CAGLIARI
Sept 2015

ELECTROMYOGRAPHY (EMG): INTRO TO THE MUSCLE ACTIVITY ASSESSMENT TECHNIQUE

Julie N. Côté, PhD

Associate Professor, Department of Kinesiology and Physical Education, Associate Dean, research & graduate studies, Faculty of Education, McGill University, Montreal, Canada

Director, Occupational Biomechanics and Ergonomics Lab (OBEL), Laval, Canada (part of the Center for Interdisciplinary Research in Rehabilitation of Greater Montreal, Canada)

julie.cote2@mcgill.ca

Lab website: http://www.mcgill.ca/edu-kpe/facilities/obel/

ResearchGate: https://www.researchgate.net/profile/Julie_Cote

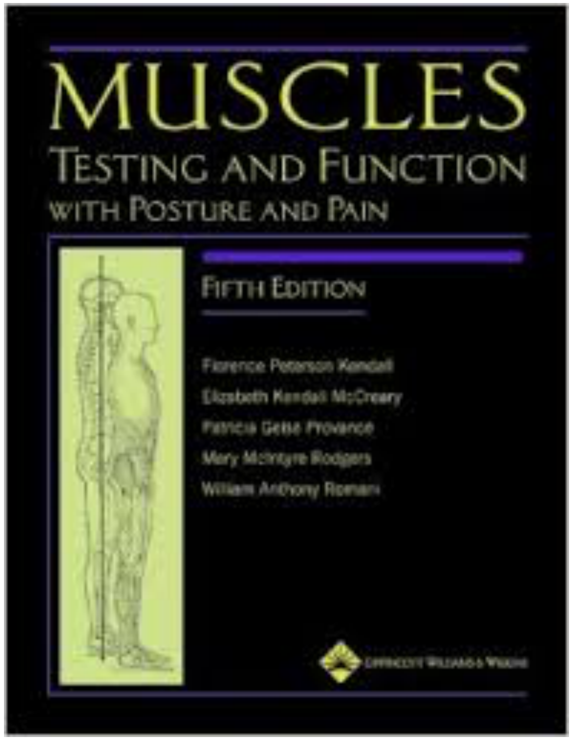
THREE MAIN SOURCES FOR TODAY'S LECTURE ON EMG METHODOLOGY

1) Noraxon©'s ABC of EMG (available online)

- EMG data acquisition system's manual

2) www.seniam.org

- SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles) is a European concerted action in the Biomedical Health and Research Program (BIOMED II) of the European Union
  - Published recommendations on EMG best practices

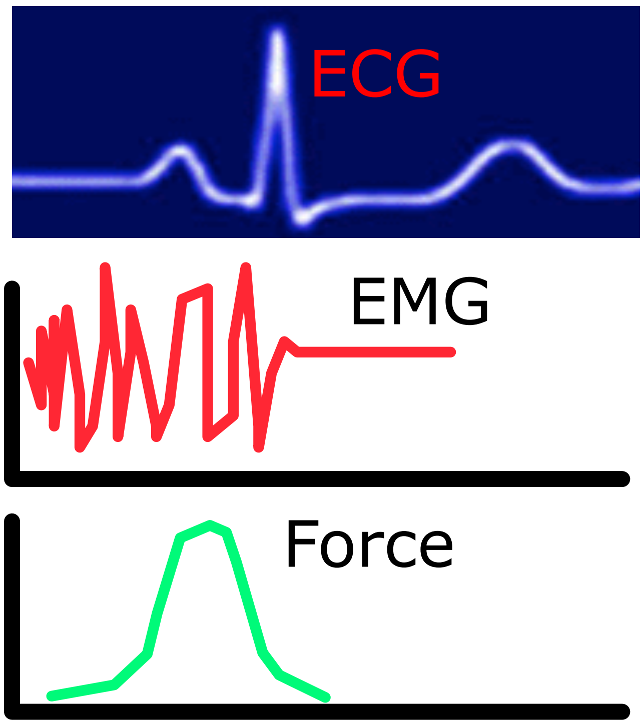


3) Kendall's Handbook on Manual Muscle Testing

- Often referred to when deciding how to conduct reference contractions
- MMT8 (shortened version) available online

WHAT IS ELECTROMYOGRAPHY (EMG)?

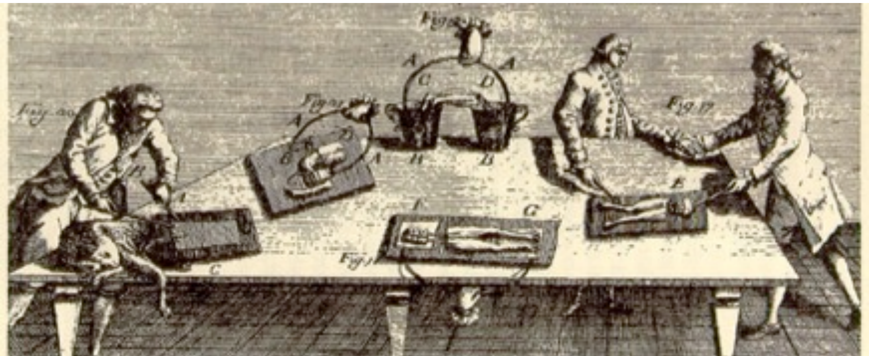
- Technique of recording the electrical activity of motor unit firing
  - Not muscle force per se, but the electrical signal sent by the motor nerves to muscle fibers to create force
- The electromyogram is the trace of the electrical signal detected by the electrode
- Uses electrodes applied on the skin (surface) or implanted into the muscle (indwelling) as "antennas" to pick up voltage signals
- Similar to ECG (EKG)
  – ECG is in fact electromyography of the heart muscle



EMG HISTORICAL LANDMARKS

- 1664 Croone — concluded from nerve section experiments that the brain must send a signal to the muscles to cause contraction
- 1791 Galvani (Bologna) — showed that electrical stimulation of muscular tissues produces contraction and force
- 1849 Dubois-Reymond — Was the first to discover and describe that contraction and force production of skeletal muscles were associated with electrical signals originating from the muscle
- 1867 Duchenne — Was the first to perform systematic investigations of muscular function using an electrical stimulation approach
- 1985 Basmaijan & De Luca

Summarized the existing knowledge and research on muscle function, as revealed by electromyographic studies (reference book)

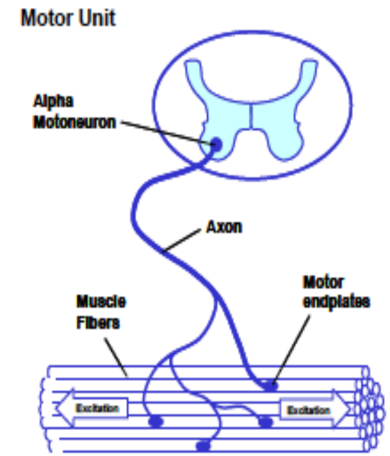

Luigi Galvani’s experiments, 1791

WHAT ELECTROMYOGRAPHY CAN TELL US

- Whether muscle is active or inactive in a given task
- When does the muscle turn on and off?
- Is there a temporal relationship between the muscles of interest?
- Is the magnitude of the EMG activity greater (implying higher stress)?
- Is the muscle fatigued?
- is the muscle injured or diseased? (some pathological profiles can be extracted from the EMG signature; e.g. MS)

THE FUNCTIONAL UNIT OF THE NEUROMUSCULAR SYSTEM:

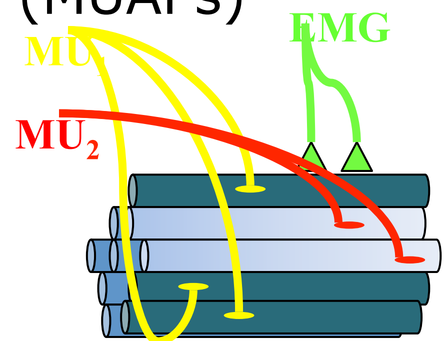
- **The Motor Unit (MU)**: comprised of:
  - The cell body and dendrites of ONE motor neuron
  - The multiple branches of its axon
  - The muscle fibers that are innervated by this neuron

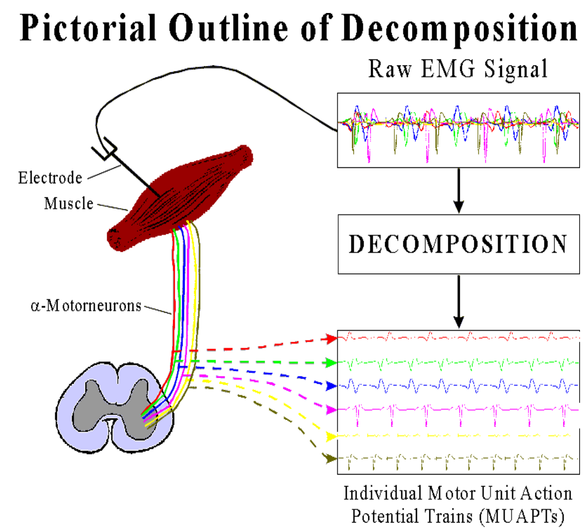


- Motor unit size can greatly vary:
  - As little as 5-10 muscle fibers innervated by one motor neuron
    - Where fine motor control is required (e.g. eye)
  - As many as thousands of muscle fibers in the biggest motor units
    - In muscles providing strength (e.g. quadriceps)

ORIGIN OF THE EMG SIGNAL

- The EMG signal (as perceived from surface electrodes) is composed of many individual motor unit action potentials (MUAPs)



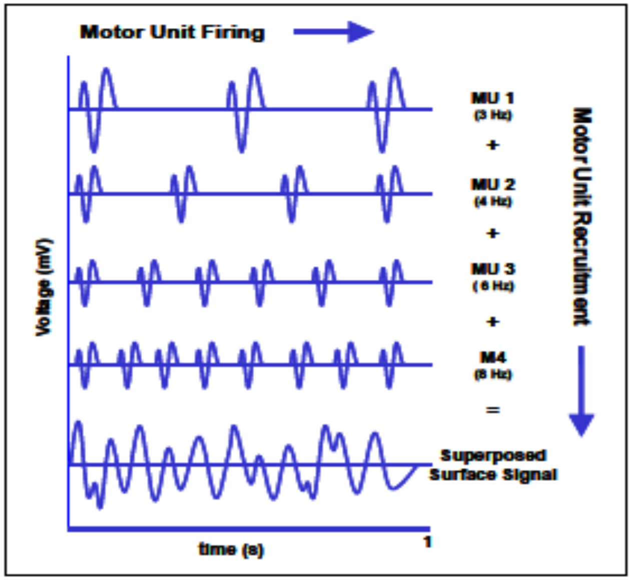


- Each MUAP has its own unique firing profile

- Muscular efforts usually require the activation of more than 1 motor unit

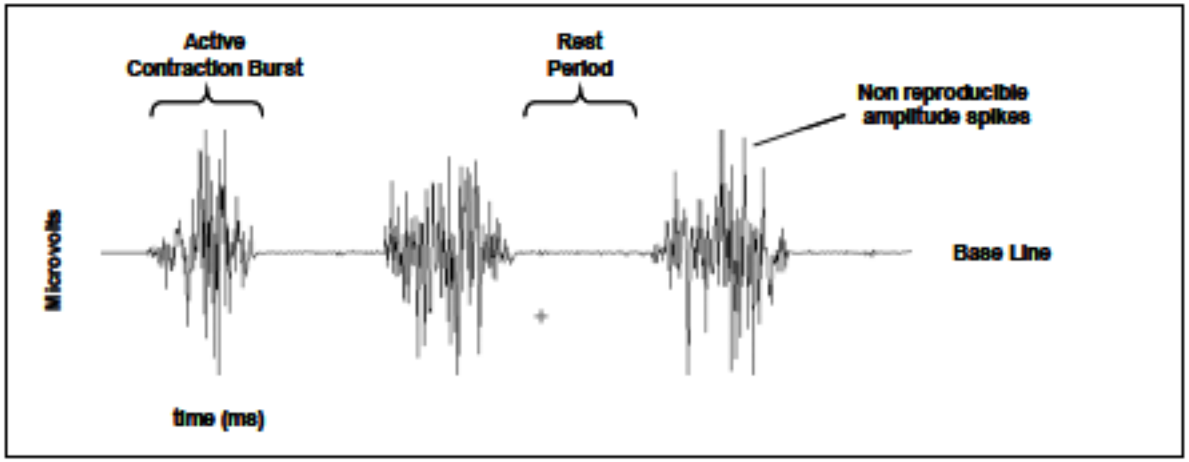
- According to Henneman's size principle, to increase strength, you recruit increasingly large, rapidly firing motor units

- The result is a curve summation that can be difficult to analyze and interpret



MAIN CHARACTERISTICS OF THE EMG SIGNAL

- As a result of the addition of many MUAPs, you get something like this:



- Dynamic: repetitive activation is easy to see (clear bursts)
- Tonic: static activation is more difficult to see
- There is always some baseline noise (at least 1-2 microvolts)
- Typical amplitude: microvolts (up to a few thousands in athletes)
- Typical frequency: 20 – 150 Hz

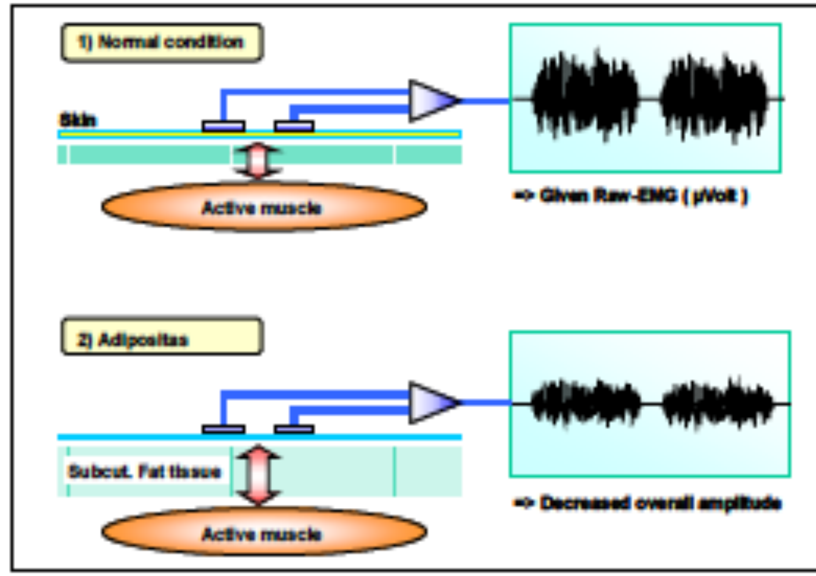
FACTORS AFFECTING THE ELECTROMYOGRAM

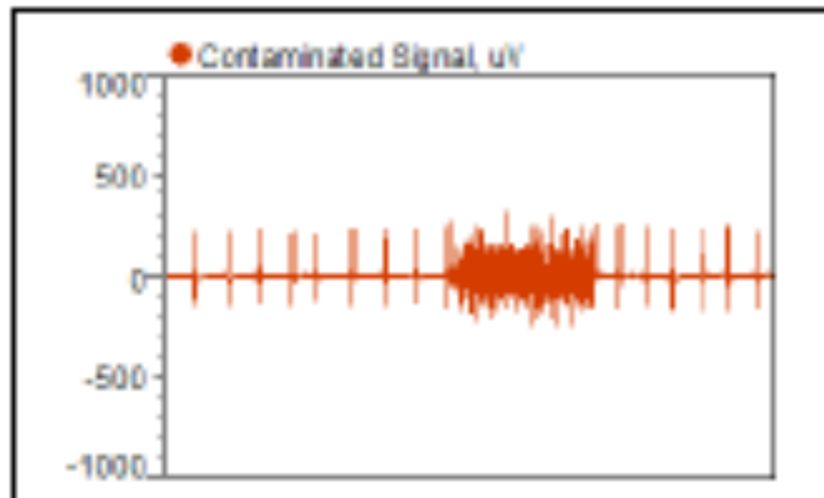
- INTRINSIC FACTORS:
  - Muscle fiber diameter involved in the signal
  - Number of muscle fibers involved in the signal
  - Muscle fiber conduction velocity
  - Muscle fiber type
  - Muscle fiber location
  - Motor unit firing rate
  - Muscle blood flow
  - Distance from the electrode to the muscle fiber
  - Amount and type of tissue surrounding the muscle
  - Hydration state of the muscle
  - Number of active motor units
  - Fatigue
  - Temperature

- EXTRINSIC FACTORS:
  - Characteristics of the electrode-skin interface
  - Signal conditioning
  - Inter-Electrode spacing
  - **Ambient noise**
    - **Power line hum**
    - **Machinery**
    - **Cross – talk (signals from sources other than what is studied)**
  - Distance between the electrode and the motor point

MOST IMPORTANT SOURCES OF « NOISE »

- ***Tissue characteristics***
  - Skin impedence, superficial fat, etc.
- ***Physiological cross-talk***
  - From neighboring muscles
  - From ECG, breathing, etc.
  - From cable movement (if not wireless)
- ***Ambiant noise***
  - Most common: sources of electrical current (North America: 60 Hz)
- ***Quality of electrodes and amplifiers***
- Most of these can be minimized with optimal preparation (skin preparation) or in post-processing (60 Hz)

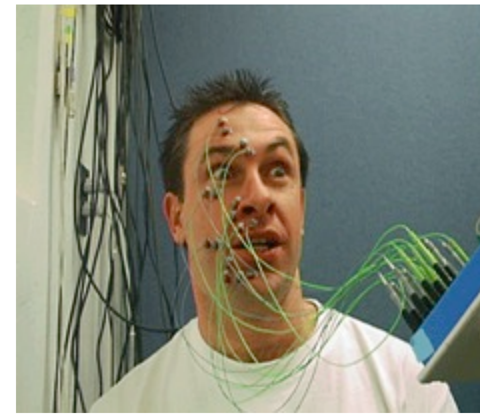




SETTING UP AN EXPERIMENT: SOME PRELIMINARY CHOICES TO MAKE

- Choose the muscles
- Choose the sampling frequency
  - Nyquist theorem: to reconstruct a signal adequately, the sampling frequency should be twice the highest expected frequency
  - To be sure, we consider that it is possible to capture frequencies around 500 Hz: sample at 1000 Hz (***1200 – 1500 Hz are common***)
  - If sampling frequency is ***too low***: aliasing (not enough data points to reconstruct the original signal)
  - If sampling frequency is ***too high***: Spectral recovering (record harmonics that may hide the real signal)
- Choose some analog filters
  - Usually inherent to the data acquisition system and amplifier that you have
  - You may want to apply select a ***band-pass filter, 10-500 Hz*** (cut the low frequencies that could be due to movement, or some other noise)
  - Consider applying a notch filter to cut 60 Hz ambient power noise (tough choice)

CHOOSING ELECTRODES



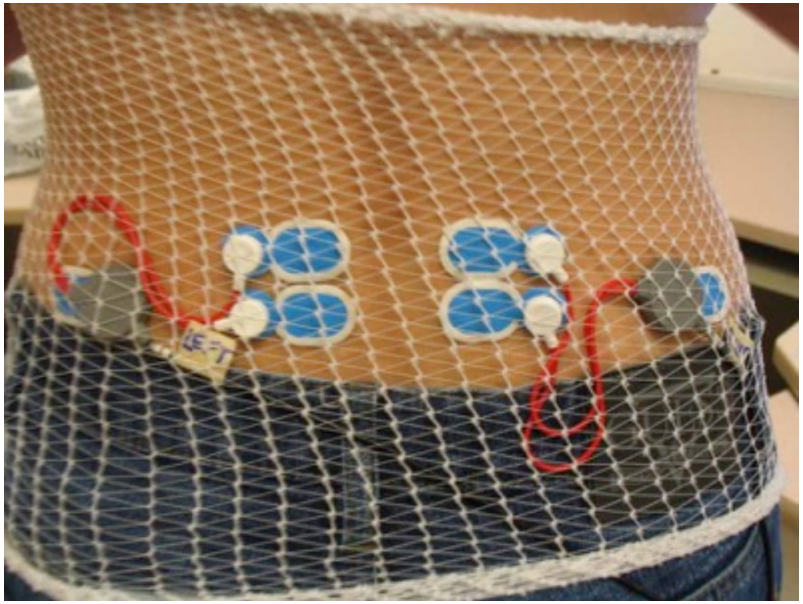
- Electrodes are electrically conductive material
  - Acts like an antenna
  - Detection zone: volume, with r proportional to electrode's radius squared
  - Records biological electrical signals
    - EMG, ECG, EEG

- Role of electrodes: transform ionic signals resulting from Na++ and K+ ion transport into electric signals (V)

- Biological material between the muscle and the electrode and its thickness *acts as a low-pass filter*
  - Attenuates the high frequency portions of the detected signal

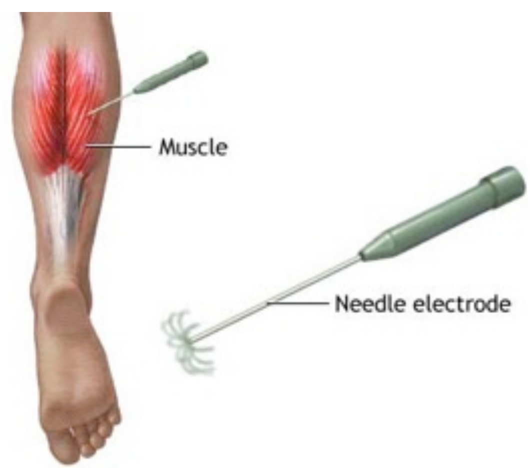
SURFACE ELECTRODES

- Detection of electrical signals arriving at the skin surface
- Advantages:
  - **Non invasive**
  - **No discomfort**
- Disadvantages:
  - **Cross-talk from other muscles**
    - **Neighboring muscles: possible to reduce**
    - **Deep muscles: not much reduction possible**
- Typical applications: sports, work, studying big strong, superficial muscles



INDWELLING (NEEDLE) ELECTRODES

- Direct measurement within the muscle
- Advantages:
  - Possibility to investigate individual MUs
  - Possibility to record the activity of deep or small muscles or weak contractions
  - Less signal interference
  - More sensitive to fatigue
- Disadvantages:
  - Pain (during insertion, during movement)
  - Limits applications in fatigue and rehabilitation studies
  - Contractions may change wire position
  - Risk of contamination
- Use when studying a deep muscle and-or a specific disease

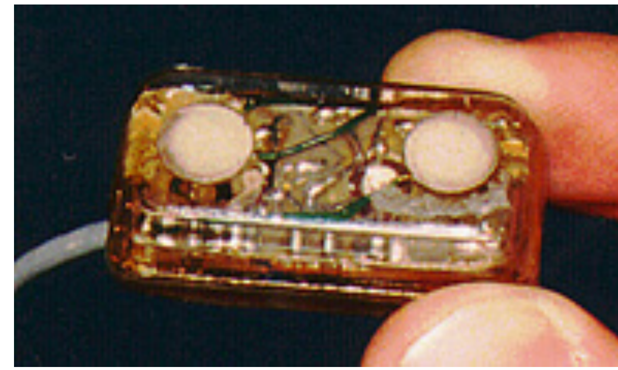


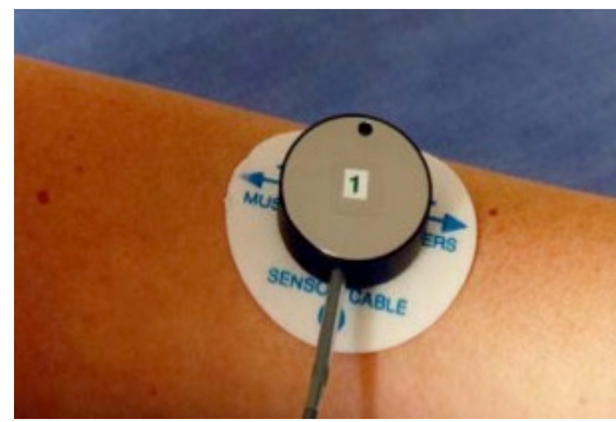
ACTIVE vs. PASSIVE ELECTRODES

- Active = includes an on-site amplifier
- Advantages
  - Picks up and amplifies the signal before some sources of contamination get to it
    - Electricity
    - Cable movement
- Disadvantages
  - Bigger and heavier
  - don't fit as closely to the skin
  - May be damaged more easily
- New technology: wireless EMG
  - Active electrodes better that way

ELECTRODE CONFIGURATIONS

- Most common: bipolar
  - Two electrodes are used, the signal difference is considered (= proportional to the signal strength)
  - Noise common to both sites is cancelled (= common mode rejection)
  - Difference is calculated at the (differential) amplifier
  - Inter-electrode distance: 4 x the radius of individual electrodes

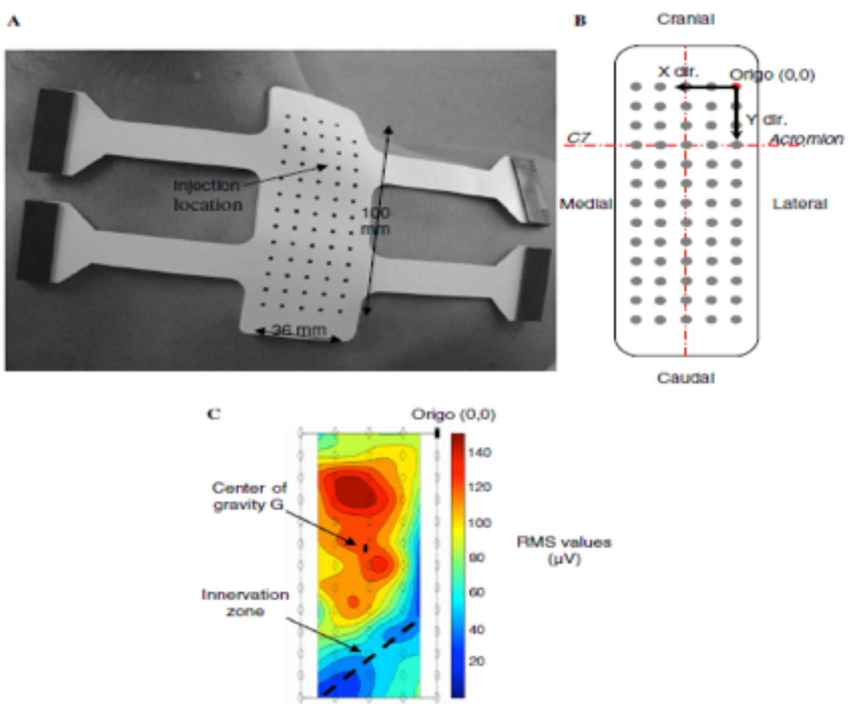


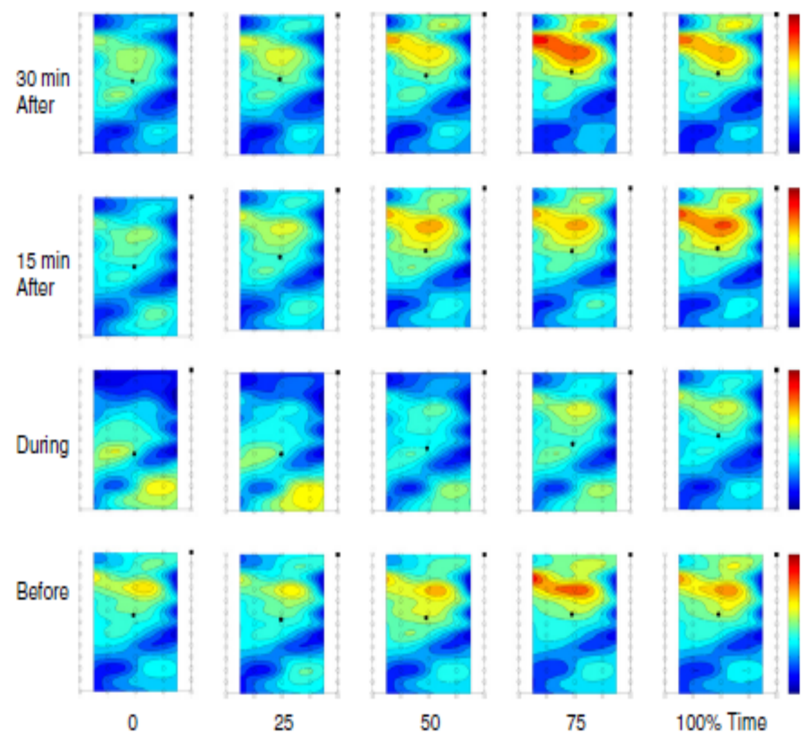


- Sometimes monopolar is used
  - Especially for isometric recordings

MULTIELECTRODE MATRICES

- Madeleine et al., 2006: 2D Visual and quantitative inspection of zones of highest activity in muscles
- Advantages: 1) study muscle parts, 2) apply spatial filters
- Disadvantages: may not be that precise (depends on anatomy,…)

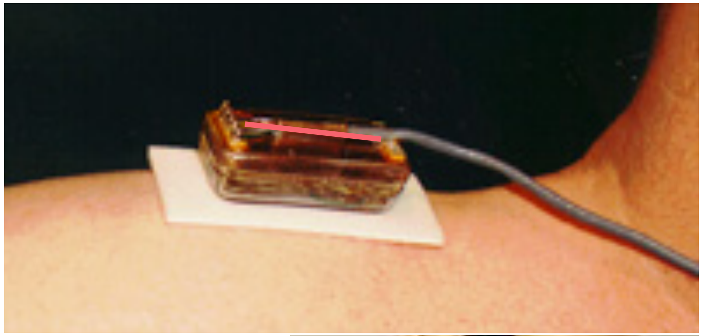


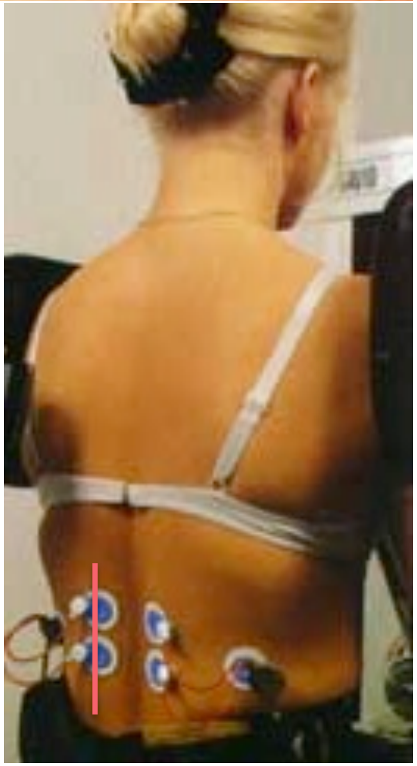


MOVING ON TO THE EXPERIMENT!

- Preparing the subject
  - Objective: reduce material optimize conductance at the electrode-skin interface
  - Noraxon: you should shave the subject
  - SENIAM: shave if the skin surface on which electrodes are to be placed is covered with hair
  - You may want to shave to minimize pain when removing the electrodes…
  - Not as crucial if you do within-subject analyses
  - After shaving (or not): lightly abrade the skin to remove dead skin
  - Finally, clean the site with alcohol, let it dry
  - Make sure there is no air between electrode and skin
  - Fix cables (if there are) with elastic bands or adhesive tape

PREPARING TO PLACE THE ELECTRODES

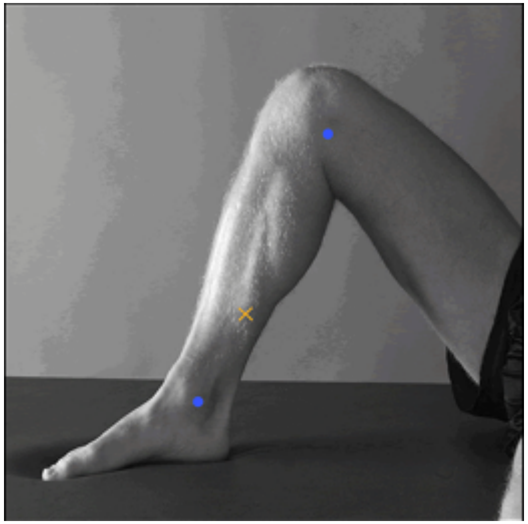




- Location: ***always*** place the electrodes on the muscle belly, away from tendons
- Orientation: always place the (bipolar) electrodes parallel to muscle fibers
  - The ***imaginary line*** joining the two electrode centers should be as parallel as possible to the muscle fibers underneath
- Usually you need to place a ground electrode at a bony landmark
  - Avoid creating internal currents (small)

IDENTIFYING THE BODY LOCATIONS

- As precisely and objectively as possible
  - E.g. cervical erector spinae: 2cm lateral to C7
  - Ensures ***valid*** (you are measuring what you want to measure) and ***reliable*** (you can make repeated measures at the same site) as possible
- Refer to previously published papers or guidelines
  - Basmaijan
  - Noraxon
  - Seniam (very precise!)
- Palpate and place the electrode when the subject is approximately in expected mid-range of movement

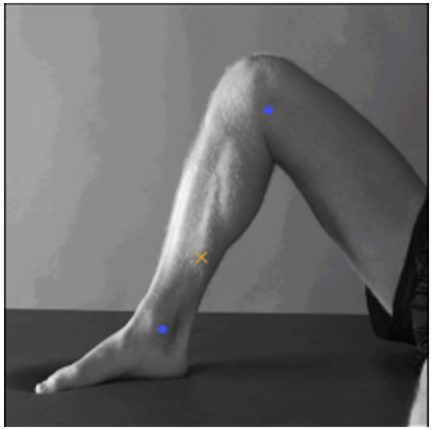


PRELIMINARY TRIALS

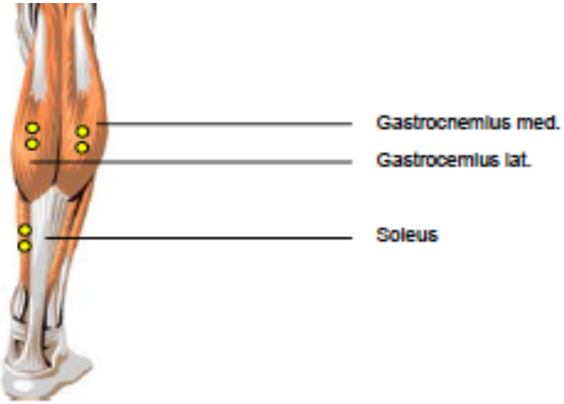
- Check that all signals are working
  - Malfunctioning electrodes are usually easy to detect (flat line, 60 Hz,…)

- Conduct reference trials
  - Purpose:
    - Express experimental values relative to standard actions (reduces some inter-subject variance)
    - Cancel out some noise that could be present during both reference and experimental trials
  - Two kinds:
    - Maximal voluntary ***isometric*** contractions (***MVIC***): apply resistance in a direction opposite to muscle action, keep effort isometric (see Kendall, Noraxon)
    - Sub-maximal (reference voluntary ***isometric*** contractions (***RVIC***): standard efforts (e.g. hold the arms horizontal, abducted); preferred in patients who may not easily perform MVIC

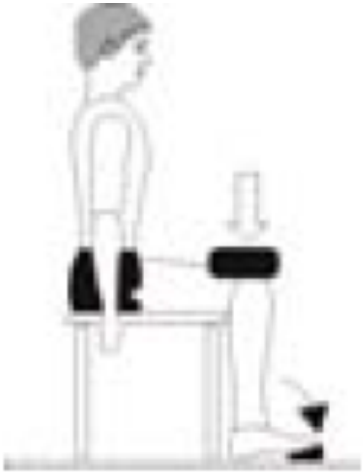
EXAMPLE: SOLEUS



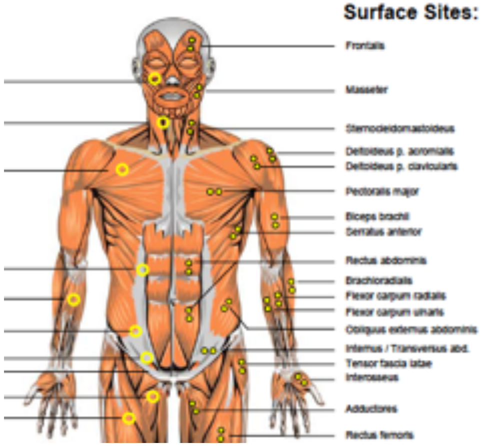
- Electrode placement:
  - SENIAM: 2/3 of the line between the medial condyle of the femus and the medial malleolus
  - NORAXON: see picture



- MVIC:
  - SENIAM: seated: put a hand on the knee and keep / push the knee downward while asking the subject / patient to lift the heel from the floor.
  - NORAXON: about the same (specify that it is very important to do this seated, this decreases the activation of gastrocnemius)



EXAMPLE: BICEPS BRACHII



- Electrode placement:
  - SENIAM: on the line between the medial acromion and the fossa cubit at 1/3 from the fossa cubit
  - NORAXON: see picture

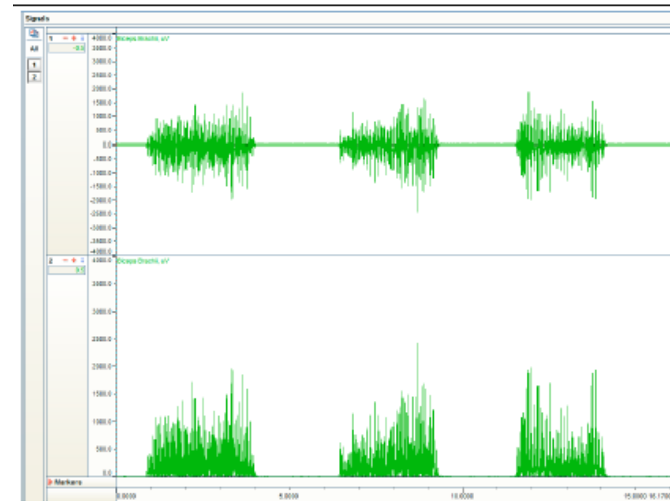
- MVIC:
  - SENIAM: Place one hand under the elbow to cushion it from table pressure and flex the elbow slightly below or at a right angle, with the forearm in ***supination***. Press against the forearm in the direction of extension.
  - NORAXON: ***stabilize elbow and trunk***: seated or kneeling
  - Kendall: similar to SENIAM
    - Gravity-eliminated (patients): patient sitting with shoulder abducted or sidelying

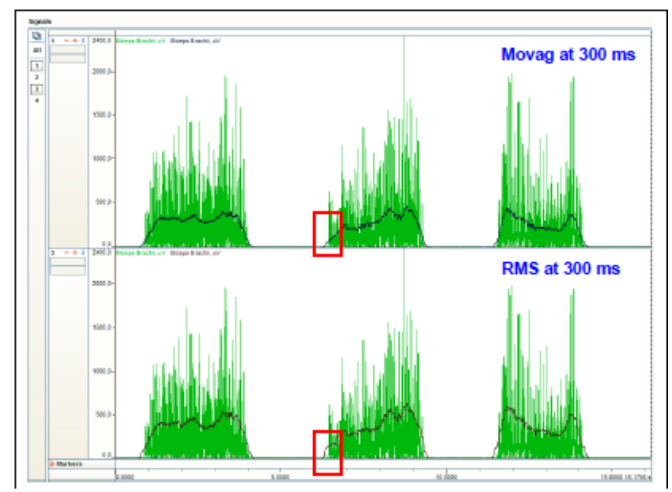
SIGNAL PROCESSING

- Step 1: signal rectification
  - Otherwise, your average signal would be zero!
  - Two options:
    - Full wave: take the absolute values
    - Half wave: keep only the positive data

- Step 2: linear envelope
  - Filter out the high-frequency content
  - Output: a smooth pattern that represents the volume of activity
  - Various techniques (e.g. moving average, RMS)

- Other signal treatments: digital filters (e.g. Butterworth), integration, amplitude normalization (to MVIC or RVIC), time normalization (to 100%),…



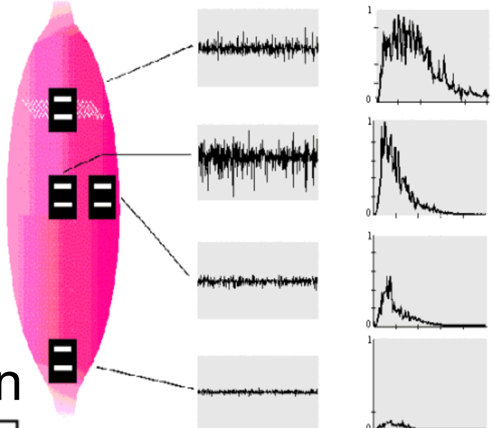


EMG SIGNAL CHARACTERISTICS

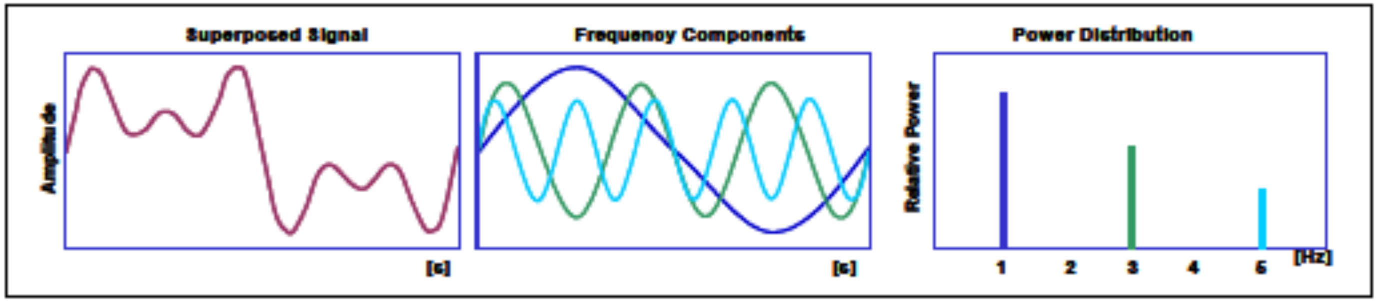
AMPLITUDE CHARACTERISTICS (TIME DOMAIN)

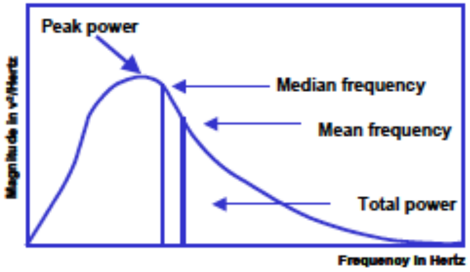
- EMG amplitude parameters most often studied:
  - Maximum, minimum, mean, RMS, burst onset – duration – offset, time to peak

FREQUENCY CHARACTERISTICS (Fourrier transform)



- EMG frequency spectrum:
  - Amount of signal in each frequency bandwidth
- Parameters most often used:
  - Mean, median, peak power frequency
- Number of zero crossings
  - A measure of frequency, but start from time domain





ADDITIONAL EMG MEASURES

- ***Co-activation***
  - Simultaneous activation of agonist-antagonist muscle pairs
  - Sign of stiffness, rigidity, injury protection, fatigue?...

- ***Cross-correlation***
  - Computational technique to calculate co-activation

- ***Mutual information (functional connectivity)***
  - Another technique to quantify shared activation between muscle pairs (accounts for both linear and non-linear commonalities between signals)

- ***Variability***: SD or Coefficient of Variation (SD/mean)

- ***Amplitude probability distribution functions (APDF)***
  - Amount of the signal contained below or above certain levels of activity (e.g. APDF 10%MVIC)

OTHER USES OF EMG

- Biofeedback, e.g. to learn to relax muscles
  - http://www.youtube.com/watch?v=zibNKUXCTGQ
- Prosthesis control
  - http://www.youtube.com/watch?v=FhoTjI2K2-U

FATIGUE

Julie Côté, PhD

Associate Professor,
Department of Kinesiology and Physical Education
McGill University

Occupational Biomechanics and Ergonomics Laboratory (OBEL)

Michael Feil and Ted Oberfeld/CRIR Research Centre
Jewish Rehabilitation Hospital, Laval

julie.cote2@mcgill.ca

DEFINITIONS

"It ought to be generally known that the source of our pleasure, merriment, laughter, amusement, as of our grief, pain, anxiety and tears, is none other than the brain"

Hippocrates

DEFINITIONS OF FATIGUE

- Edwards 1981, Bigland-Ritchie et al. 1995:
  - Any reduction in the ability to exert force in response to voluntary effort
    - Relates the definition to a peripheral mechanism
- Enoka and Stuart (1992), Jones and Hunter (1983):
  - Ongoing process that results in impairment in performance that leads to both the inability to maintain a certain level of force and an increased perception of task difficulty.
    - More general and also accounts for central (motor and perceptual) influences
- Clinical context (Chaudhuri and O Behan, 2004):

  Clinical fatigue can be diagnosed from a difficulty in initiation of or sustaining voluntary activities

VARIOUS KINDS OF FATIGUE

- General body fatigue (physiological / cardiovascular system)

- Muscular fatigue (physiological/ musculoskeletal system)
- Mental fatigue (brain, psycho/physiological)

CARDIOVASCULAR FATIGUE

- Related to long-duration, low-intensity, whole-body efforts

- Ways to assess cardiovascular fatigue:
  - Directly, using cardiovascular indices of exertion
    - Gas analysis techniques
    - Heart rate
    - Blood lactate levels
    - O2 saturation levels

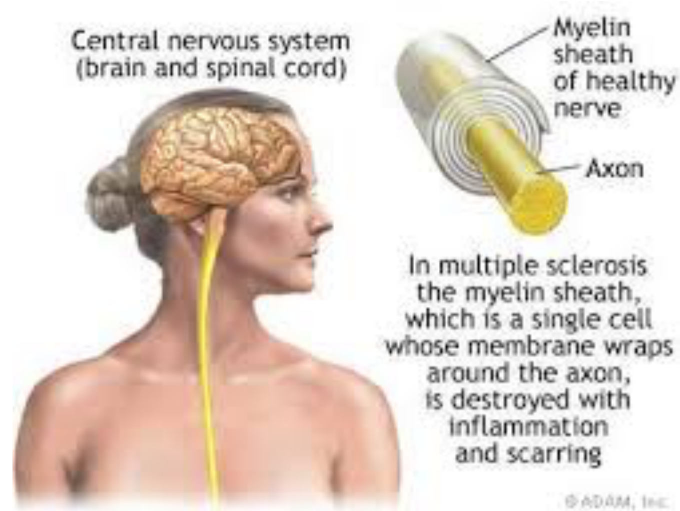
  - Indirectly, using questionnaires / scales
    - Borg general scale (1970, scale goes from 6 to 20 and roughly corresponds to current heart rate / 10)

MENTAL FATIGUE

- Slugishness
- Difficulty focussing, thinking
- Related to many serious problems

NEUROMUSCULAR CONDITIONS LINKED WITH FATIGUE

- NEUROLOGICAL DISORDERS
  - Fibromyalgia
  - Chronic fatigue syndrome
  - Multiple sclerosis



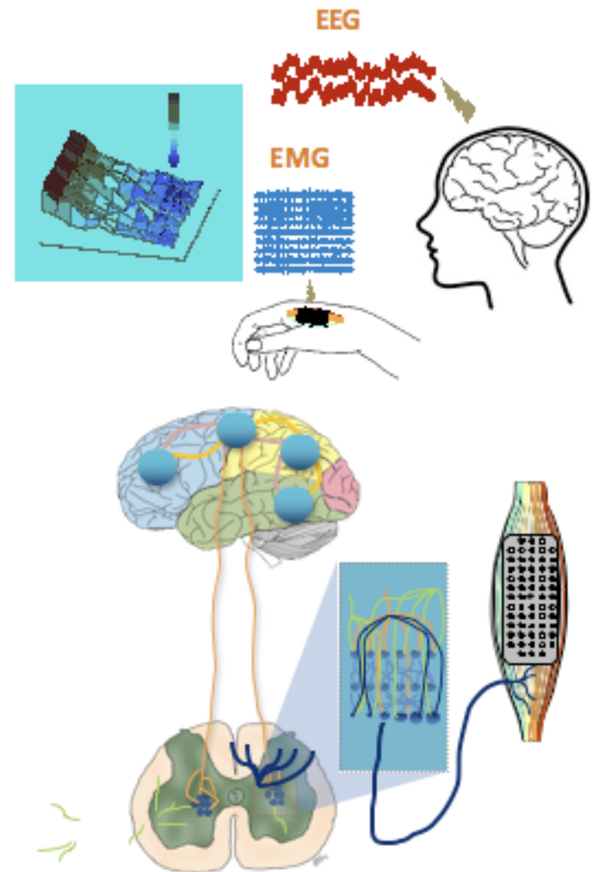
- MUSCLE DISEASES (myopathies)
  - Deficiencies in enzymatic activities

CENTRAL VS PERIPHERAL FATIGUE

(Cote & Hoeger Bement, 2010)

- Central (supraspinal and spinal)
  - Any exercise-induced reduction in maximal voluntary contraction (MVC) force which is not accompanied by the same reduction in maximal evocable force

- Peripheral fatigue
  - Mechanisms occurring at the muscle site that are accompanied by reductions in evocable force

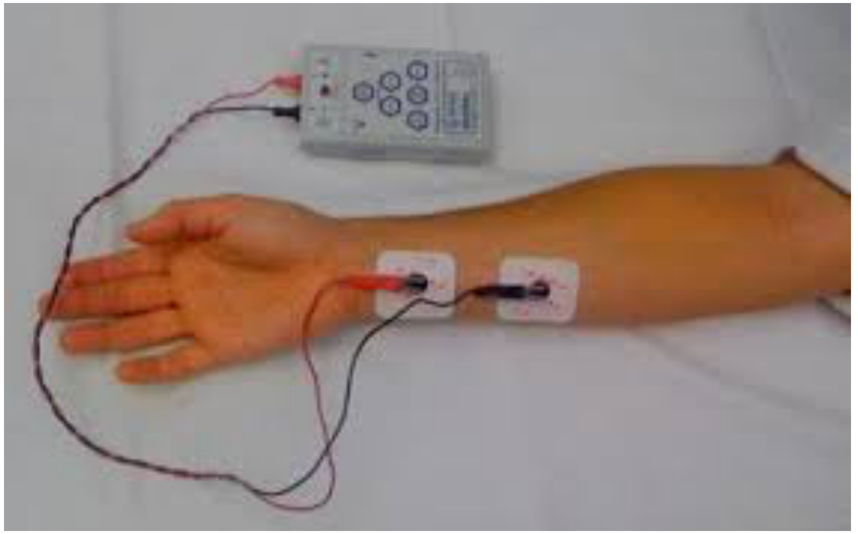


Invited Prof. Julie Côté, PhD

Protocols to distinguish central vs peripheral fatigue

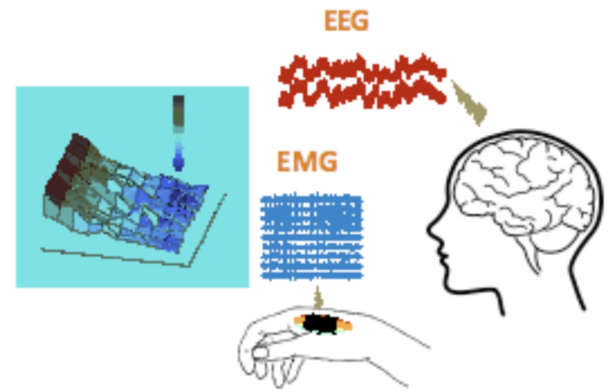
- Apply an electrical stimulus to the peripheral nerves and
  - Compare the decline in muscle force during a voluntary contraction with that evoked by the imposed electrical stimulation, or
  - Quantify the extra muscle force that electrical stimulation can elicit during a maximal voluntary effort of the muscle (interpolated twitch technique)

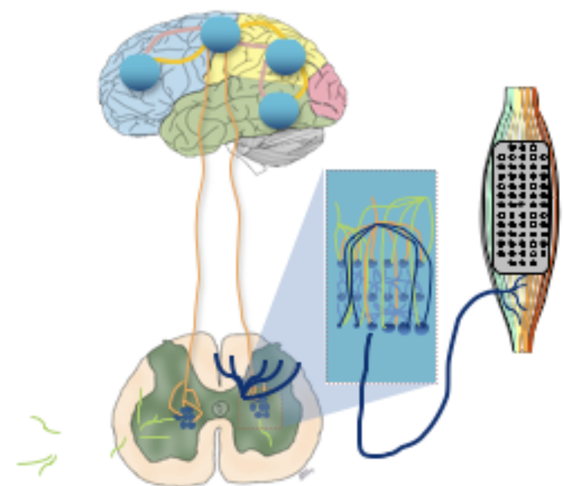
- When the muscle force evoked by the stimulus exceeds the force that can be exerted by the voluntary contraction, the decline in voluntary force is at least partially caused by an impairment of neural mechanisms



MECHANISMS OF CENTRAL FATIGUE
Taylor, 2006

- Altered EMG responses to transcranial stimulation during fatigue suggest both increased excitation and increased inhibition in the motor cortex occurring with fatigue
- One factor that may contribute to supraspinal fatigue is the firing of fatigue-sensitive muscle afferents that may act to impair voluntary descending drive
  - Protective mechanism?





Measurement approaches to study fatigue

ALLEN, LAMB, AND WESTERBLAD

Table 1. *Advantages and disadvantages of various approaches to the study of fatigue*

Muscle in vivo	Advantages	All physiological mechanisms present
		Fatigue can be central or peripheral
		All types of fatigue can be studied
		Stimulation patterns appropriate for fiber types and stage of fatigue
	Disadvantages	Mixture of fiber types
		Complex activation patterns
		Produces correlative data; hard to identify mechanisms
		Experimental interventions very limited
Isolated muscle	Advantages	Central fatigue eliminated
		Dissection simple
	Disadvantages	Mixture of fiber types
		Inevitable extracellular gradients of O_2, CO_2, K^+, lactic acid
		Mechanisms of fatigue biased by presence of extracellular gradients
		Drugs cannot be applied rapidly because of diffusion gradients
Isolated single fiber	Advantages	Only one fiber type present
		Force and other changes (ionic, metabolic) can be unequivocally correlated
		Fluorescent measurements of ions, metabolites, membrane potential, etc. possible
		Easy and rapid application of extracellular drugs, ions, metabolites, etc.
	Disadvantages	Dissection difficult
		Environment different to in vivo
		K^+ accumulation and other in vivo changes absent
		Prone to damage at physiological temperatures
		Small size makes analysis of metabolites difficult
Skinned fiber	Advantages	Precise solutions can be applied
		Possible to study myofibrillar properties, SR release and uptake, AP/Ca^{2+} release coupling
		Metabolic and ionic changes associated with fatigue can be studied in isolation
	Disadvantages	Relevance to fatigue can be questionable
		May lose important intracellular constituents
		Relevant metabolites to study must be identified in other systems

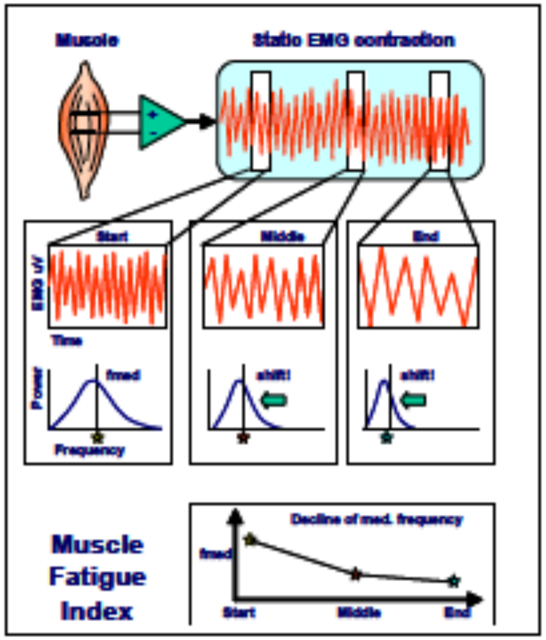
OUTCOMES RELATED TO MUSCLE FATIGUE

- Reduced capacity to generate maximal force
- Reduced motor unit action potential conduction velocity
- Reduced velocity of muscle contraction and relaxation
  - Derecruitment of fast fatiguable MUs
  - Firing rate reduction during voluntary contraction
- Reduced power output

EMG CORRELATES OF FATIGUE

- *EMG changes in the frequency domain (fmean, fmed,…)*
  - Spectral compression towards lower frequencies (left spectral shift)
    - Reduction in average muscle fiber conduction velocity
    - Alteration of motor unit synchronization and grouping
    - Possible derecruitment of MUs

- *EMG changes in the time domain (peak EMG, RMS)*
  - High force fatigue: decreased EMG amplitude (central fatigue, system failure)
  - Low force fatigue (50% MVIC or less): Increased EMG amplitude due to the recruitment of new MUs (Henneman's size principle of MU recruitment order), changes in synchronization and grouping of MUs

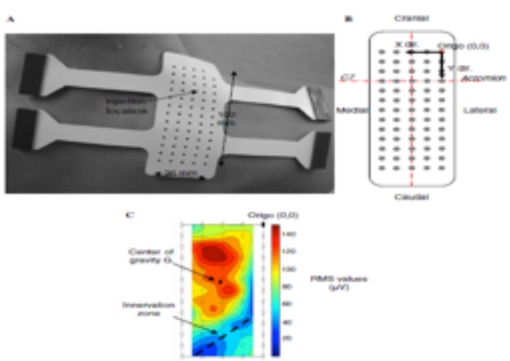


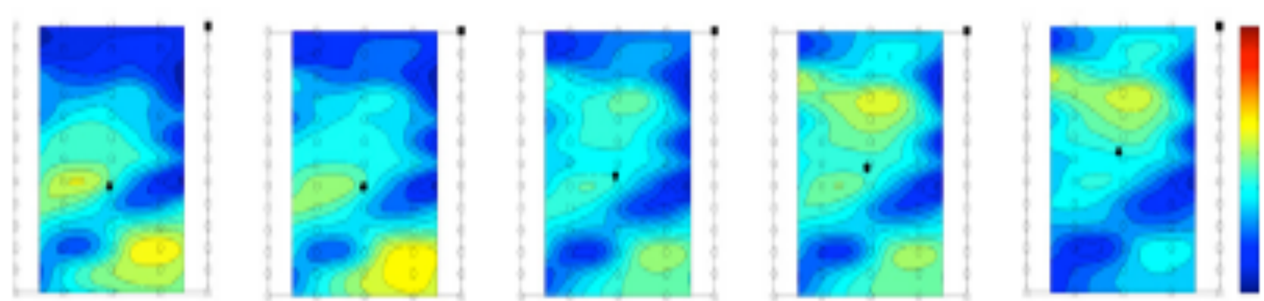
- *Increased co-activation (simultaneous activation of agonist / antagonist)*

Invited Prof. Julie Côté, PhD

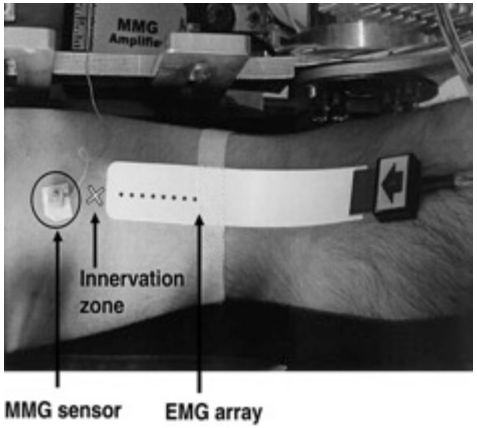
MORE COMPLEX CONSEQUENCES OF MUSCULAR FATIGUE

- EMG gaps
  - Reduced number of gaps (micropauses) on a given interval
  - Not clear if it's a cause or consequence of fatigue or injury
- Changes in relative activation patterns among synergistic muscles and between different parts of a muscle
  - Synkinesis (Gandevia, 2001)
- Increased motor variability with fatigue
  - Translates into more variable EMG, movement, force signals





OTHER TECHNIQUES USED TO STUDY MUSCLE FATIGUE



- MECHANOMYOGRAPHY (MMG)
  - Muscle fiber acceleration created by force of contraction
  - Can be detected by mini-accelerometers placed on the muscle belly
- NEAR INFRA-RED SPECTROSCOPY
  - Measurement of muscle metabolites using infra-red light reflection
- SONOGRAPHY
  - Recording of low-frequency sounds emitted when muscles contract
  - Condensed microphones, low wave detection

- ULTRASOUND
  - Reflective properties of high frequency sounds

IMAGING OF MUSCLE FATIGUE

- Shi et al., 2007, sonomyography: muscle thickness gradients

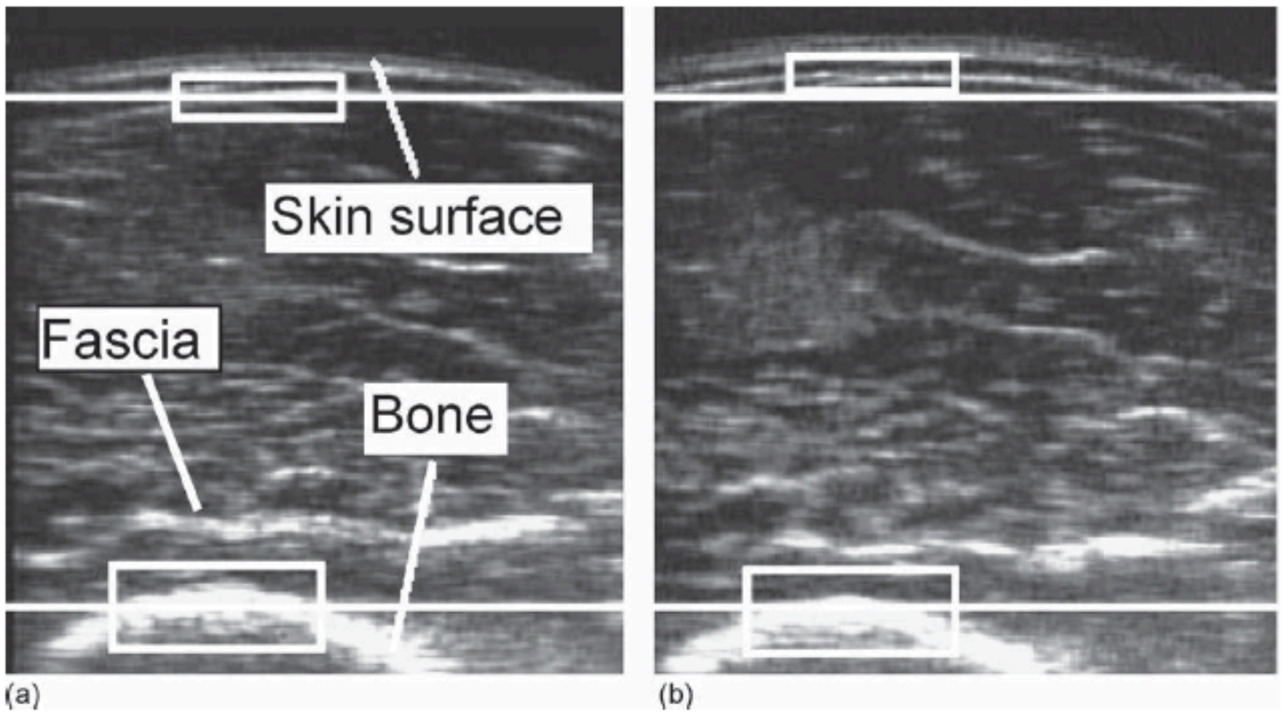
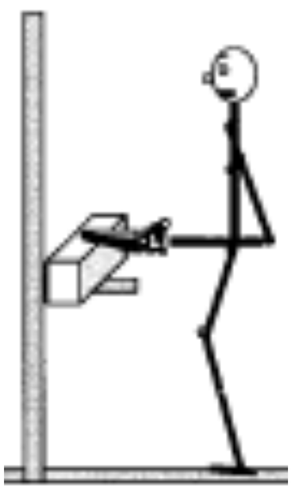
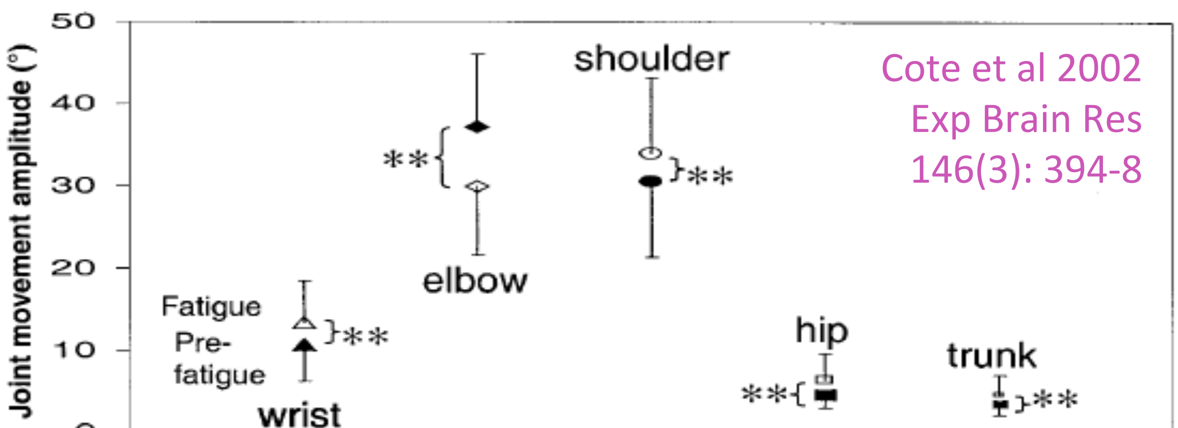


Fig. 2. Motion tracking for the ultrasound images using the two dimensional cross-correlation algorithm. (a) The image taken at the moment when the torque first reached 80% MVC and (b) the image taken when the torque started to decrease below 80% MVC. Two rectangular blocks were selected on the upper and lower boundaries of the cross-sectional image of the biceps brachii, respectively.

FATIGUE AND POSTURE-MOVEMENT COORDINATION - SAWING

- Repetitively sawing into a piece of wood until fatigue (Borg = 8/10, 20min)
- 2D (sagittal plane) kinematic analysis
- Fatigue effects:
  - Movement amplitude: ↓ at the elbow, ↑ at all other joints
  - No change in the main task characteristics (movement time, saw amplitude)



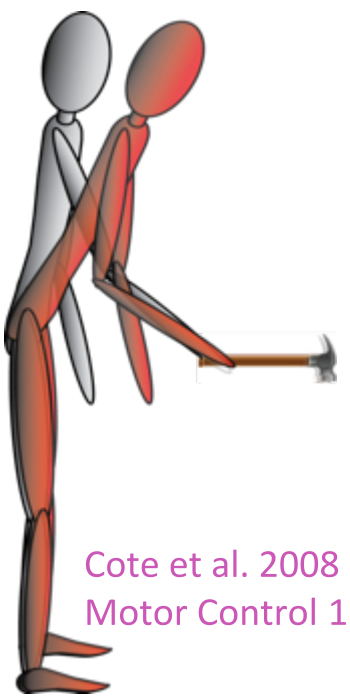


Cote et al 2002
Exp Brain Res
146(3): 394-8

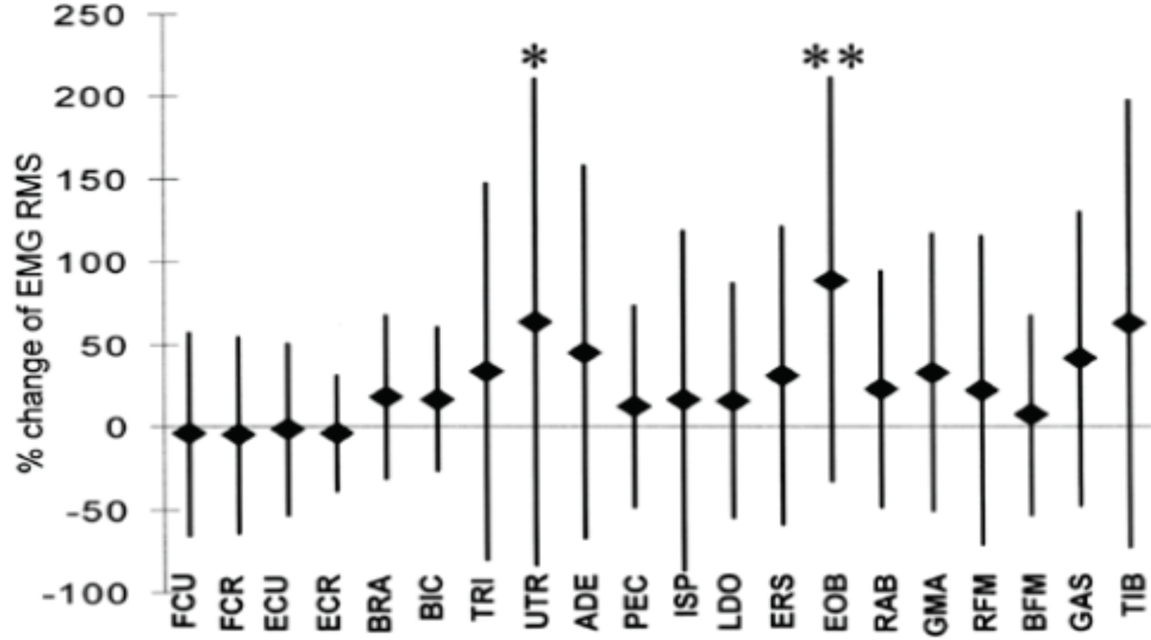
What are the muscle activity correlates?

FATIGUE AND HAMMERING

- Repetitive hammering on a piece of wood, Borg 8/10 (20min)
- 2D sagittal plane kinematic analysis, surface EMG of 20 muscles of the body
- Smaller elbow, bigger trunk movement amplitudes during hammering
- *Increased EMG activity amplitude at the upper trapezius and external oblique*



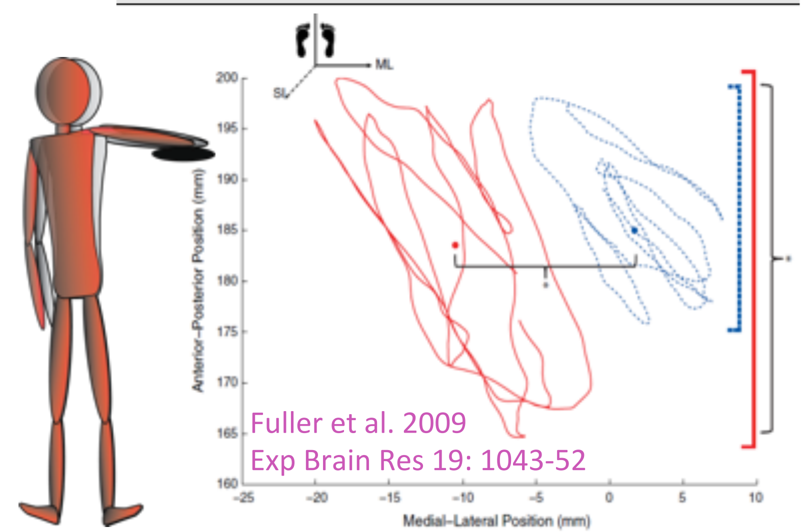
Cote et al. 2008
Motor Control 12: 79-92



FATIGUE AND POINTING

- Repetitive pointing between two targets at shoulder height
- Evidence of fatigue at termination (8')
- When fatigued, subjects elevate the moving shoulder, decrease the average shoulder abduction angle and still avoid the obstacle
- When fatigued, they lean on the contralateral side and oscillate more in the AP direction
- No effect of fatigue on endpoint parameters

Parameter	No-fatigue	Fatigue-terminal	% Change	Fatigue main effect $p <$
Heart rate (beast/min)	73.8 (14.2)	82.3 (12.7)	12.9 (12.4)	0.01
Shoulder elevation MVIE force (N)	412.1 (67.5)	392.1 (73.1)	−4.9 (8.3)	0.05
Shoulder flexion MVIE force (N)	199.4 (75.2)	185.2 (86.8)	−6.9 (21.4)	ns
Elbow flexion MVIE force (N)	311.3 (120.6)	307.4 (90.1)	4.53 (29.7)	ns
Elbow extension MVIE force (N)	230.6 (62.0)	241.0 (84.1)	3.4 (18.5)	ns
Descending trapezius RMS (mV)	0.181 (0.081)	0.264 (0.129)	46.5 (49.9)	0.005
Anterior deltoid RMS (mV)	0.163 (0.086)	0.206 (0.127)	29.0 (42.3)	ns
Biceps RMS (mV)	0.097 (0.058)	0.134 (0.090)	40.6 (49.3)	0.05
Triceps RMS (mV)	0.116 (0.336)	0.133 (0.367)	28.0 (34.5)	ns



Fuller et al. 2009
Exp Brain Res 19: 1043-52

Parameter	Direction	Change in average position	Fatigue $p<$
Shoulder joint angle (°)	Abd/Add	−8.3 (4.4)	0.0005
	Flx/Ext	−3.0 (5.1)	
Shoulder joint (mm)	AP	−11.9 (13.6)	0.005
	ML	−23.5 (15.2)	
	SI	11.7 (10.5)	
Endpoint (mm)	AP	−7.6 (19.2)	ns
	ML	0.1 (5.4)	
	SI	−1.1 (8.5)	

TEMPORAL PROGRESSION OF FATIGUE

- Now we know about the spatial changes that occur across the body with repetitive motion (e.g. RoM, average joint positions), but what about the temporal aspects of the task?

  - Objectives: describe the effects of the repetitive reaching task on the following time-related aspects:
    - The development of changes from one minute to the next (when do changes start to occur?)
    - Variability from one movement to the next
      - Previously shown to increase with fatigue, decrease with pain
    - Within-reach temporal coordination characteristics

When do changes start to occur?

- About halfway to the end of the task (≈ 4th min.)
  - The system uses pre-planned responses, possibly based on feedback from agonist muscles, in implementing some changes early on, to actively delay fatigue?...

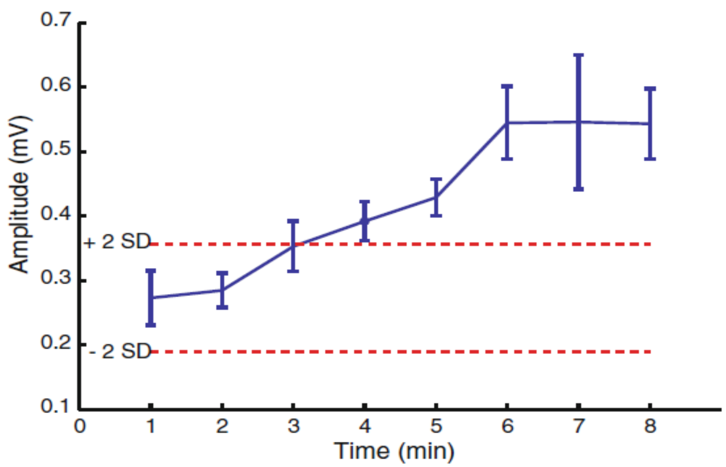


Fig. 1 Average Trapezius root-mean-squared amplitude (*solid blue line*) and 1 SD error bars at each minute of the reaching task (representative subject). *Red-dashed lines* represent ±2 SDs of the mean Trapezius EMG RMS during the initial minute. *Blue filled dot* represents the minute the average Trapezius root-mean-squared amplitude exceeded ±2 SDs of the first minute value

Parameter	*N*	Time (%)	SD (%)
AP elbow	13	42.9	29.5
ML COP	12	44.4	36.4
ML COM	11	46.4	37.1
ML shoulder	13	50.6	29.7
SI shoulder	14	51.0	27.9
Shoulder abduction	13	52.6	25.1
Trapezius EMG RMS	11	65.5	27.3

Fuller et al. 2011, Exp Brain Res 211: 133-43

How does fatigue affect variability?

- Increased movement variability in all directions at the shoulder
- No change in variability of CoM-AP, CoP, endpoint

Parameter	Direction	P	No-Fatigue		Fatigue-Terminal	
			Mean	SD	Mean	SD
Shoulder angle (°)	Abd/add	ns	2.2	2.1	3.5	3.8
	Horizontal abd	ns	2.9	1.2	3.8	2.2
Shoulder joint (mm)	AP	0.049	7.1	2.8	11.9	7.4
	ML	0.022	3.9	1.2	7.4	5.3
	SI	0.003	1.5	0.8	3.6	2.5
Elbow angle (°)	Flx/Ext	ns	2.8	1.7	3.9	2.6
Elbow joint (mm)	AP	0.018	8.2	4.7	17.2	12.1
	ML	ns	6.7	2.9	9.1	6.3
	SI	ns	6.3	4.2	10.3	6.7
Endpoint (mm)	AP	ns	3.6	1.8	6.6	7.3
	ML	ns	5.3	2.1	5.9	2.3
	SI	ns	6.7	3.3	8.8	3.3
COM (mm)	AP	ns	4.1	2.0	5.4	3.7
	ML	0.014	1.8	0.7	3.7	2.6
	SI	0.03	0.6	0.5	1.1	0.7
COP (mm)	AP	ns	7.1	3.3	9.1	5.4
	ML	ns	3.1	1.5	8.9	12.2

Fuller et al. 2011, Exp Brain Res 211: 133-43

How does fatigue affect inter-joint timing?

- More en block patterns of temporal coordination

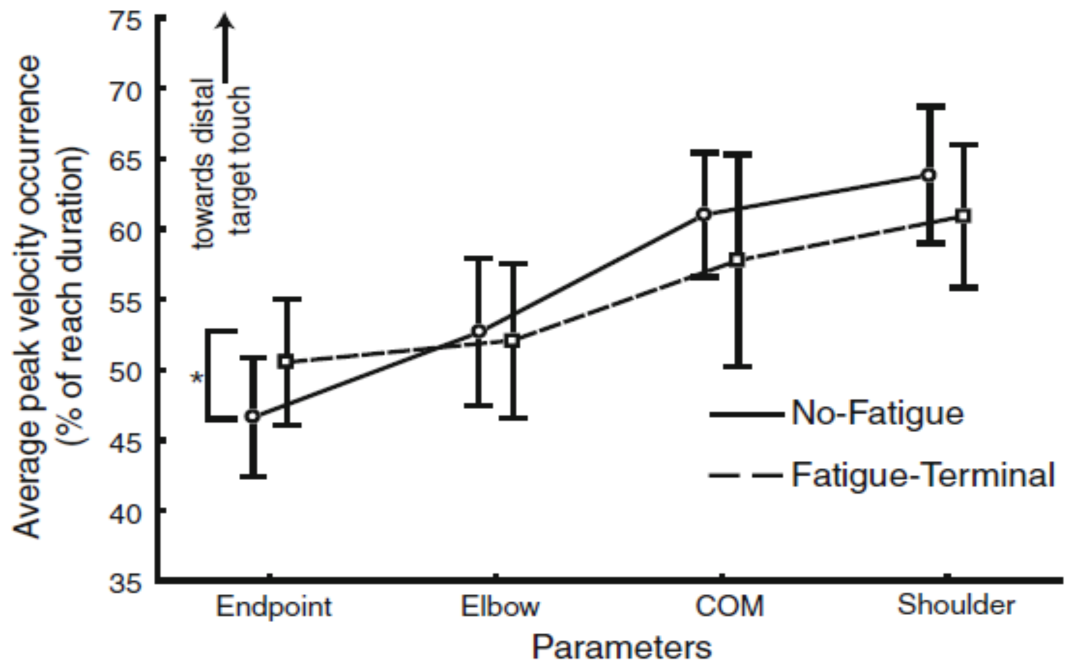


Fig. 3 Group averages and 1 SD error bars of occurrences of peak velocity of endpoint, elbow, COM, and shoulder, in the AP direction (*blue line*: No-Fatigue, *red-dashed line*: Fatigue-Terminal)

Fuller et al. 2011, Exp Brain Res 211: 133-43

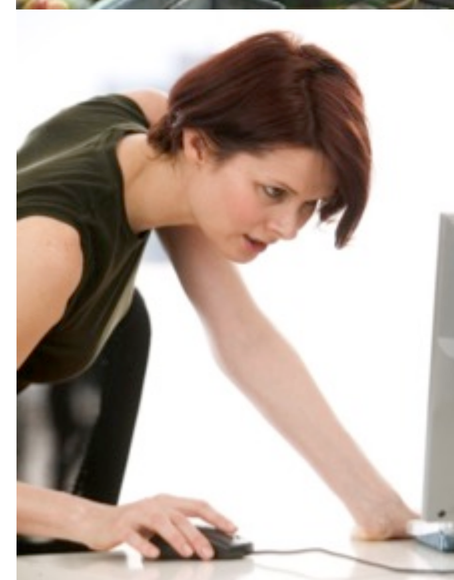
EMG @ OBEL: EMG TO PREDICT ENDURANCE

- Fedorowich et al, JEK 2013: during a repetitive task: initially highly variable patterns of EMG predict a longer time to exhaustion
  - … mostly in women
  - In men, it is specific inter-muscular patterns (functional connectivity between pairs of agonist muscles) that predict high endurance

OTHER ASPECTS OF MOTOR CONTROL

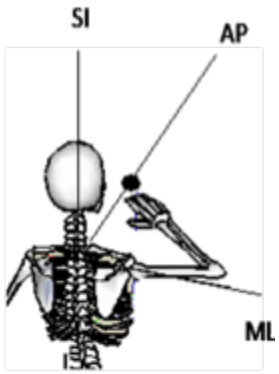
- Muscle fatigue and injury also affect proprioception
  - Deficits in position sense can represent loss in productivity and risk factors for injury

- Can we compensate for neck-shoulder proprioceptive deficits with other muscles and joints to maintain accurate endpoint (finger) position sense?

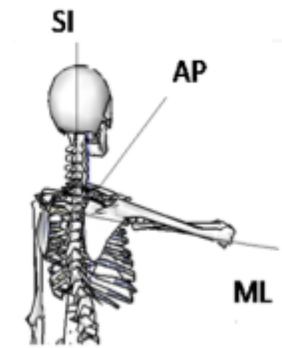


EXPERIMENTAL TASKS

- Starting position: index finger on the manubrium of sternum; elbow passive
- Endpoint position sense (EPS) task (eyes closed):
  - Move the index finger forward and stop at 50% arm length
  - *<u>Measures</u>*: 3D finger terminal position, error (distance away from the position of the real target, recorded after the trials)



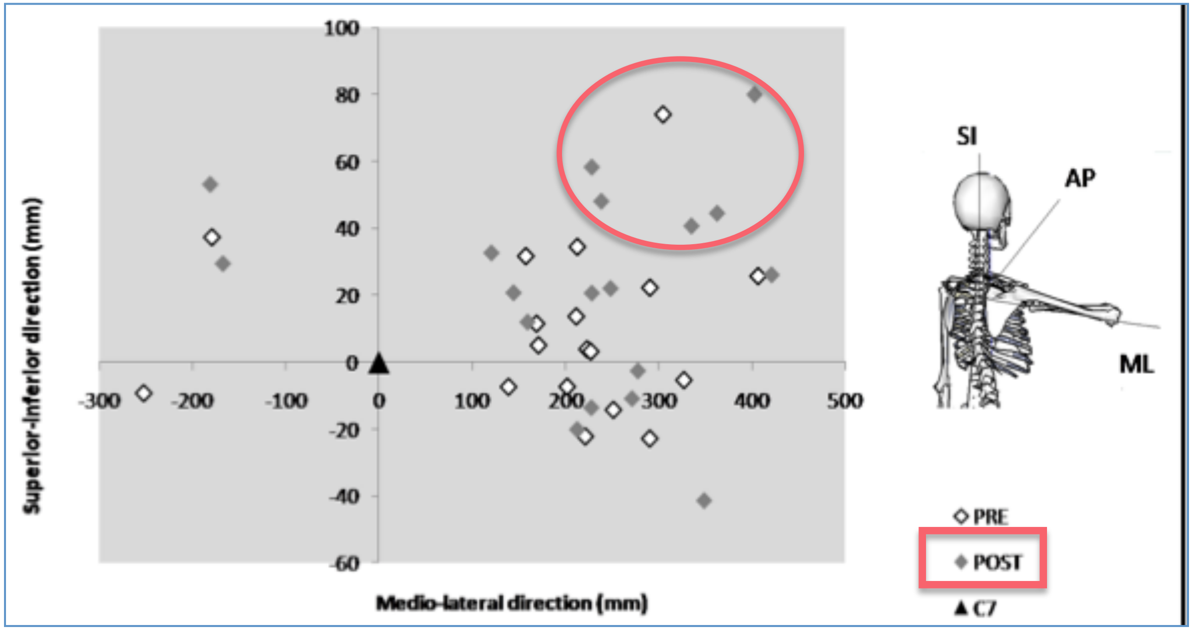
- Shoulder position sense (EPS) task (eyes closed):
  - Abduct the upper arm to the perceived horizontal
    - Main protocol: active movement
    - Follow-up experiment: arm passively moved by a motorized elevating table
  - *<u>Measures</u>*: vertical distance between elbow, C7 markers



Emery and Cote, Exp Brain Res

FINDINGS – SHOULDER POSITION SENSE

- Muscular fatigue at task termination, during post-fatigue position sense trials
  - Higher EMG, 7 muscles
- Significant *time effect* in shoulder position sense (p = 0.014)



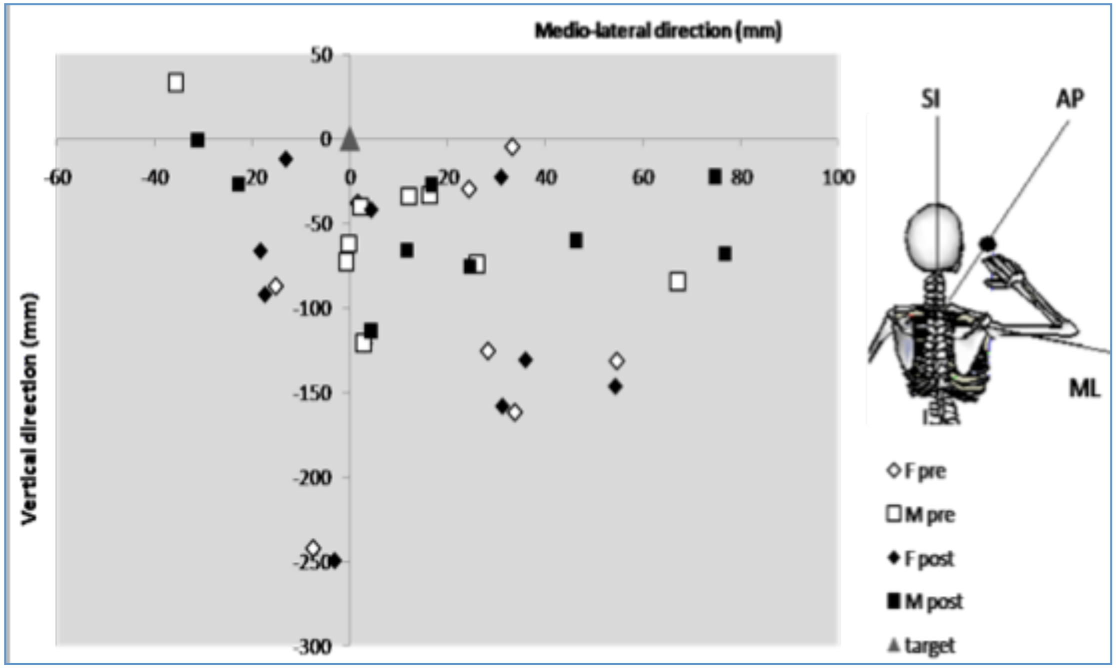
  - Before fatigue: subjects abducted slightly above horizontal (0.9 ± 2.4cm)
  - After fatigue: subjects abducted even higher (2.2 ± 3.1 cm above horizontal)

- Related to increased sense of effort with fatigue? (Allen et al ’06)

Emery and Cote, Exp Brain Res

FINDINGS – FINGER POSITION SENSE

- *<u>No effect</u>* of fatigue on endpoint (finger)position sense
  - Both before and after fatigue, subjects pointed slightly below, laterally, and behind the perceived target



- Evidence of compensations for deficits in shoulder position sense = finger position sense unaffected
- Consistent with this: sensory detection thresholds also decreased at the shoulder but not at more remote body sites

Emery and Cote, Exp Brain Res

FATIGUE AND QUANTITATIVE SENSORY TESTING

- Is it possible that proprioception is reduced because the senses are affected?
- Using the same fatiguing experimental task, we measured, before and after fatigue:
  - Sensory detection thresholds (QST)
  - Pain detection thresholds (PPT)
  - At the neck-shoulder and at the leg (would represent central sensitization)
- Results (unpublished): yes, increased QST and PPT of (only) the main agonist (anterior deltoid) with fatigue
- Next: if we apply a sensory stimulus on the surface of the fatiguing muscle, will subjects fatigue less quickly? Potentially good for workers

SUMMARY OF FINDINGS

- Low-force fatigue (increased Borg ratings) is associated with…
  - Reduced movement amplitude of fatigued joints
  - Increased movement amplitude of remote joints
  - Postural changes that facilitate task performance
  - Increased EMG activity of target muscles
  - Increased EMG activity of some compensatory muscles
  - Changes in interjoint timing
  - Increased movement variability
  - Changes that develop before task failure
  - Reductions in proprioception outcomes at fatigued joints
  - Reductions in sensory and pain sensitivity outcomes at fatigued joints
  - Maintenance of important task characteristics constant = evidence of ability to develop compensatory strategies

REFERENCES

Madeleine P, Leclerc F, Arendt-Nielsen L, Ravier P, Farina D. Experimental muscle pain changes the spatial distribution of upper trapezius muscle activity during sustained contraction. Clin Neurophysiol. 2006 Nov;117(11):2436-45

Edwards RH. Human muscle function and fatigue. Ciba Found Symp. 1981;82:1-18.

Bigland-Ritchie B, Rice CL, Garland SJ, Walsh ML. Task-dependent factors in fatigue of human voluntary contractions. Adv Exp Med Biol. **1995**;384:361-80. Review.

Enoka RM, **Stuart** DG. Neurobiology of muscle fatigue. J Appl Physiol (1985). **1992** May;72(5):1631-48. Review.

Jones LA, **Hunter** IW. Effect of fatigue on force sensation. Exp Neurol. **1983** Sep;81(3):640-50.

Chaudhuri A1, Behan PO. **Fatigue in neurological disorders. Lancet. 2004 Mar 20;363(9413):978-88.**

Borg G. Perceived exertion as an indicator of somatic stress. Scand J Rehabil Med. **1970**;2(2):92-8.

Côté JN, Hoeger Bement, M (2010) Update on the Relation Between Pain and Movement: Consequences for Clinical Practice. *Clinical Journal of Pain* 26(9): 754-62.

Taylor JL, Todd G, Gandevia SC. Evidence for a supraspinal contribution to human muscle fatigue. Clin Exp Pharmacol Physiol. **2006** Apr;33(4):400-5. Review.

Allen DG, **Lamb** GD, **Westerblad** H. Skeletal muscle fatigue: cellular mechanisms. Physiol Rev. 2008 Jan; 88(1):287-332.

Gandevia SC. Spinal and supraspinal factors in human muscle fatigue. Physiol Rev. **2001** Oct;81(4): 1725-89. Review.

Shi J, Zheng YP, Chen X, Huang QH. Assessment of muscle fatigue using sonomyography: muscle thickness change detected from ultrasound images. Med Eng Phys. **2007** May;29(4):472-9

Côté JN, Mathieu PA, Levin MF, Feldman AG (2002) Movement reorganization to compensate for fatigue during sawing. *Experimental Brain Research* 146: 394-398.

Côté JN, Levin MF, Raymond D, Mathieu PA, Feldman AG (2005) Differences in multijoint kinematic patterns of repetitive hammering in healthy, fatigued and shoulder-injured individuals. *Clinical Biomechanics* 20: 581-590.

Côté JN, Mathieu PA, Feldman AG and Levin MF (2008) Effects of fatigue on intermuscular coordination during repetitive hammering. *Motor Control* 12(2): 79-92.

Fuller J, Lomond K, Fung J, **Côté JN** (2009) Posture-movement changes following repetitive motion-induced shoulder muscle fatigue. *Journal of Electromyography and Kinesiology* 19(6): 1043-52.

Fuller J, Fung J, **Côté JN** (2011) Time-dependent adaptations to posture and movement characteristics during the development of repetitive reaching induced fatigue. *Experimental Brain Research* 211(1): 133-143.

Emery K, **Côté JN** (2012) Repetitive arm motion-induced fatigue affects shoulder but not endpoint position sense. *Experimental Brain Research* 216(4): 553-564.

Fedorowich L, Emery K, Gervasi B, **Côté JN (2013) Gender differences in neck/shoulder muscular patterns in response to repetitive motion induced fatigue. *Journal of Electromyography and Kinesiology* 23(5): 1183-9.**

Côté JN (2014) Adaptations to neck/shoulder fatigue and injury. *Advances in Experimental Medicine and Biology* 826: 205-28.