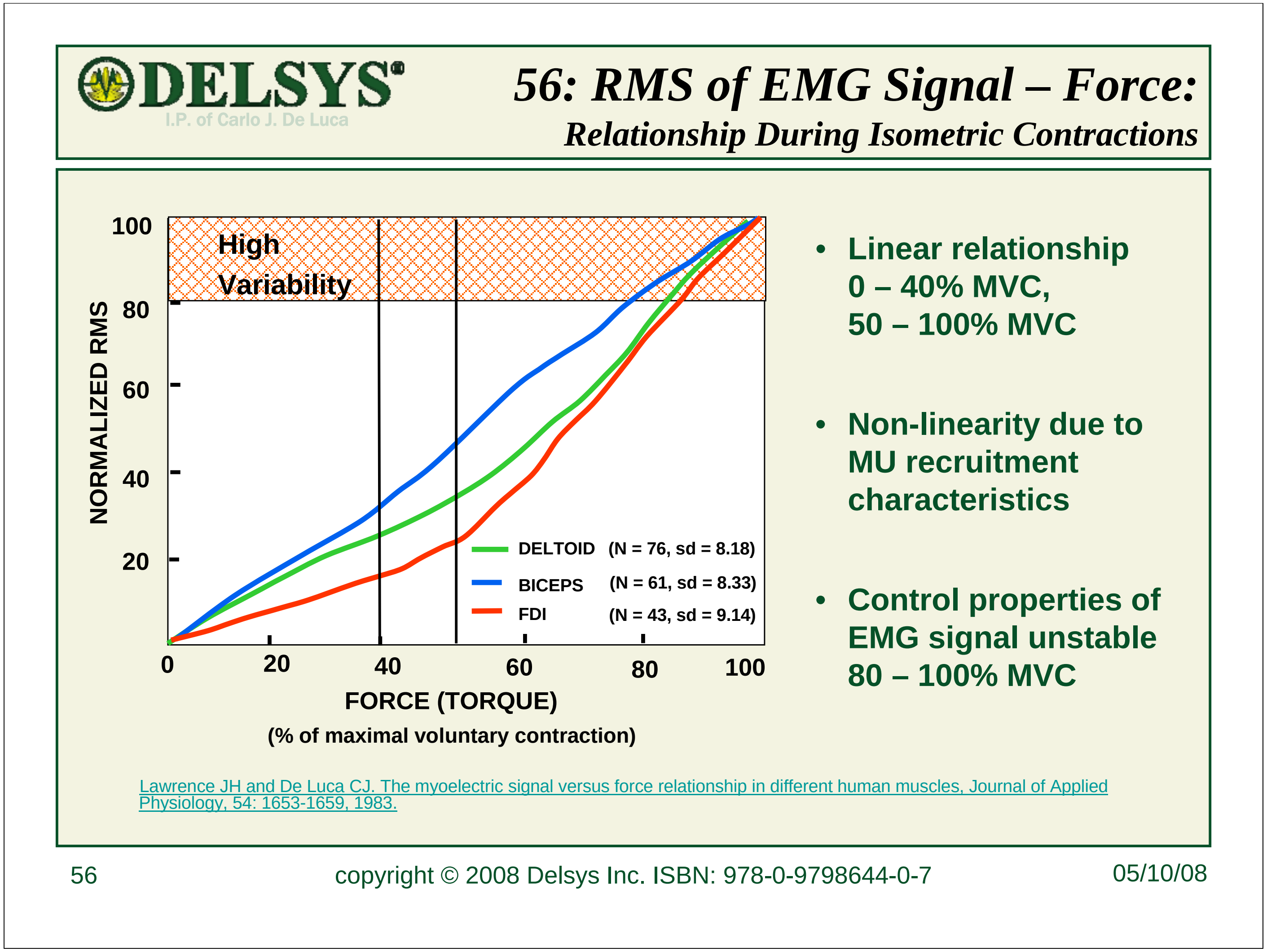
- **Force: reference to Maximal Voluntary contraction (MVC)**
  - – Useful for comparing patterns (amplitude and timing of EMG signals)
    - Choose greatest of the three values

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

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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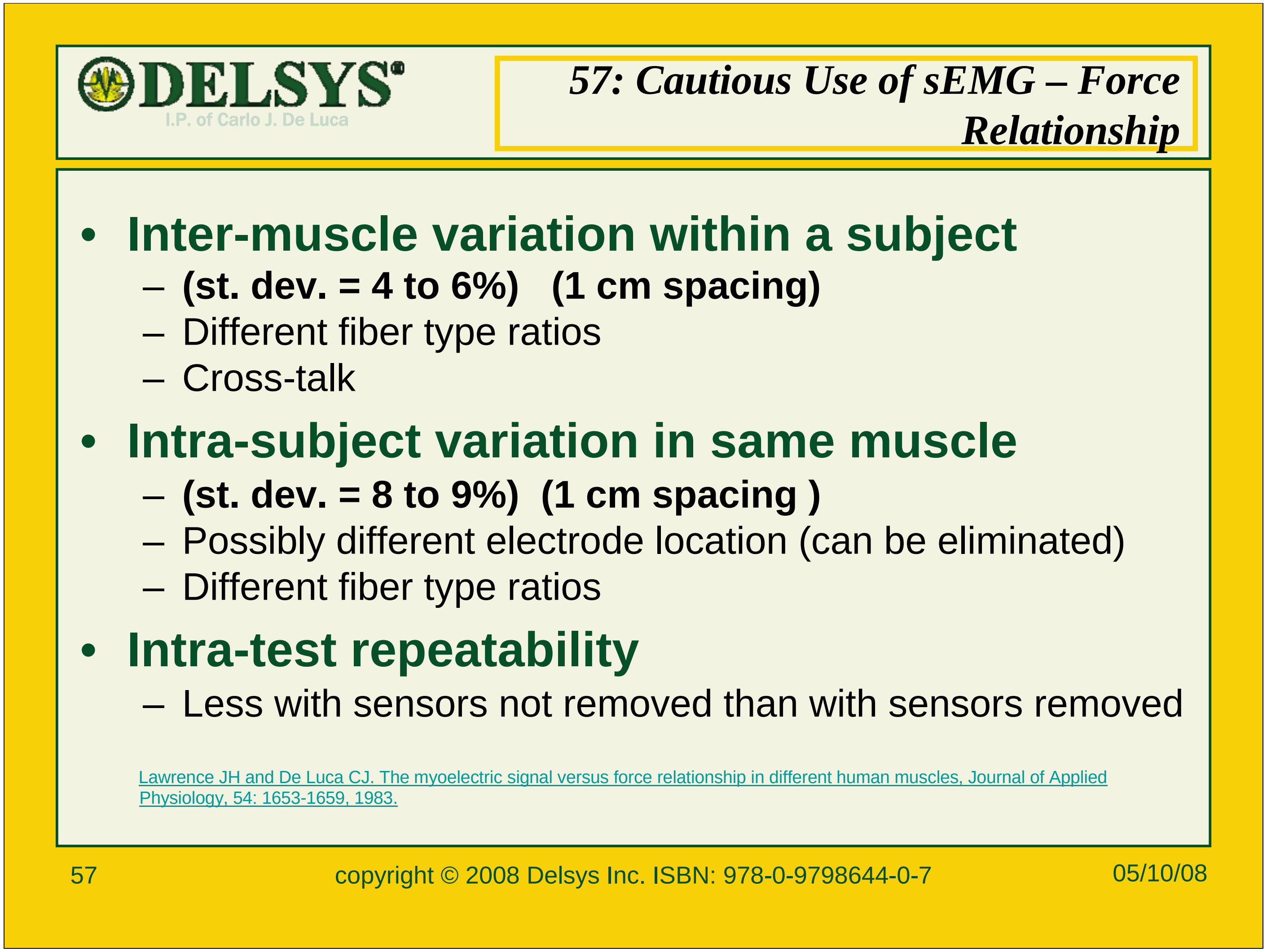
RMS of sEMG signal – force relationship during isometric contractions:

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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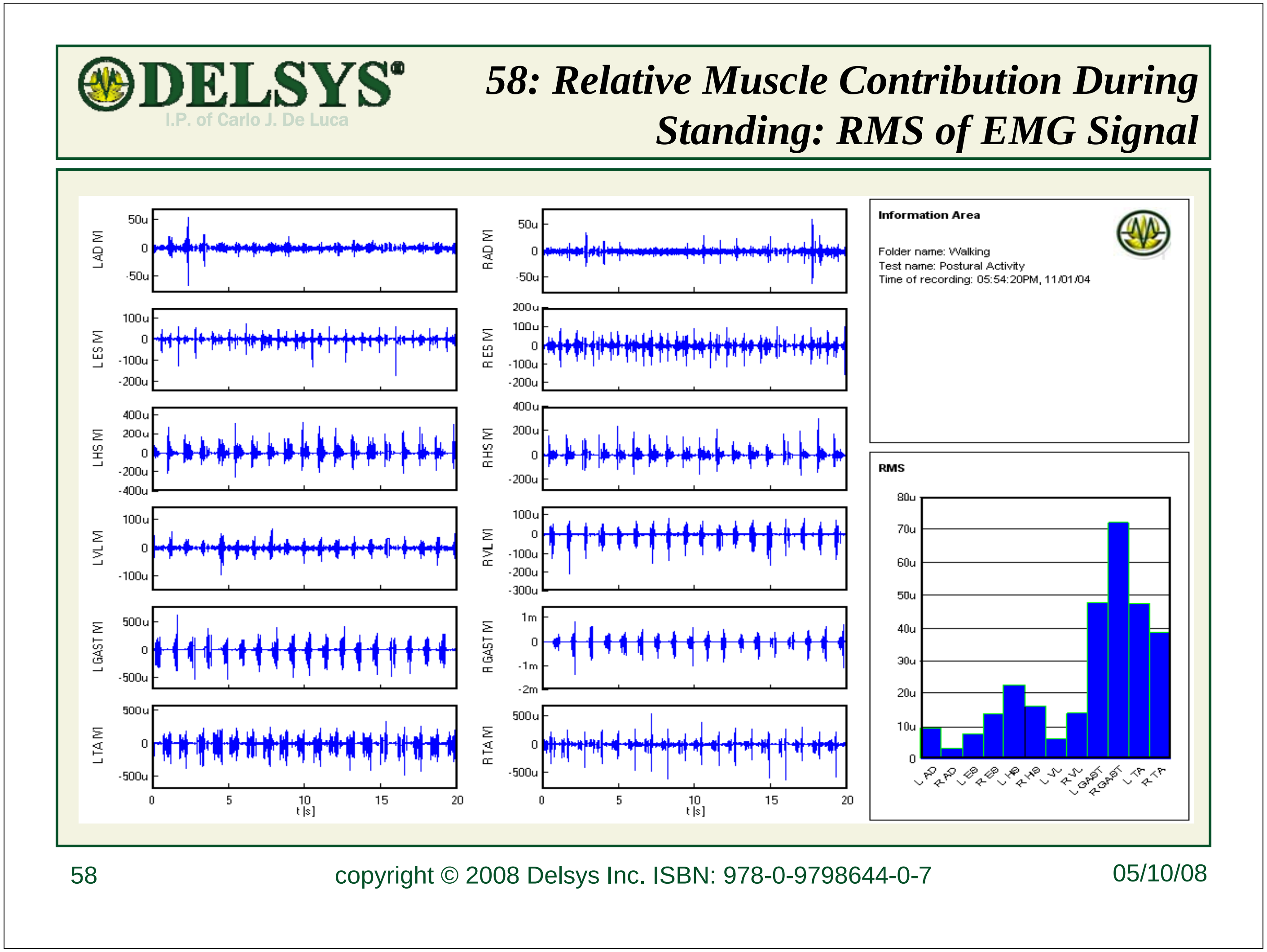
57: Cautious Use of sEMG – Force Relationship

- **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

Information Area

Folder name: Walking
Test name: Postural Activity
Time of recording: 05:54:20PM, 11/01/04

RMS

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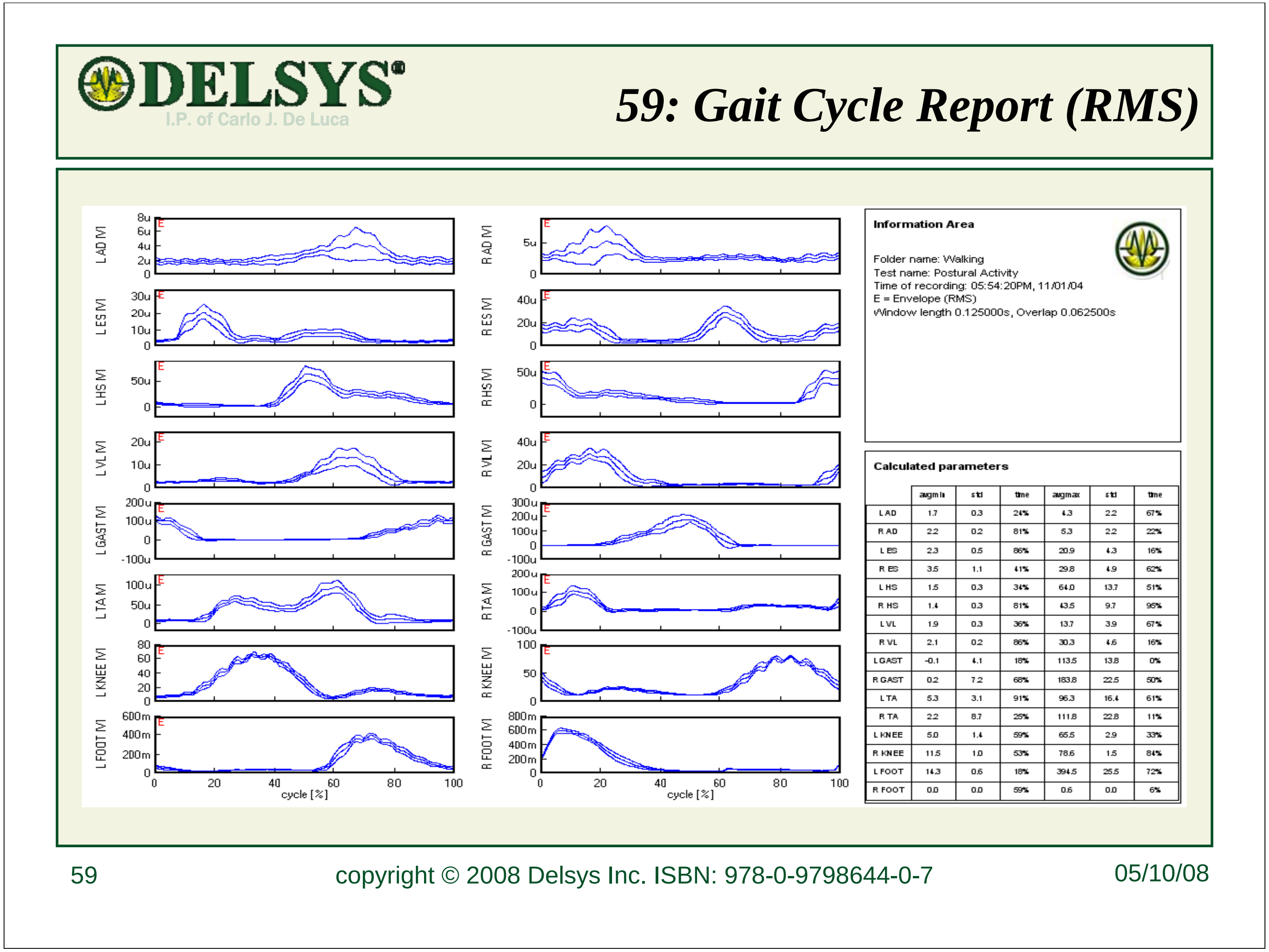
Relative muscle contribution during standing (RMS of EMG signal):

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

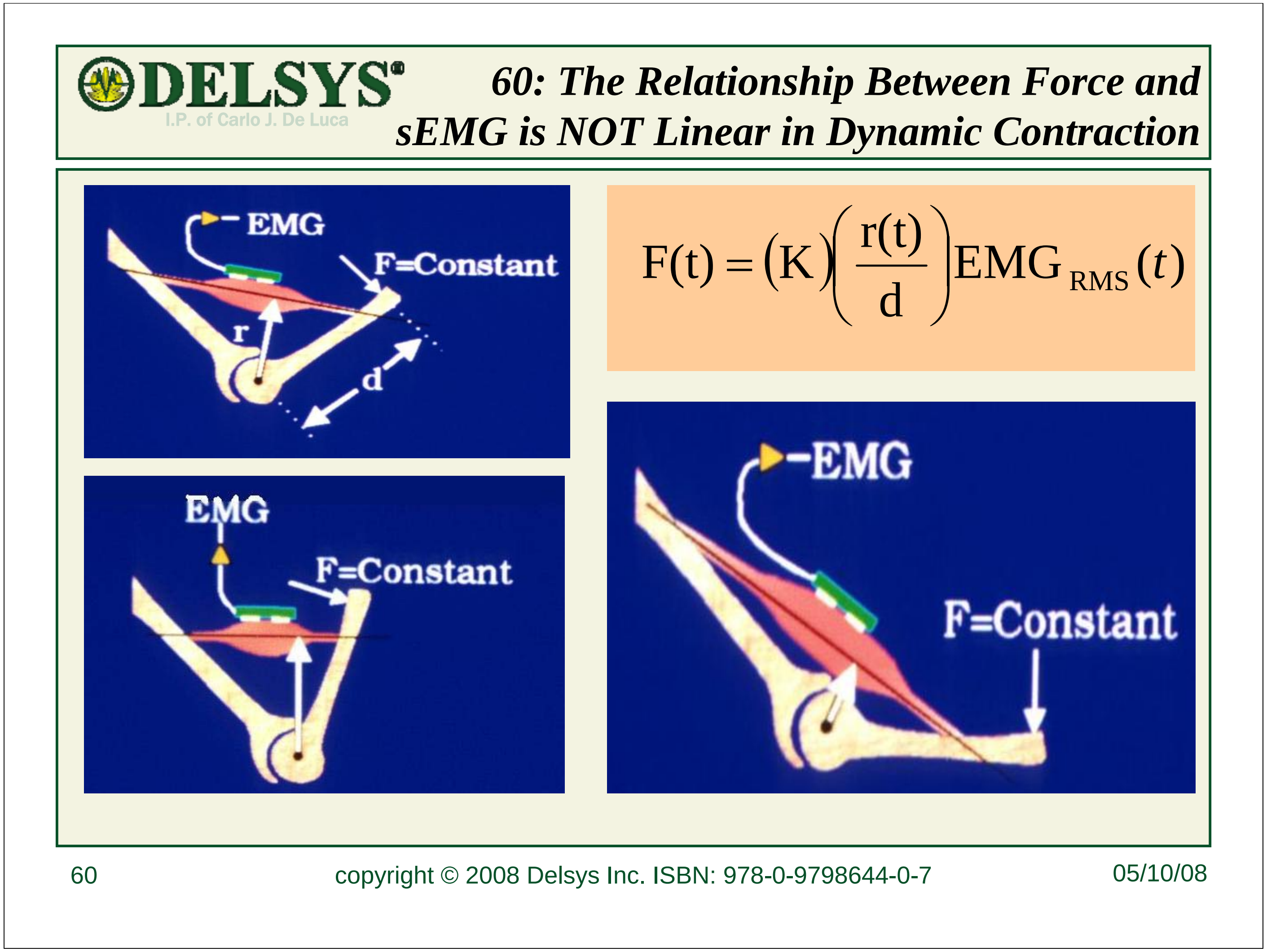
Folder name: Walking
Test name: Postural Activity
Time of recording: 05:54:20PM, 11/01/04
E = Envelope (RMS)
Window length 0.125000s, Overlap 0.062500s

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%

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

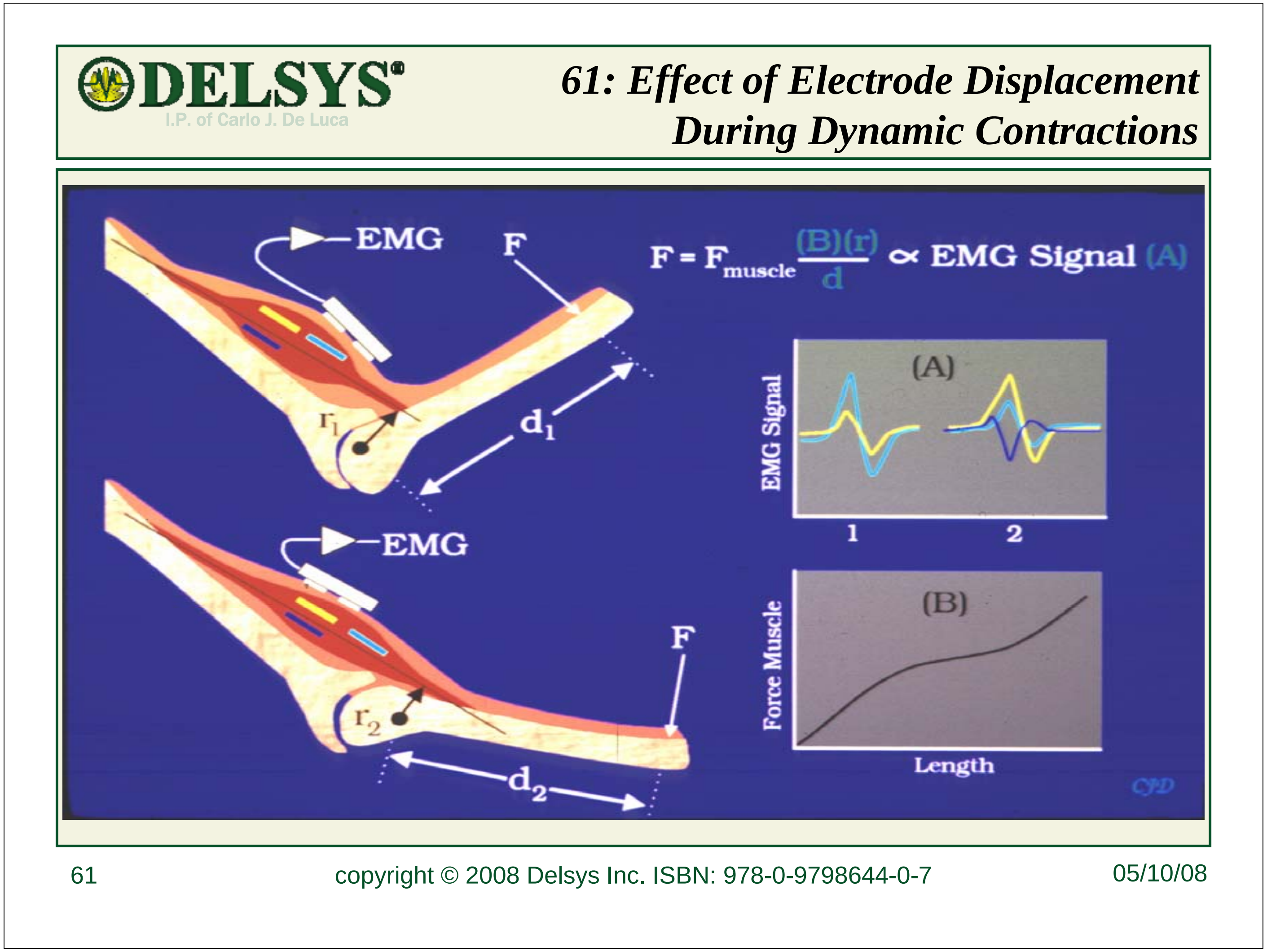
$$F(t) = (K)\left(\frac{r(t)}{d}\right)EMG_{RMS}(t)$$

60 05/10/08

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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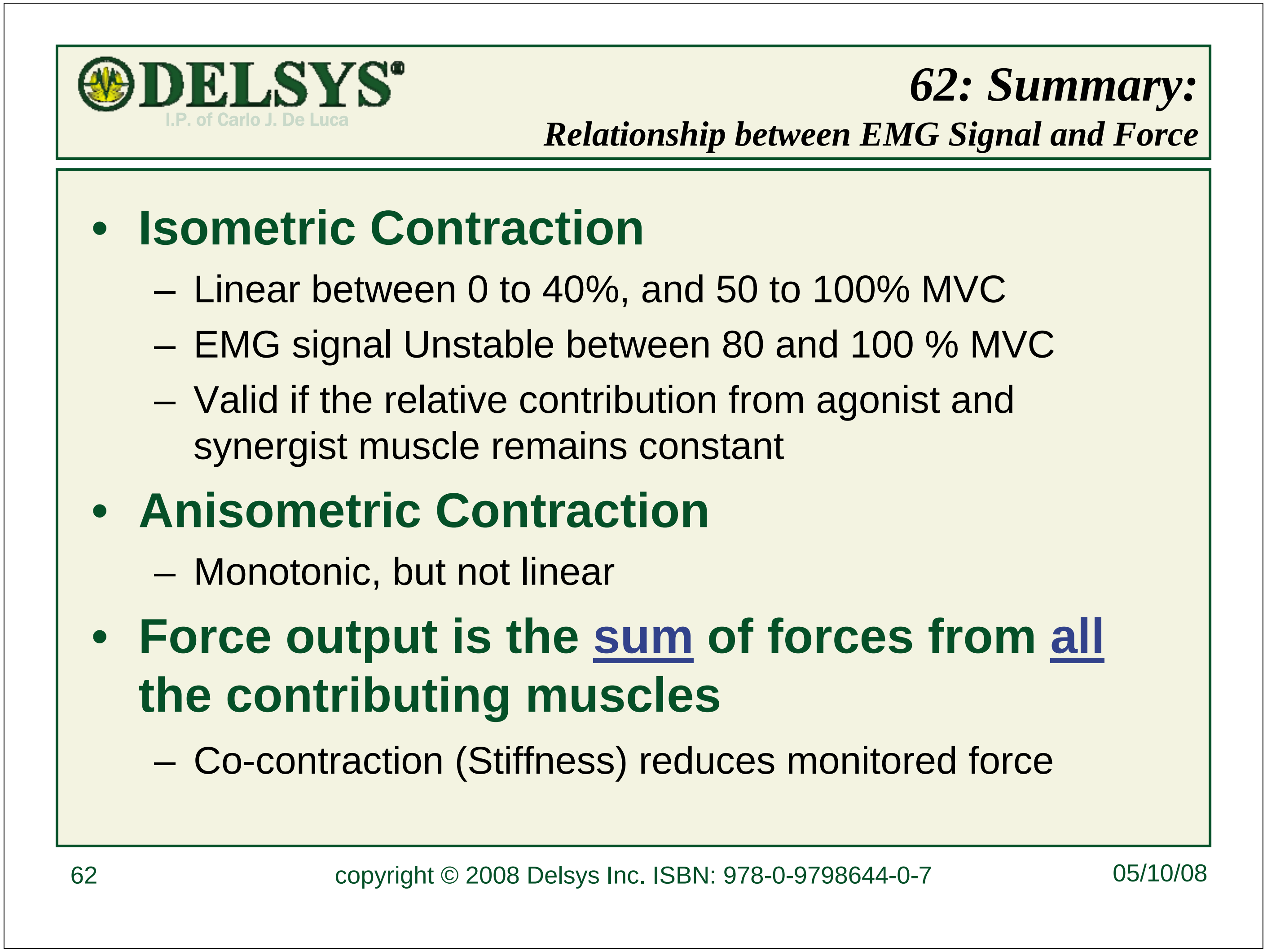
61: Effect of Electrode Displacement During Dynamic Contractions

$$F = F_{muscle}\frac{(B)(r)}{d} \propto \text{EMG Signal (A)}$$

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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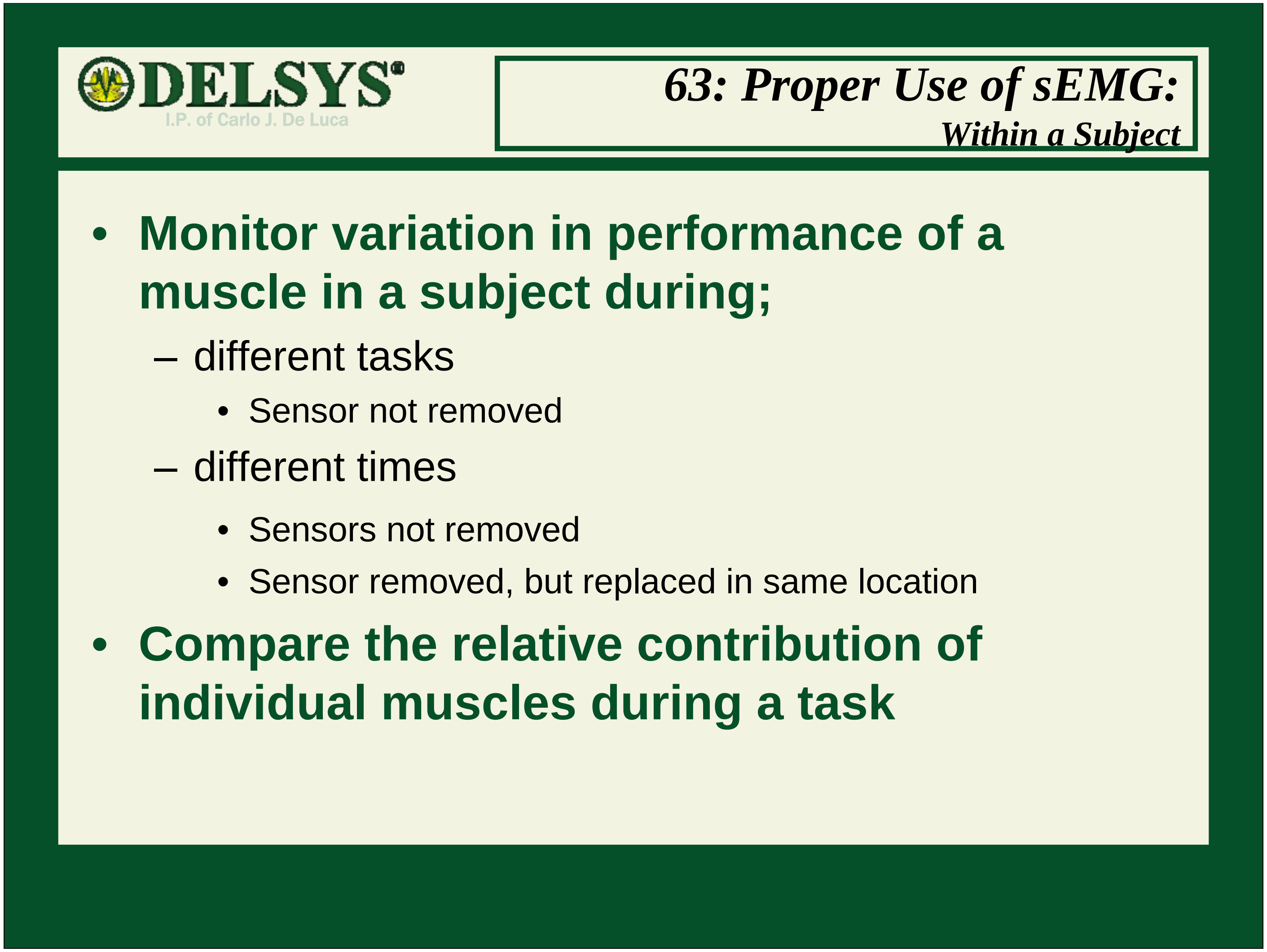
62: Summary:

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

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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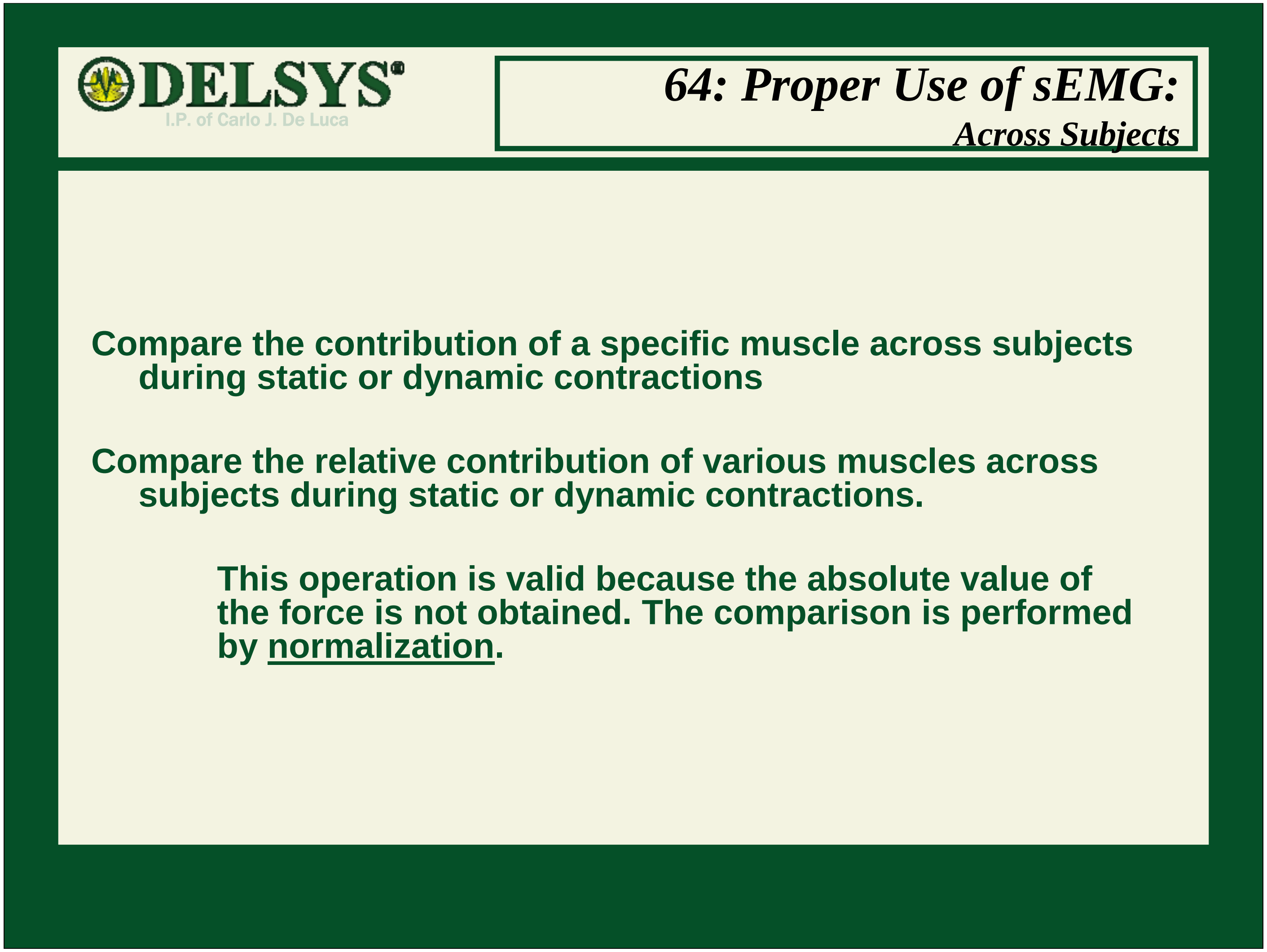
63: Proper Use of sEMG:

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.**