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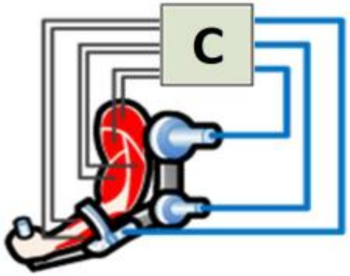
Upper Limb Exoskeleton Myoelectric Control

Towards continuous EMG-based control: the role of Neuromusculoskeletal models

(A Genetic Algorithm application for Bio-engineering)

Domenico Buongiorno, PhD
Prof. Vitoantonio Bevilacqua



Electromyographic Signal (EMG)

ELECTROMYOGRAPHY (EMG)

"Electromyography (EMG) is an electrodiagnostic medicine technique for evaluating and recording the electrical activity produced by skeletal muscles"

INTRAMUSCULAR EMG

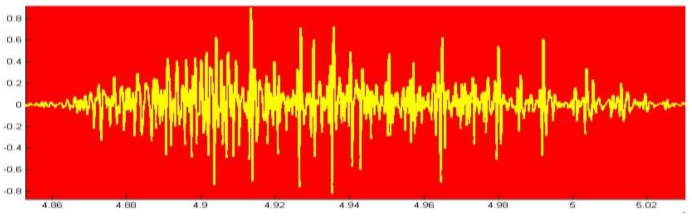
SURFACE EMG (SEMG)

Contro:

- **Hard to recognize deep muscle**
- **It is not possible to detect the contribution of a single Motor Unit**

Pro:

- **NON-INVASIVE**
- **Simultaneous acquisition of several muscles activities**
- **Potential maps**



Applications

- **Diagnostic**
- **Control of external device**
- **Investigation on muscular fatigue**
- **Motion analysis**
- **EMG-based Biofeedback**

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APPLICATIONs

Medical Research

- Orthopedic
- Surgery
- Functional Neurology
- Gait & Posture Analysis

Rehabilitation

- Post surgery/accident
- Neurological Rehabilitation
- Physical Therapy
- Active Training Therapy

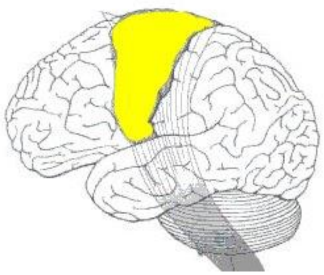
Ergonomics

- Analysis of demand
- Risk Prevention
- Ergonomics Design
- Product Certification

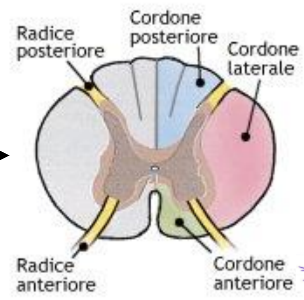
Sports Science

- Biomechanics
- Movement Analysis
- Athletes Strength Training
- Sports Rehabilitation

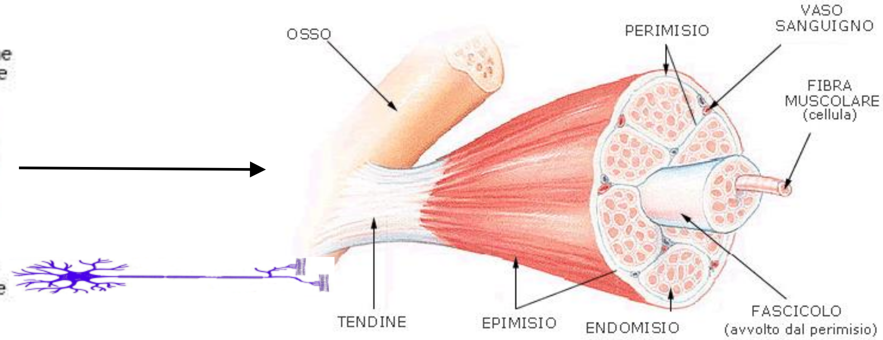
EMG SIGNAL: BIOLOGICAL BACKGROUND



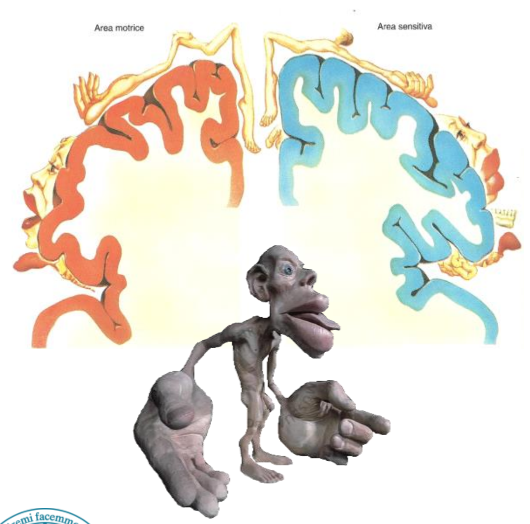
MOTOR CORTEX



SPINAL CORD



SCHELETRIC MUSCLE



MOTOR UNIT:

Motoneuron (body, axons..) + Innervated Muscular fibers

Groups of motor units often work together to coordinate the contractions of a single muscle; all of the motor units within a muscle are considered a motor pool.

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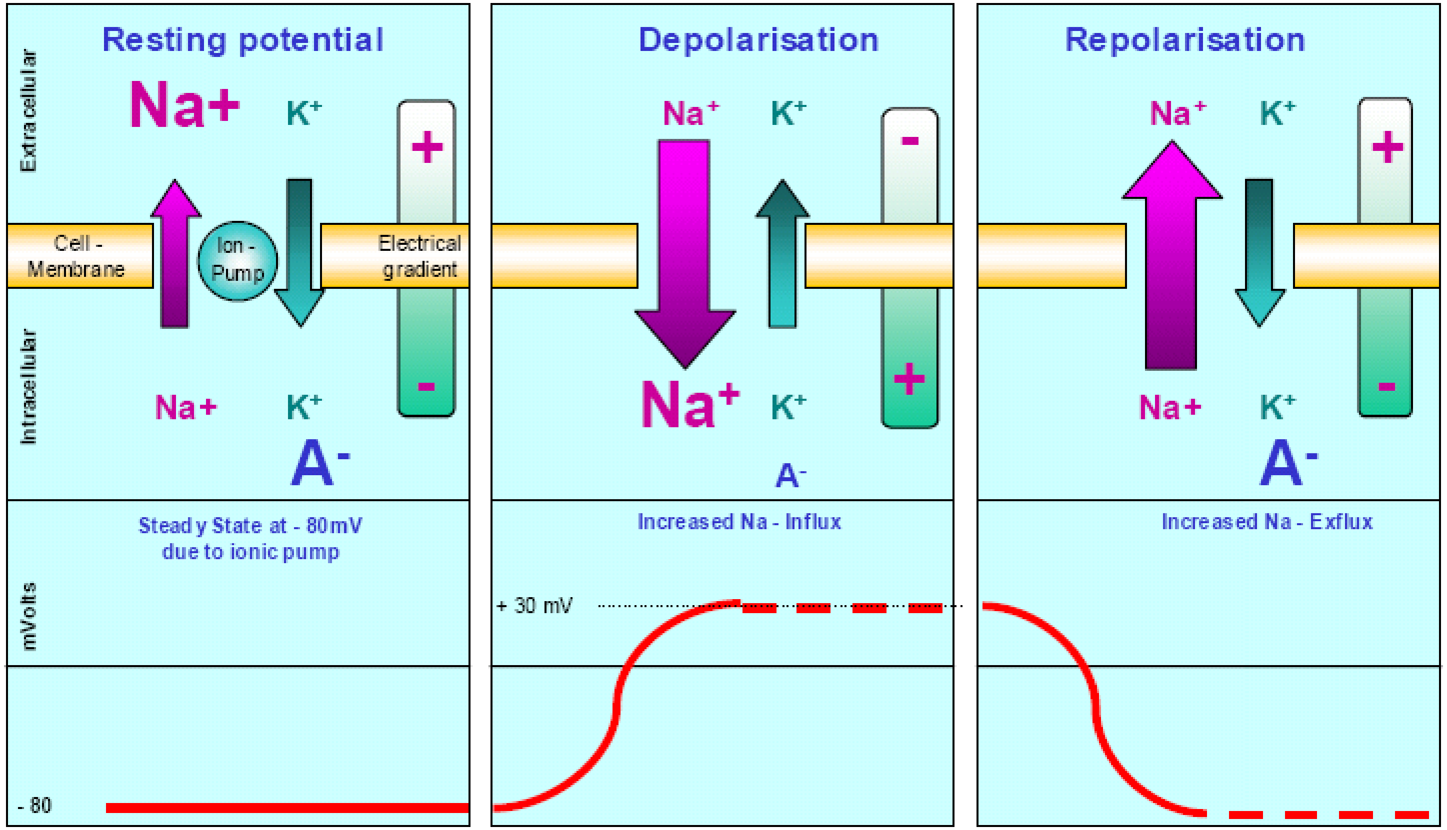
Muscle fibre excitability



Semipermeable membrane model

Ionic Equilibrium - Na+Cl- Pump

Thrashold mechanism

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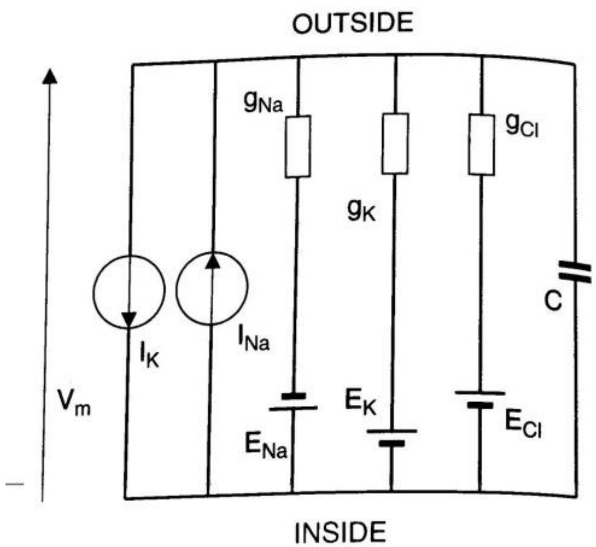
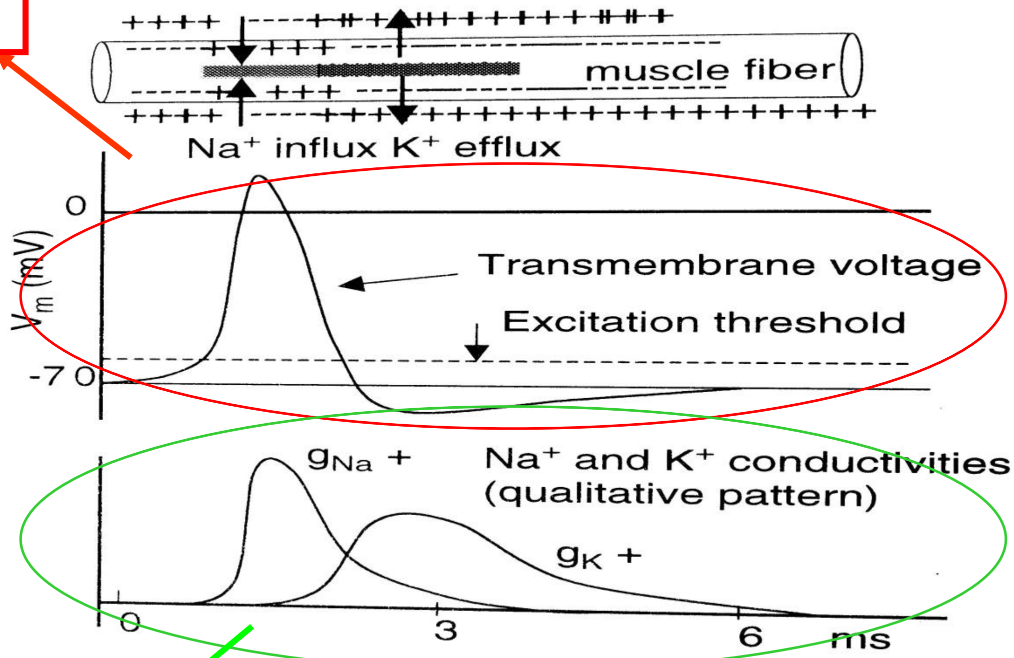
Muscle fibre excitability

ACTION POTENTIAL

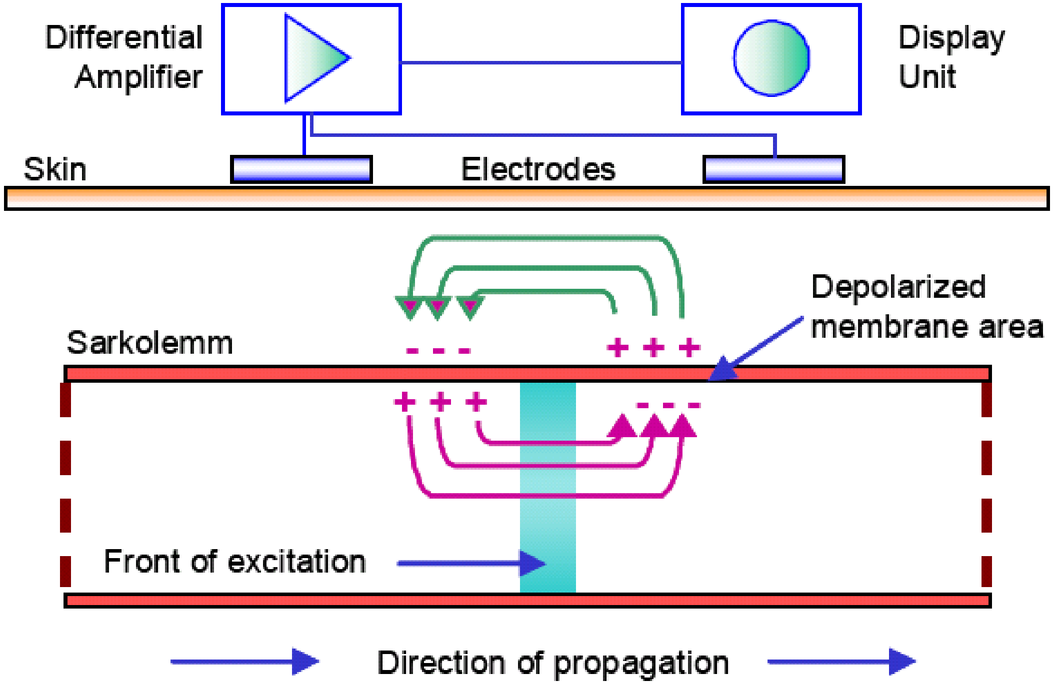


Modello di Hodgkin & Huxley



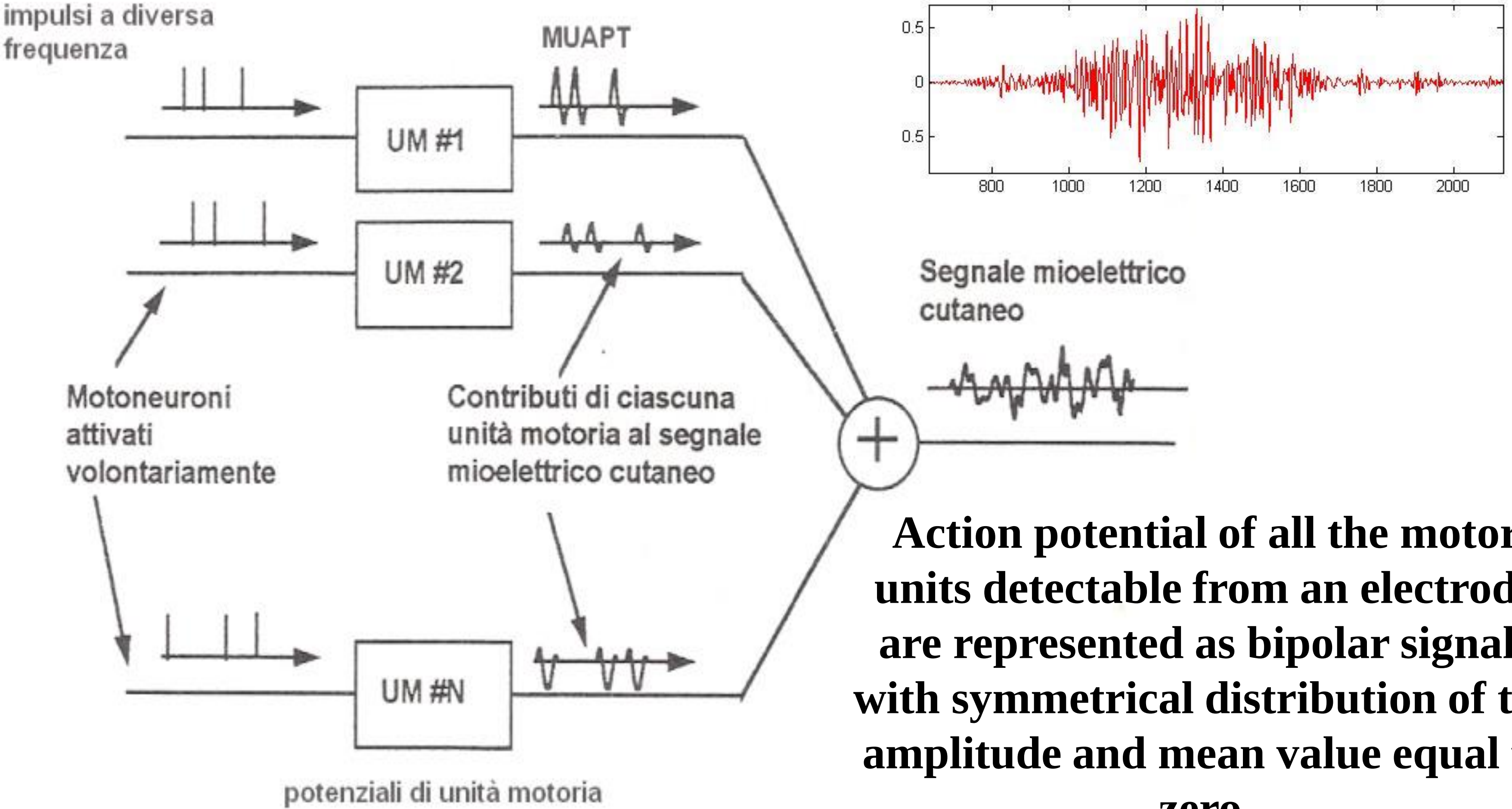
DINAMICAL BEHAVIOUR OF THE MEMBRANE

PROPAGATION OF THE ACTION POTENTIAL



The depolarization zone (1-3 mm) travel along the muscular fiber with a speed of 2-6 m/s

INTERFERENCE PATTERN



Action potential of all the motor units detectable from an electrode are represented as bipolar signals with symmetrical distribution of the amplitude and mean value equal to zero.

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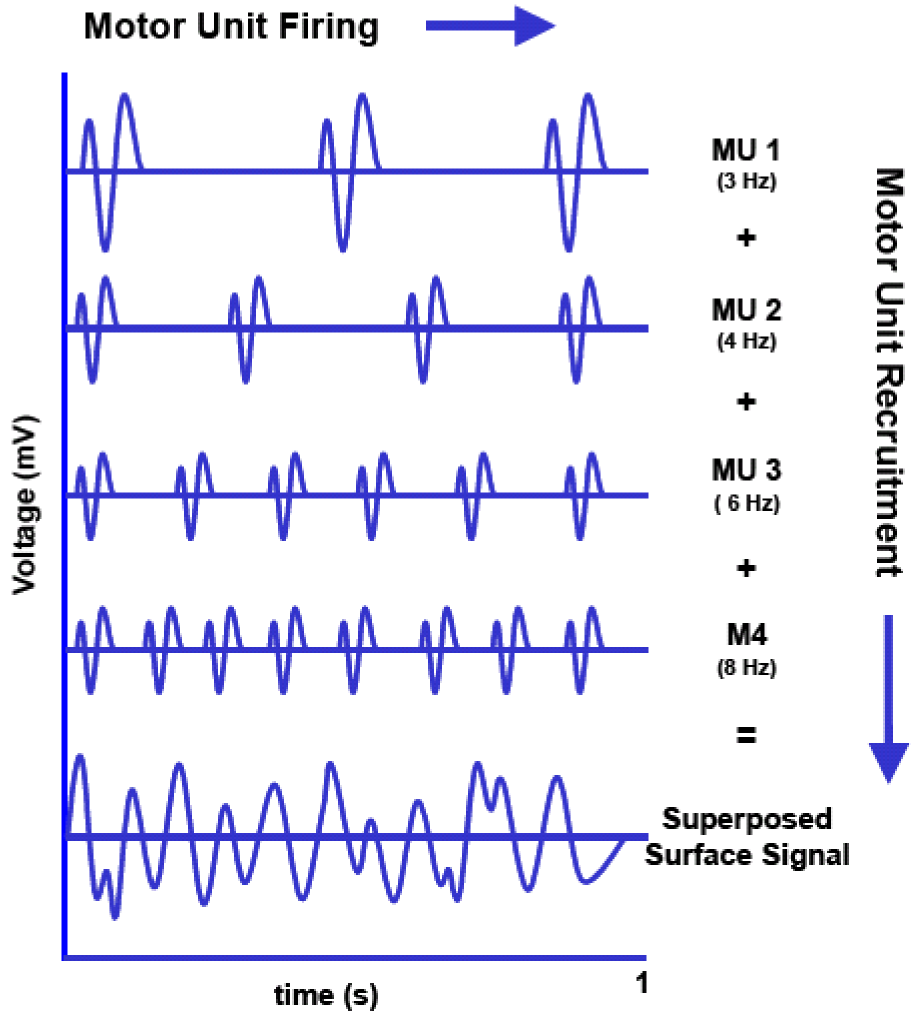
EMG SIGNAL GENERATION



EMG SIGNAL DEPENDS ON:

✓ *POTENTIAL ACTION OF INDIVIDUAL MOTOR UNIT (MUAPs)*

✓ *FIRING RATE*

FEATURES:

- AMPLITUDE: 10µV ~ 2mV
- FREQ BAND: 10Hz ~ 400Hz

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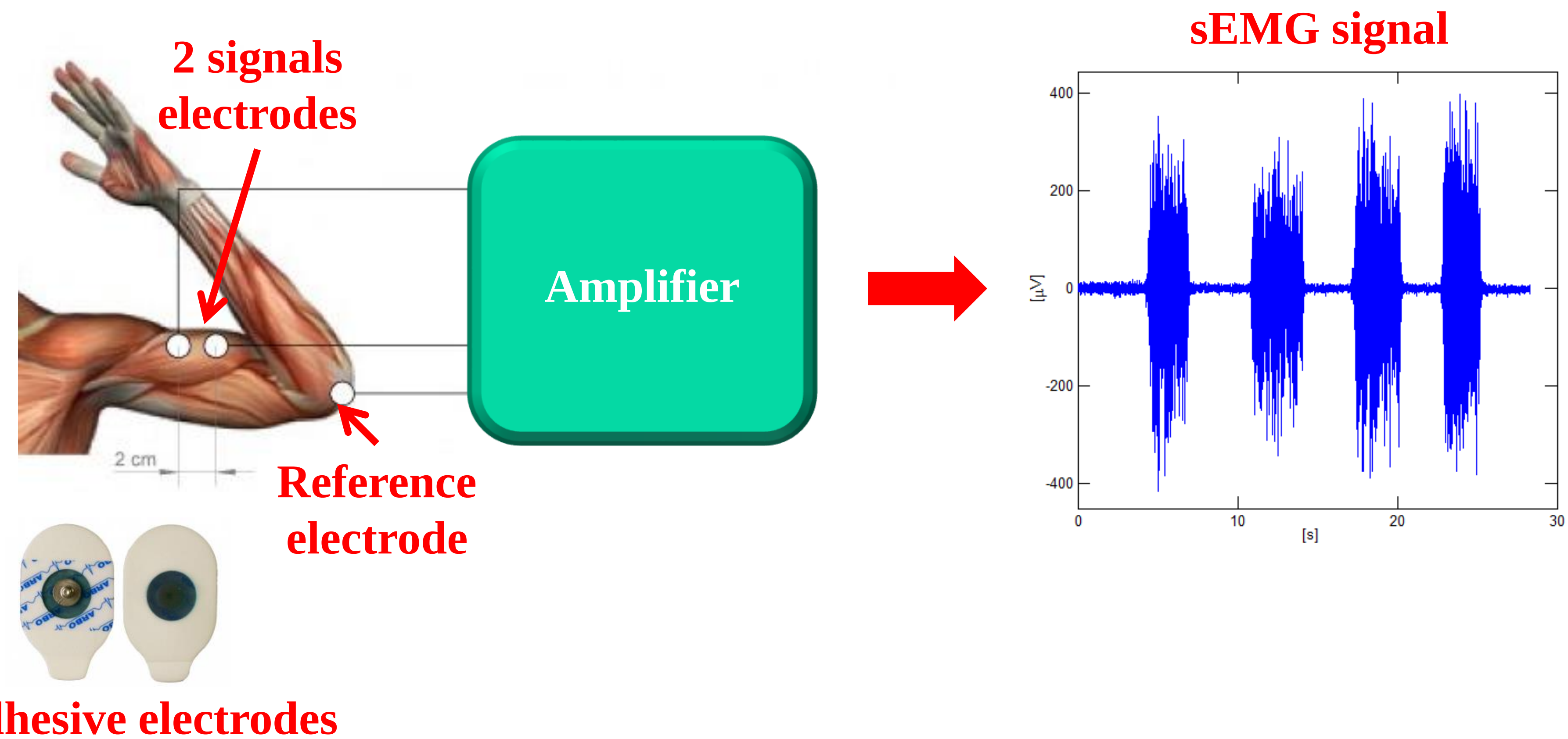
Surface ElectroMyoGraphy (sEMG)

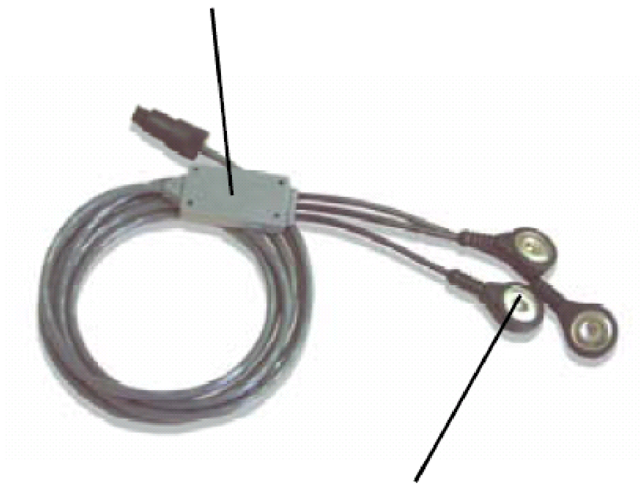
It is a non-invasive technique for measuring electrical activity of muscles.
It makes use of electrodes placed on the skin.



EMG AMPLIFIERS

Using Differential amplifier it is possible to reduce artifacts

Pre-amplifiers:
Embedded in the EMG wires



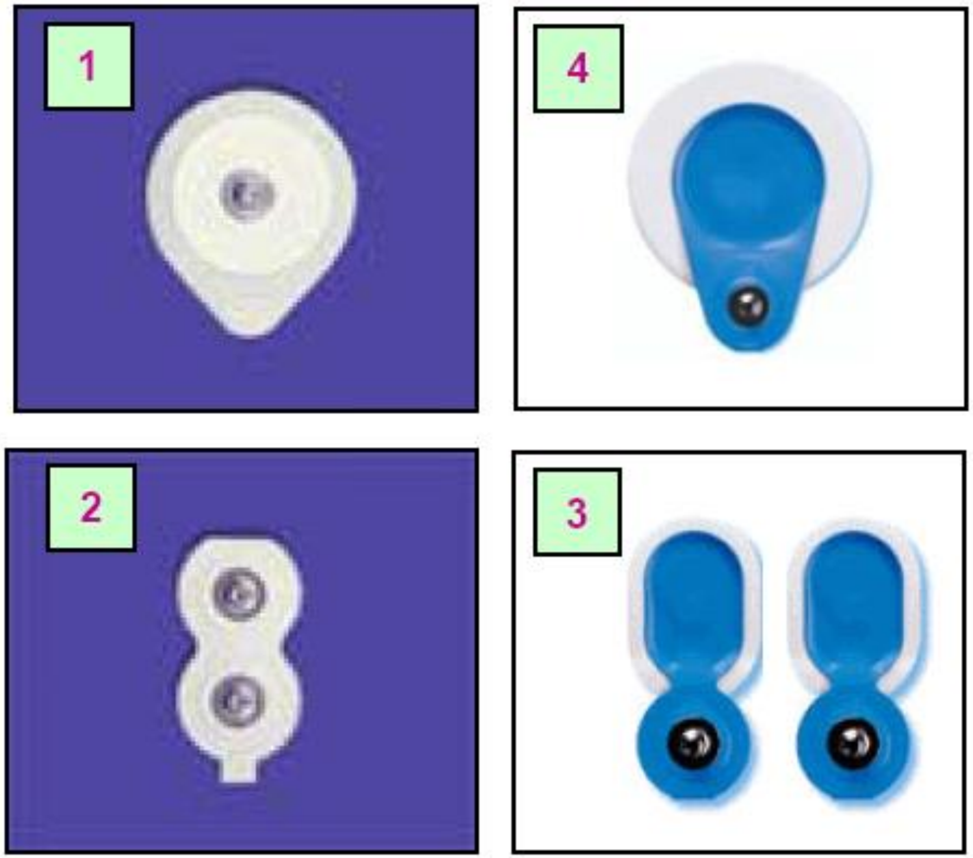
EMG signal is generally amplified with a gain of 500 - 1000

ELECTRODES

Surface electrodes (Ag/AgCl)

Circular Conductive zone with a diameter of 1cm

Commercial electrodes are often «pregelled», that means they are featured with a thin layer of gel for a better conduction obtained by adapting the impedence between the skin and the conductive zone



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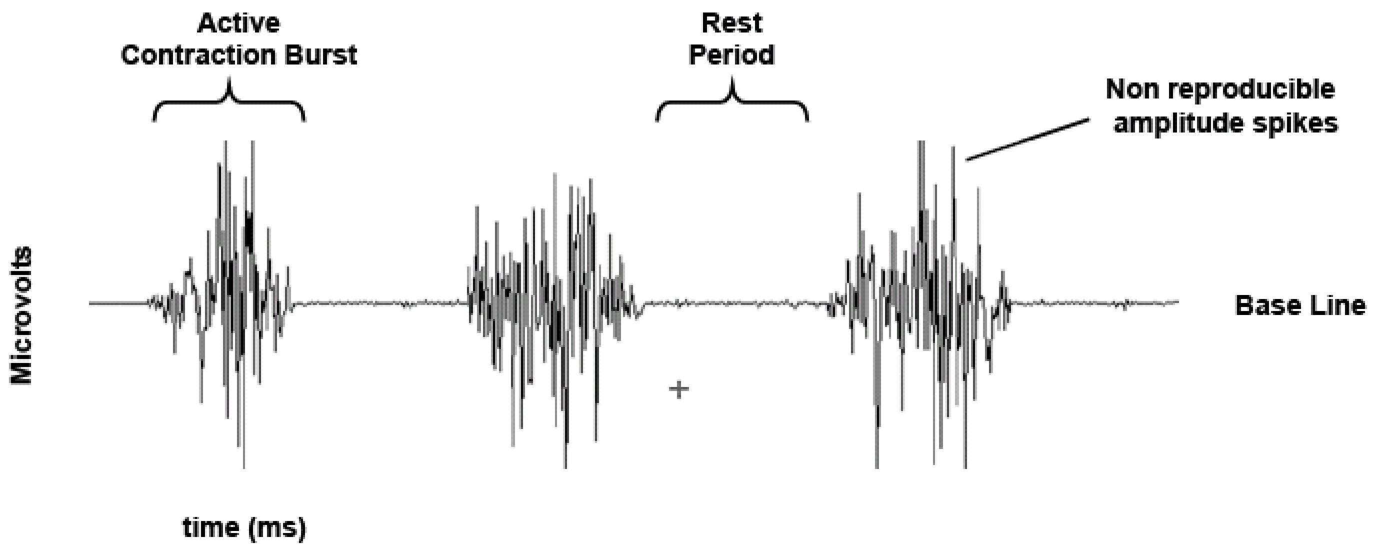
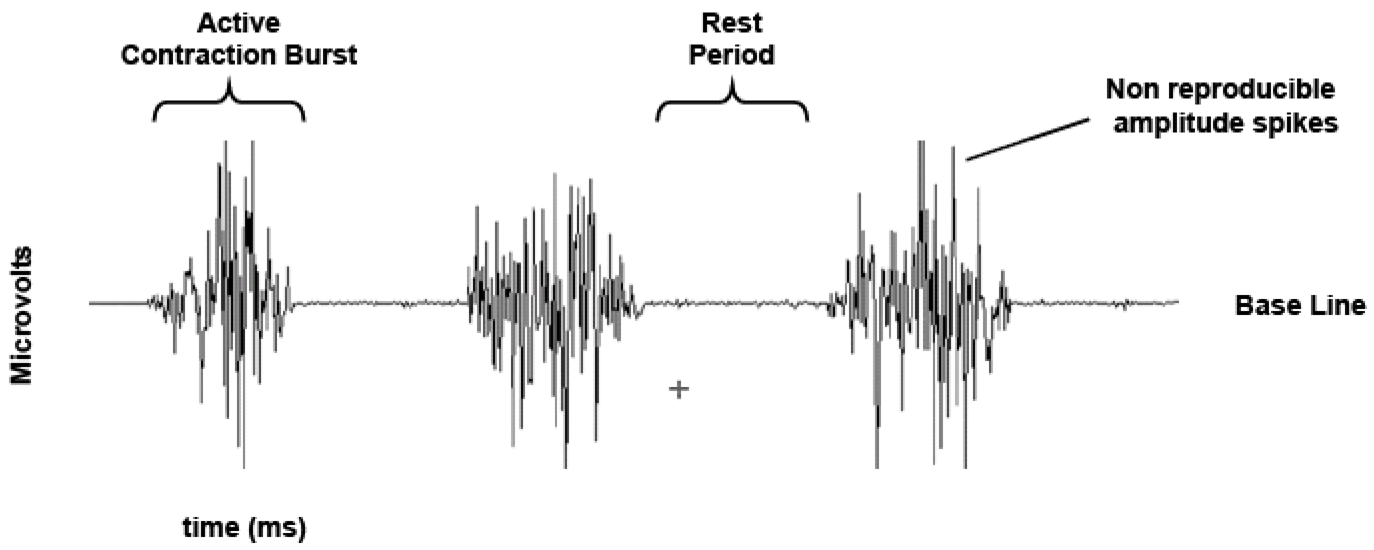
“Raw” EMG



Raw signal recorded from Brachii biceps during three consecutive contractions

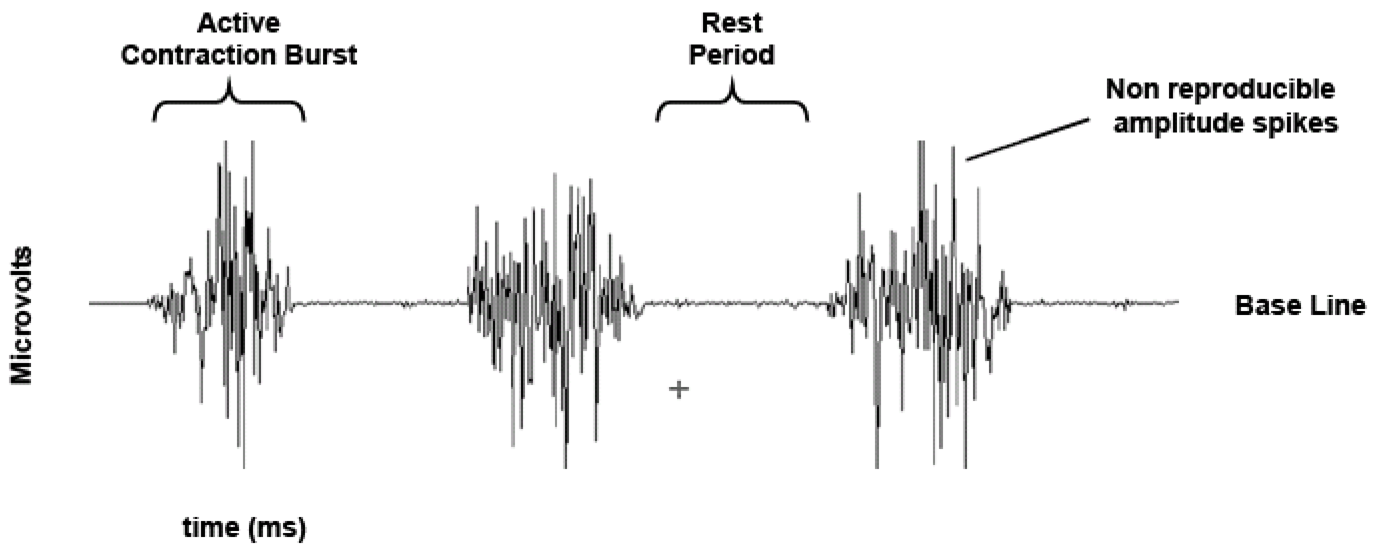
“Raw” EMG



Baseline Noise:

- *Instrumentation Quality*
- *External noise*
- *Ambient condition*

"Raw" EMG



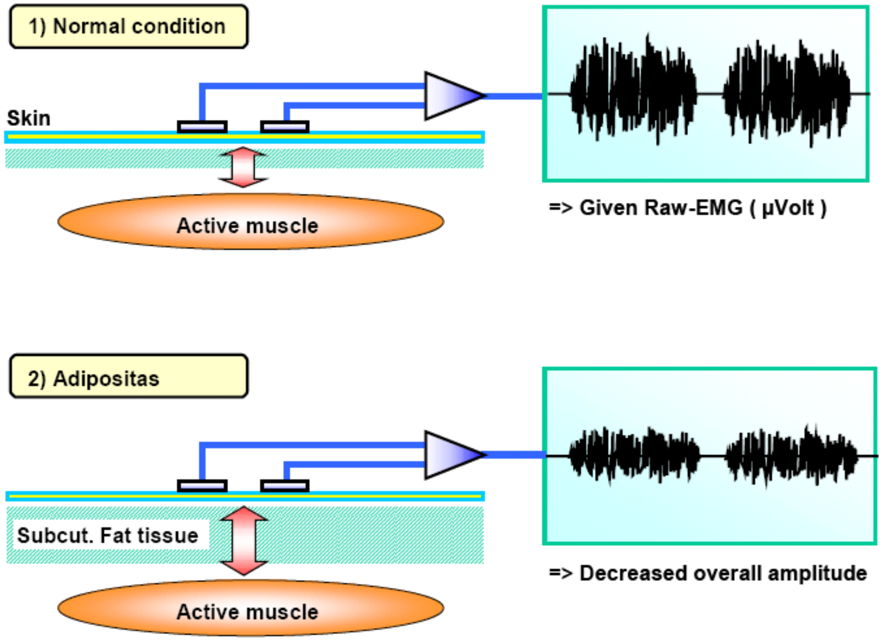
Some EMG values:

- *Baseline Noise:* *3-5 microvolt (good condition)*
- *Amplitude:* *+/- 5000 microvolt (athlets)*
- *Frequency:* *6-500 Hz*

Factors influencing the EMG signals

Tissue Features:

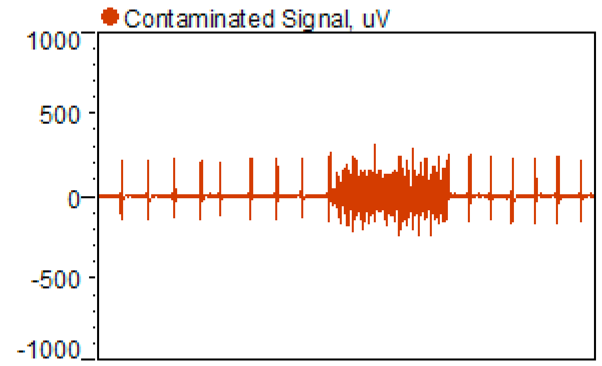
- *Type of tissue*
- *Thickness*
- *Temperature*
- *Sweat*



Factors influencing the EMG signals

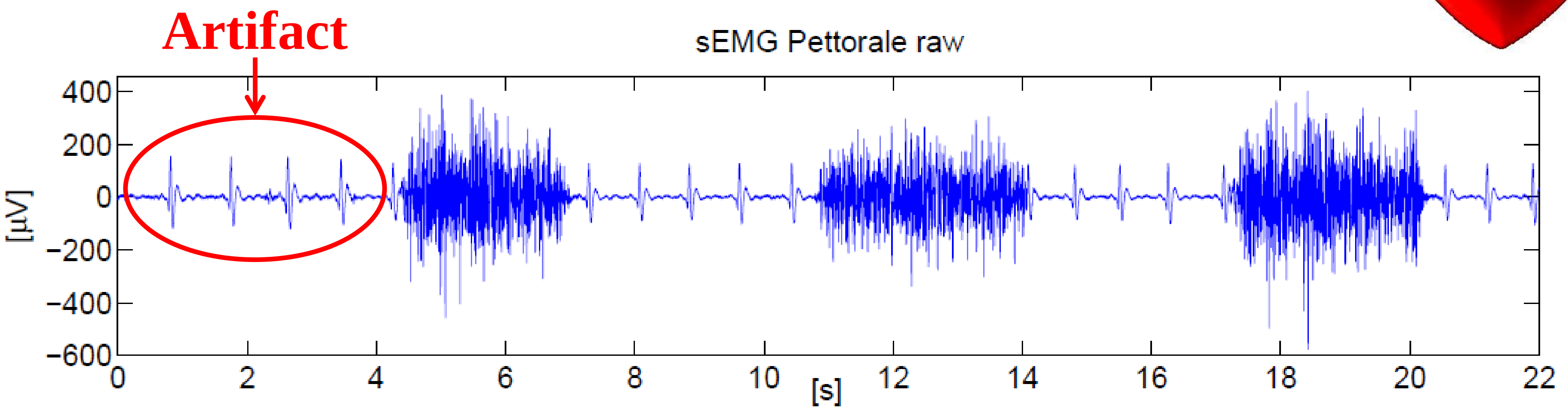
- **PHYSIOLOGICAL CROSS TALK :**

The Cross Talk Phenomenum could happen also between the electrical activities of two neighboring muscles

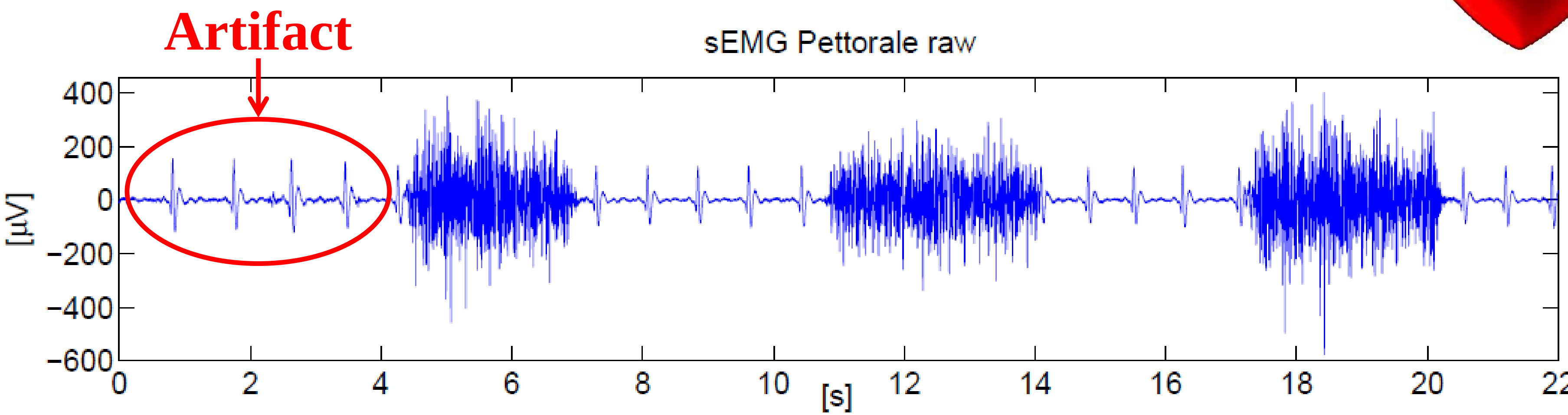


- **ELECTRODES MOVEMENTS**
- **EXTERNAL NOISE**
- **QUALITY OF THE INSTRUMENTS (electrodes, amplifier…)**

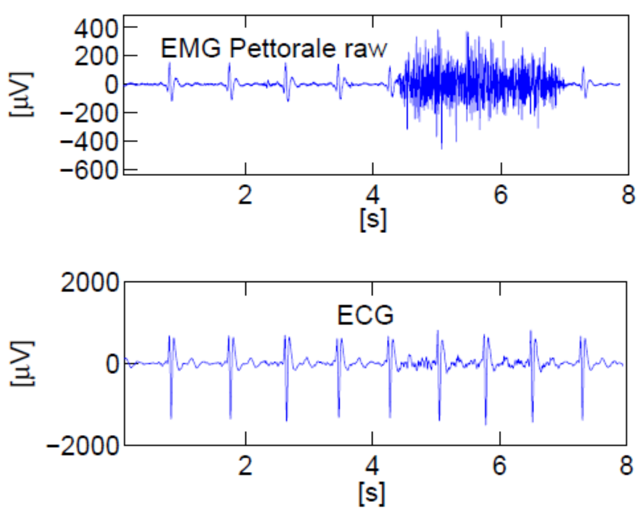
Heart Artifact

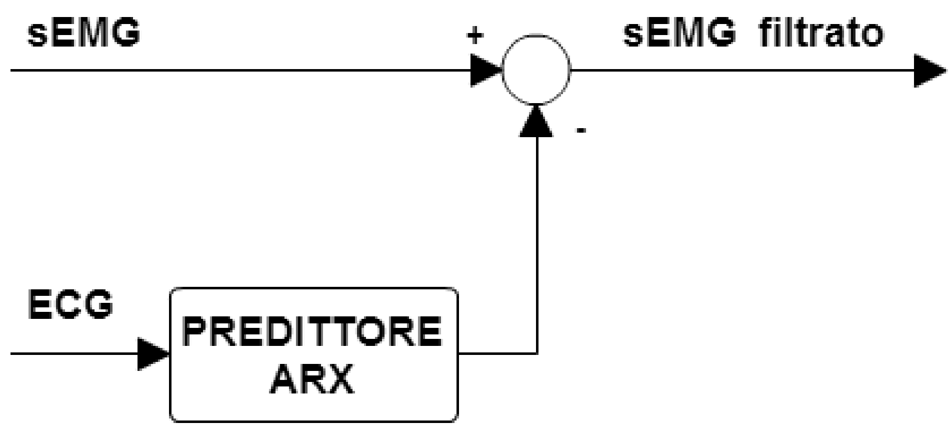


Heart Artifact

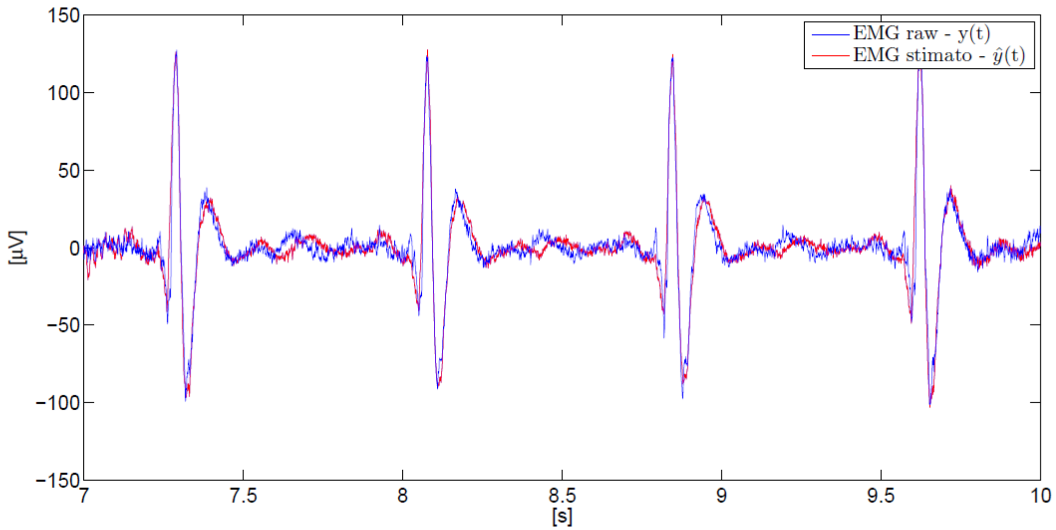


Artifact Removal



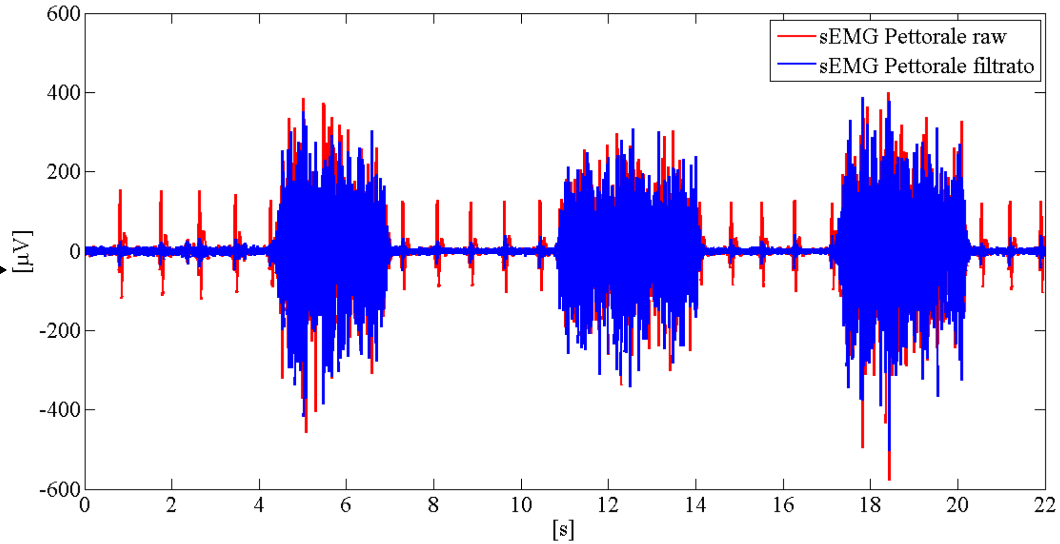


Heart Artifact



Artifact Estimation

EMG signal without artifact



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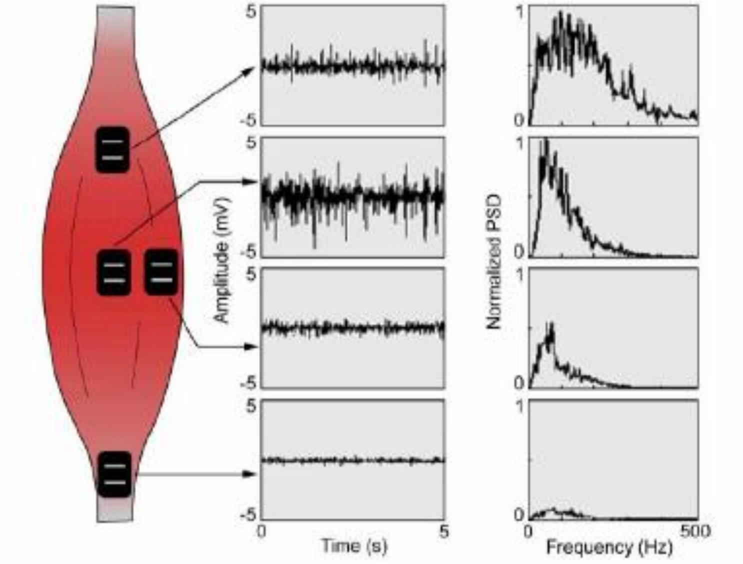
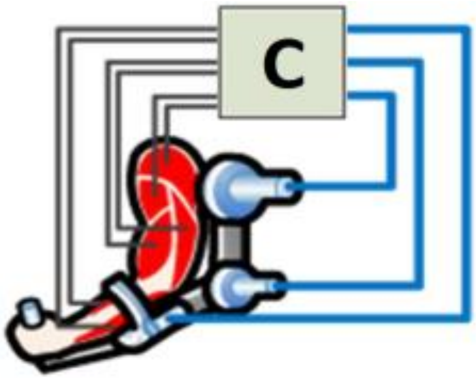
ELECTRODES PLACEMENT



BIPOLAR CONFIGURATION:
twe electrodes placed on the belly of the muscle

The GROUND ELECTRODE is used for removing the overall potential of the body and it is not «interested» on the muscle electrical activity



Neuro-Rehabilitation after stroke

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STROKE

- **Stroke** is a medical condition in which *poor blood flow* to the brain results in cell death.
- There are two main types of stroke:
  - *Ischemic*: due to lack of blood flow
  - *hemorrhagic*, due to bleeding.
- It results in part of the brain not functioning properly:
  - *inability to move or feel on one side of the body*
  - problems understanding or speaking
  - loss of vision to one side

STROKE

- Neuro-Rehabilitation is needed:

Traditional Rehabilitation

Robot-aided Rehabilitation

High-dosage and high-intensity training
High repeatability
Objective assessment
More engaging with Serious Games

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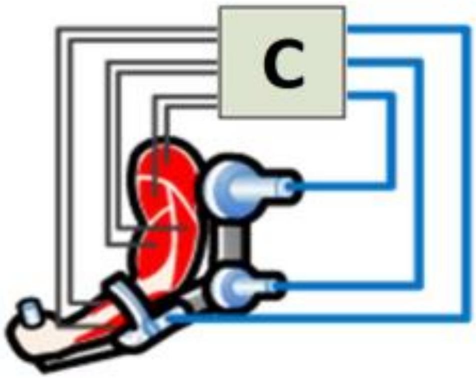

Robot-aided motor recovery after stroke

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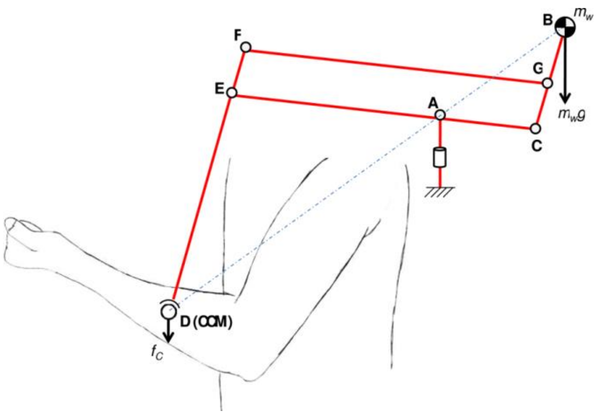
Passive Devices



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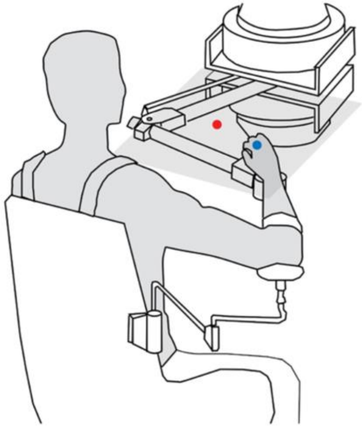
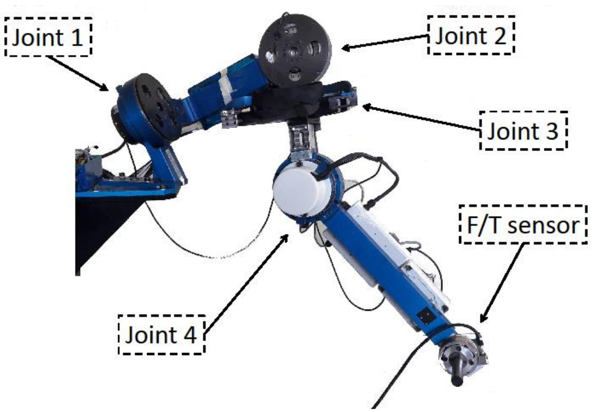
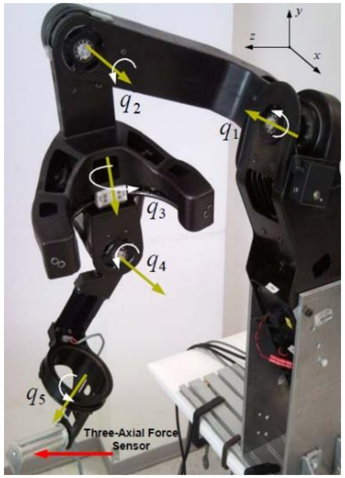
Active Devices for the arm

Manipulandum

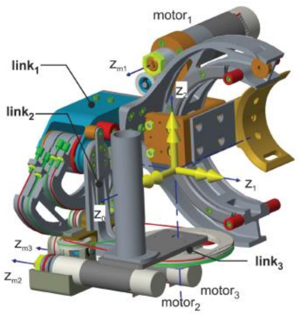


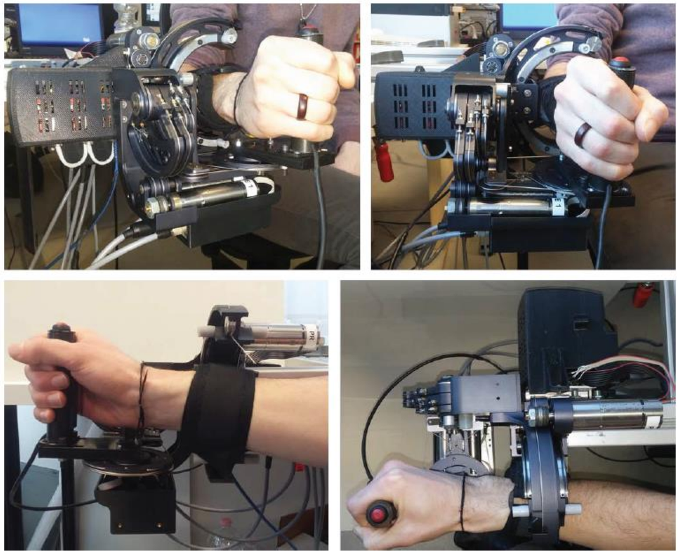
Exoskeletons

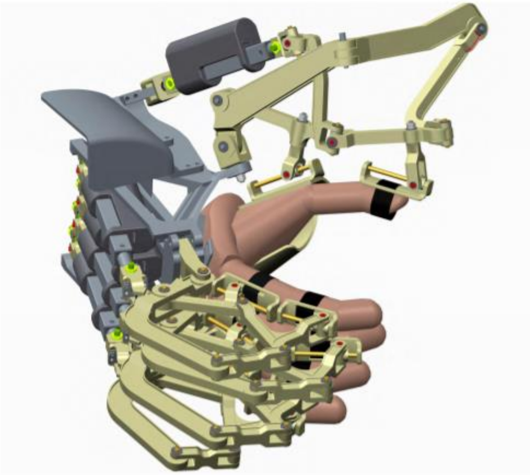


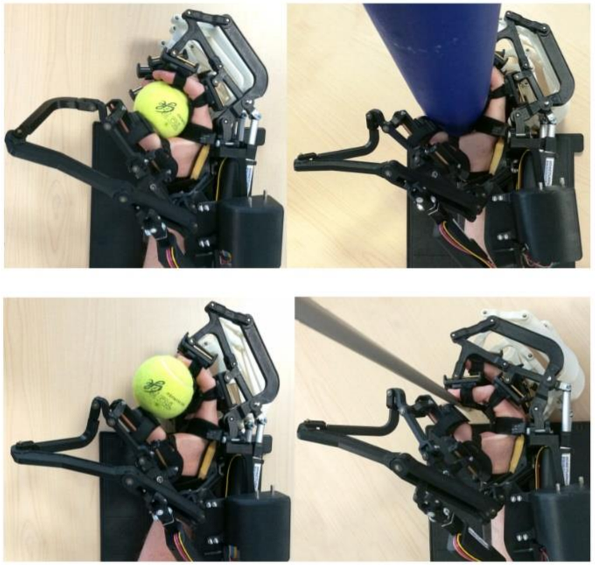


Active Devices for the wrist and the hand

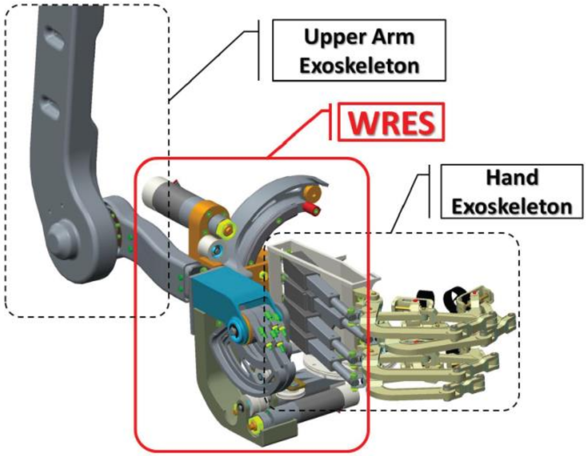


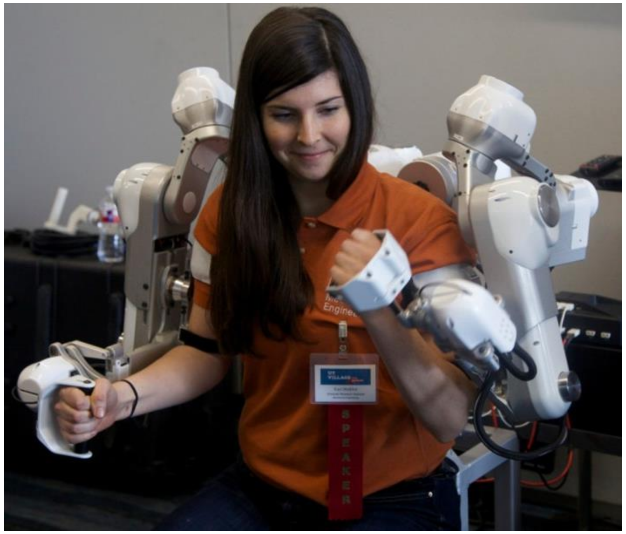


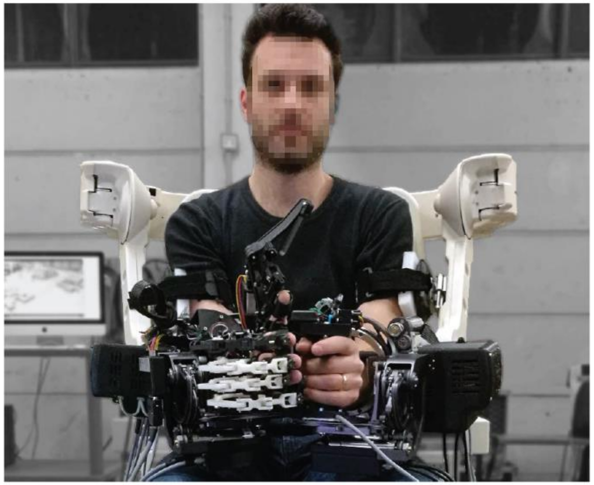




Robotic interfaces for neuro-rehabilitation







Neuro-Rehabilitation after stroke: motivation

- Several factors play a role in the process of **robot-aided** motor recovery after stroke
  - **[Task oriented training]**: movement training is associated to a task
  - **[Degree of participation]**: functional recovery requires active movement from the subject to elicit motor learning
  - **[Intensity of practice]**: Robot therapy can allow repetitive and high intensity movements

Neuro-Rehabilitation after stroke: motivation

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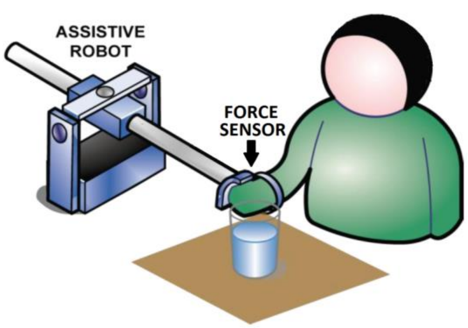
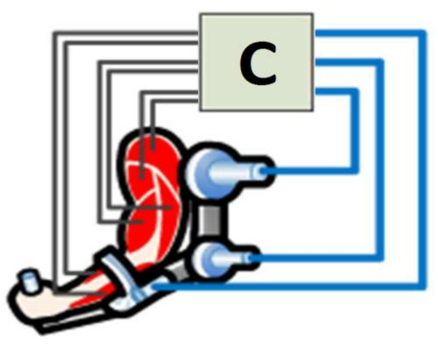
- Robotic assistance should be provided to patient based on the detection of intentional movement from patient.
- There are several approaches for movement intention detection and trigger the assistance accordingly, e.g. EEG signals, force/velocity and EMG signals.

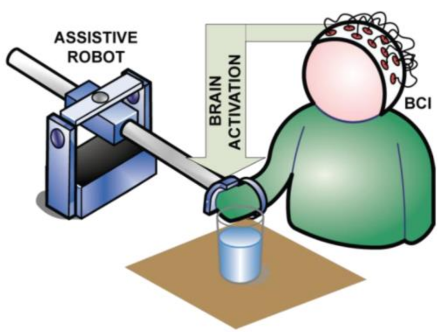
Kinematic/Dynamic-based control



EMG-based control

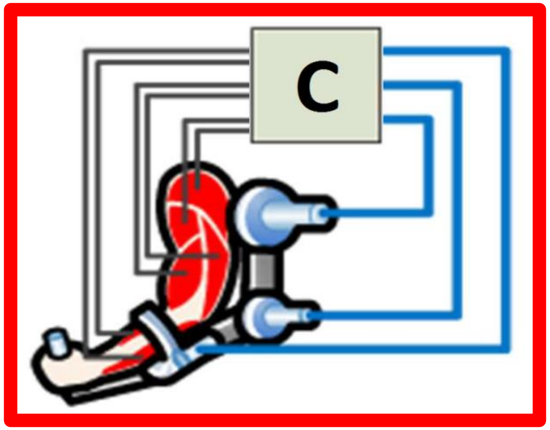


EEG-based control



EMG-based robotic assistance in neuro-rehabilitation

- **Pros**
  - Possibility to analyze the **contribution of each single muscle**, not only the resultant force;
  - Neuro-impaired patients with **residual muscle activities** could trigger robot assistance;
  - Actual movement attempt can be discriminated **avoiding compensation behaviors** (e.g., engaging their trunk to generate movements to exceed a speed/force threshold)
  - Processed EMG signals could be use **to assess the outcomes** of the rehabilitation therapy
- **Cons**
  - Complexity of muscle activation signal analysis due to:
    - ***Redundancy*** of actuation
    - ***Cross-talking*** in EMG muscle recording
    - ***Non-linearity*** of EMG-muscle force relationship
    - ***Subject-dependency***



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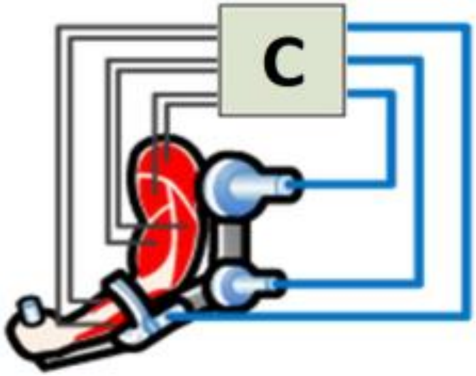
Main sEMG-based Myocontrol CLASSIFICATION

- ***Trigger-based***

A predefined motion of the assistive device is starts when the sEMG signal of one or more muscles is above a certain threshold.

- ***Continuous***

The motion of the assistive device is continuously modulated by the sEMG level signal of one or more muscles.



Upper Limb Exoskeleton Myoelectric control

Towards continuous EMG control: the role of Neuromusculoskeletal models

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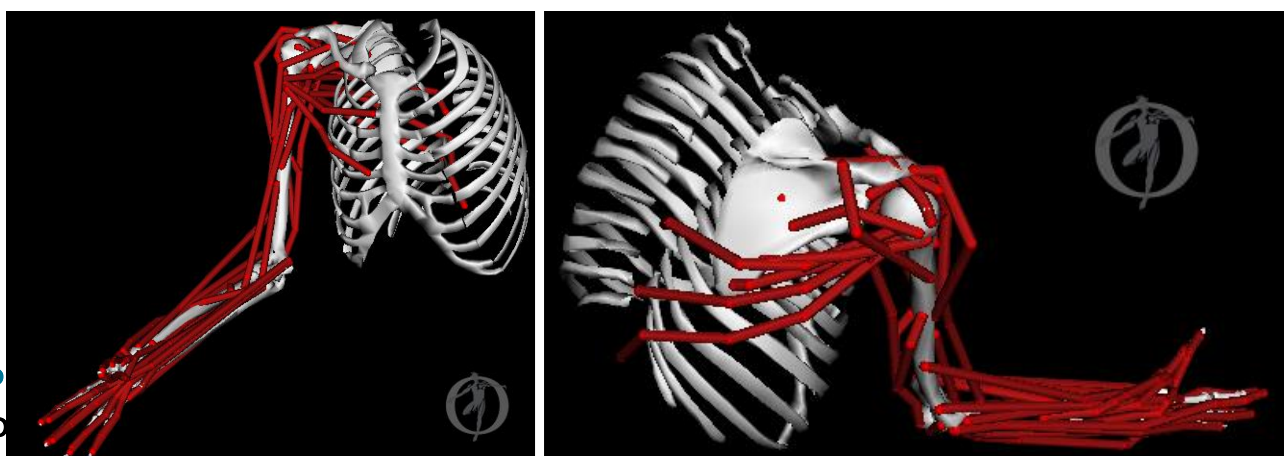
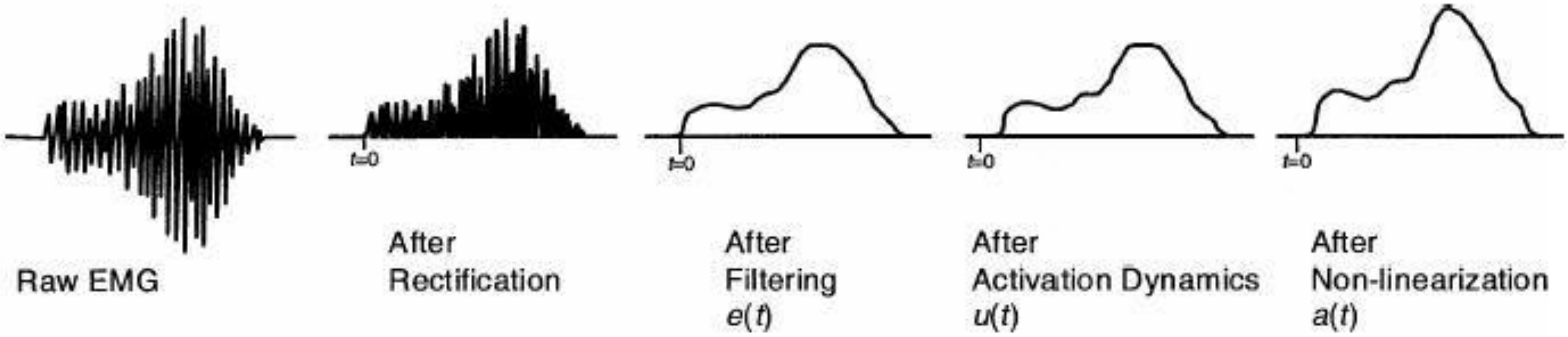
[D. Buongiorno et al. 2015, 2016a]

sEMG driven - Neuromusculoskeletal (NMS) Model

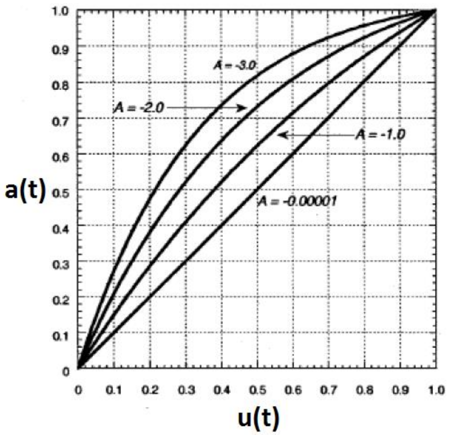
- A sEMG-driven NMS model is able to describe the process of articulation torque generation by using the knowledge of the:
  - Level of muscle activations (estimated from sEMG signals)
  - Muscle properties
  - Muscleskeletal system geometry



From sEMG signal to Muscle Activation



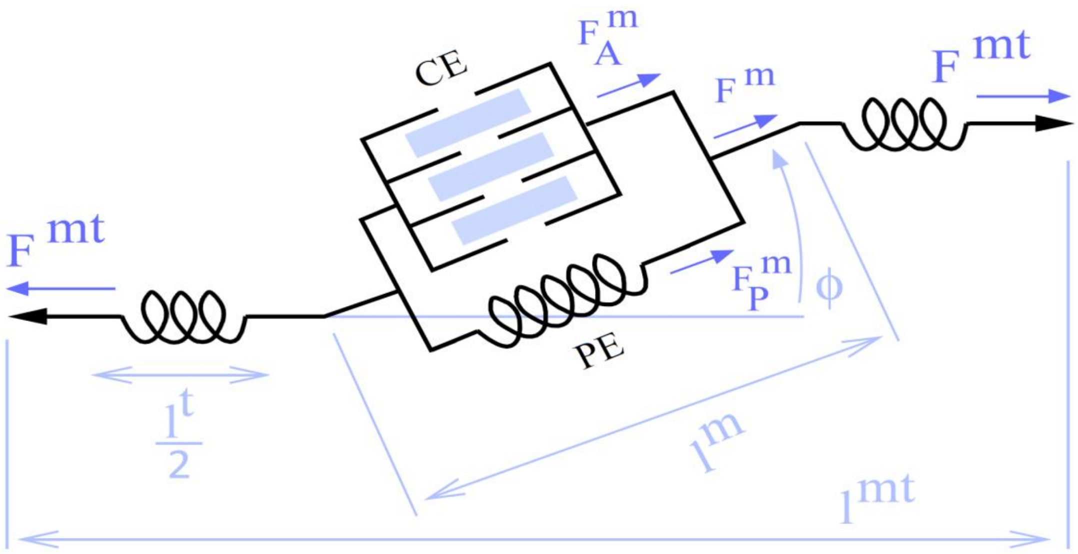
$$u(t) = \alpha\, e(t-d) - \beta_1 u(t-1) - \beta_2 u(t-2)$$



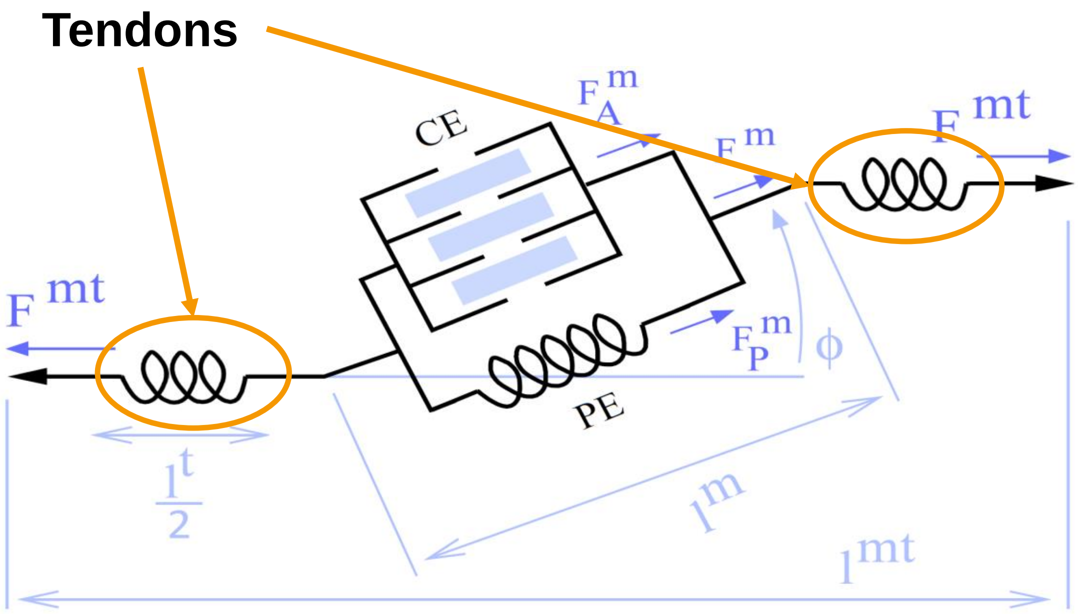
$$a(t) = \frac{e^{Au(t)} - 1}{e^{A} - 1} \quad \text{with} \quad -3 \le A < 0$$

[Lloyd & Besier, 2003; Lloyd & Buchanan, 1996]

The Hill-Type muscle model

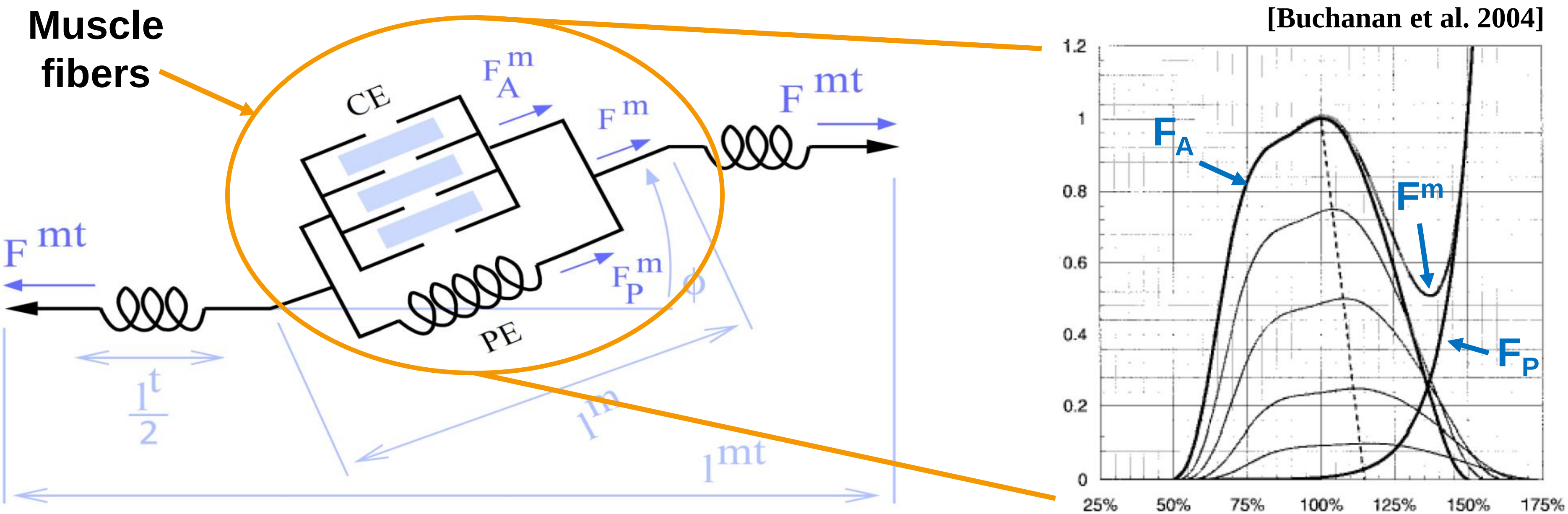


The Hill-Type muscle model



The Hill-Type muscle model

[Buchanan et al. 2004]



Muscle-Tendon Force

$$F_i^{mt}(t) = F_i^{MAX}\left[f_l(l_i^m)f_v(v_i^m)a_i(t) + f_p(l_i^m)\right]\cos(\phi_i(t))$$

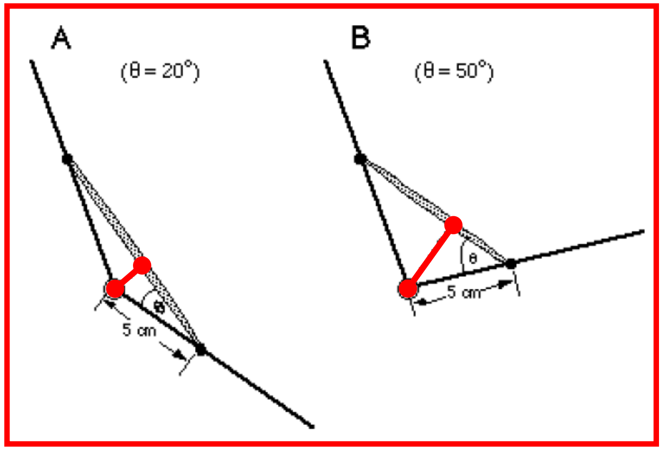
Articulation Torque

Joint Torque component generated by the single muscle

$$\tau_i^A = F_i^{mt} \cdot r_i^A(\theta^A)$$

Net Articulation Torque $$\tau^A = \sum_{i=1}^{N} \tau_i^A$$

Moment Arm
r(θ)



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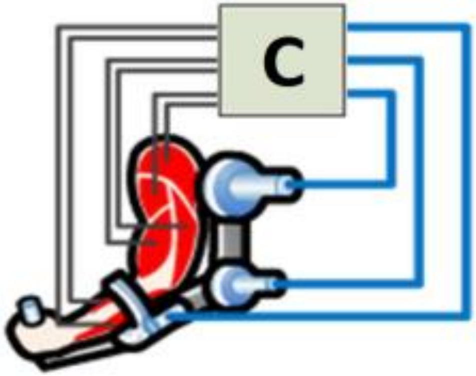

Non-linear Optimization Approach with a Genetic Algorithm

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[D. Buongiorno et al. 2015, 2016a]

Single muscle-model parameter optimization

Parameter	Description	Optimized
Single Variables per muscle/articulation		
(1) x	electromechanical delay	-
(2) A	non-linearity factor	✓
(3) l_O^m	optimal fibers length	✓
(4) ϕ_o	pennation angle	-
(5) F_O^m	maximum isometric force	✓
Relationships per muscle/articulation		
(6) $l^m(\theta)$	fibers-length/articulation-angle	✓
(7) $f_A(\tilde{l})$	normalized active-force/fiber-length	✓
(8) $f_P(\tilde{l})$	normalized passive-force/fiber-length	-
(9) $ma(\theta)$	moment-arm/articulation-angle	✓

Muscle-model parameters optimization

Parameter		Description	Optimized
Single Variables per muscle/articulation			
(1)	x	electromechanical delay	-
(2)	A	non-linearity factor	✓
(3)	l_O^m	optimal fibers length	✓
(4)	ϕ_o	pennation angle	-
(5)	F_O^m	maximum isometric force	✓
Relationships per muscle/articulation			
(6)	$l^m(\theta)$	fibers-length/articulation-angle	✓
(7)	$f_A(\tilde{l})$	normalized active-force/fiber-length	✓
(8)	$f_P(\tilde{l})$	normalized passive-force/fiber-length	-
(9)	$ma(\theta)$	moment-arm/articulation-angle	✓

Optimized subset of parameters

Muscle-model parameters optimization

Parameter	Description	Optimized
Single Variables per muscle/articulation		
(1) x	electromechanical delay	-
(2) A	non-linearity factor	✓
(3) l_O^m	optimal fibers length	✓
(4) ϕ_o	pennation angle	-
(5) F_O^m	maximum isometric force	✓
Relationships per muscle/articulation		
(6) $l^m(\theta)$	fibers-length/articulation-angle	✓
(7) $f_A(\tilde{l})$	normalized active-force/fiber-length	✓
(8) $f_P(\tilde{l})$	normalized passive-force/fiber-length	-
(9) $ma(\theta)$	moment-arm/articulation-angle	✓

Optimized subset of parameters

The optimization procedure make use 2 independent *Genetic Algorithms* [1]:

- **for Shoulder and Elbow Joint Torque Predictor**

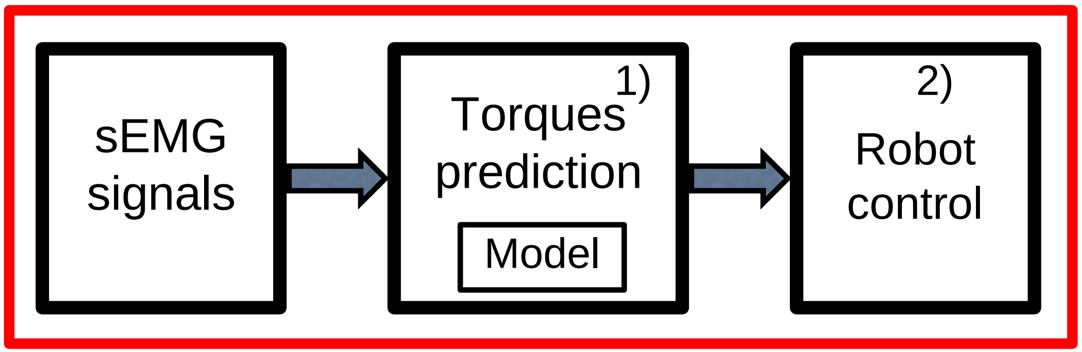
Fitness Function

$$FF_{\text{joint}} = \sum_t \left| \underbrace{\tau^P_{\text{joint}}(t)}_{\text{Predicted Torque}} - \underbrace{\left(\tau^m_{\text{joint}}(t) + \tau^g_{\text{joint}}(t)\right)}_{\text{Reference Torque}} \right|$$

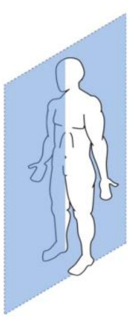
[1] "Genocop III: A co-evolutionary algorithm for numerical optimization problems with nonlinear constraints", Z. Michalewicz et al., 1995.

Approach Validation: Experimental Objectives

- To develop a myoelectric control that use a **reduced number of muscles**
  - **Model-based** prediction of the shoulder and elbow joint torques by means of surface ElectroMyoGraphic (sEMG) signals
  - **Control an upper limb exoskeleton** (along the pseudo-sagittal plane) using the predicted torques.

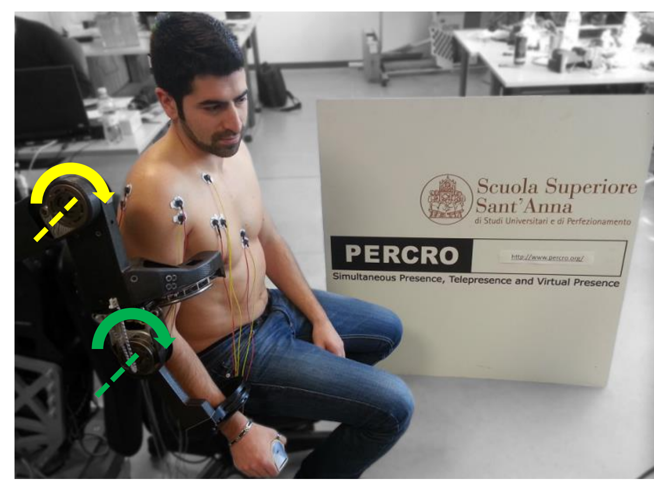


Sagittal Plane



Shoulder Joint (flexion/extension)

Elbow Joint



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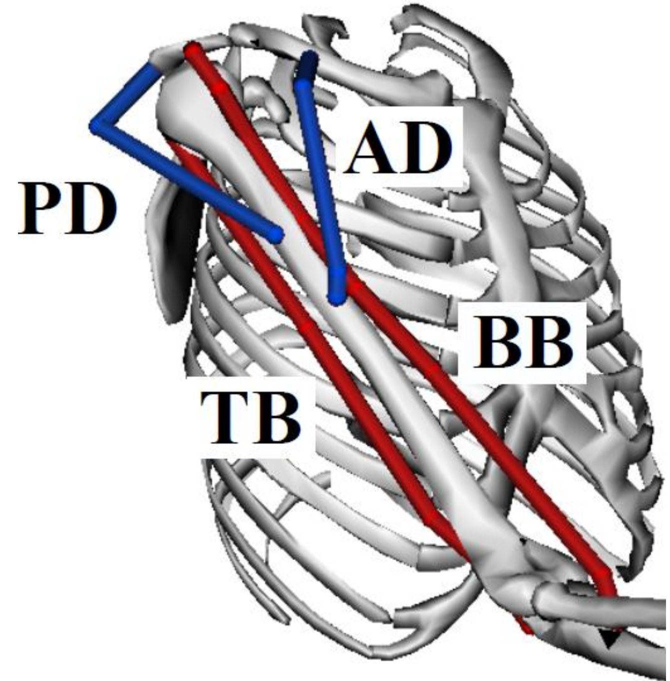
The sEMG Acquisition Preprocessing Subsystem

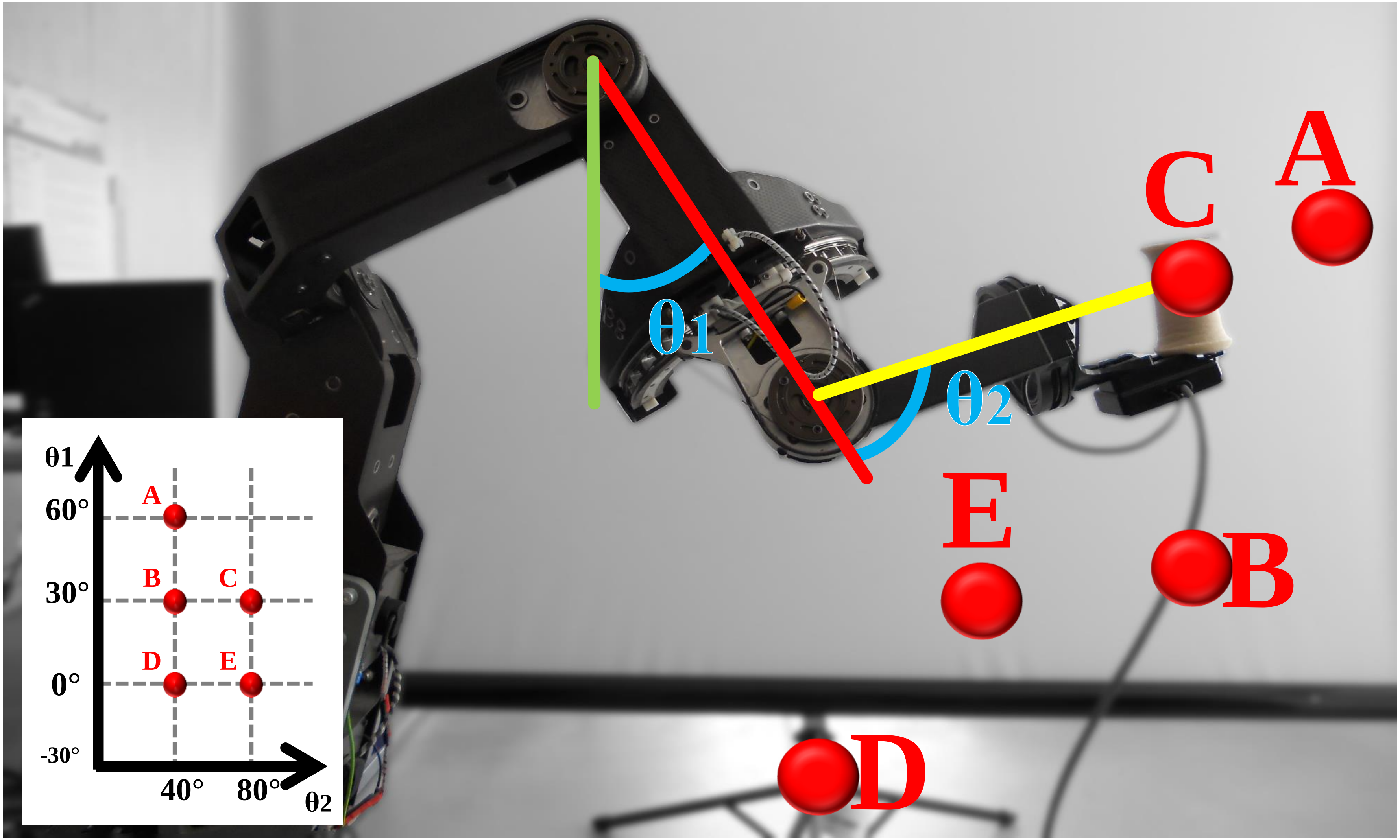
The surface ElectroMyoGraphic (sEMG) signals are recorded following SENIAM recommendations. [H. J. Hermens et al., 1999]

Shoulder Muscles
- **AD: Anterior head of Deltoid**
- **PD: Posterior head of Deltoid**

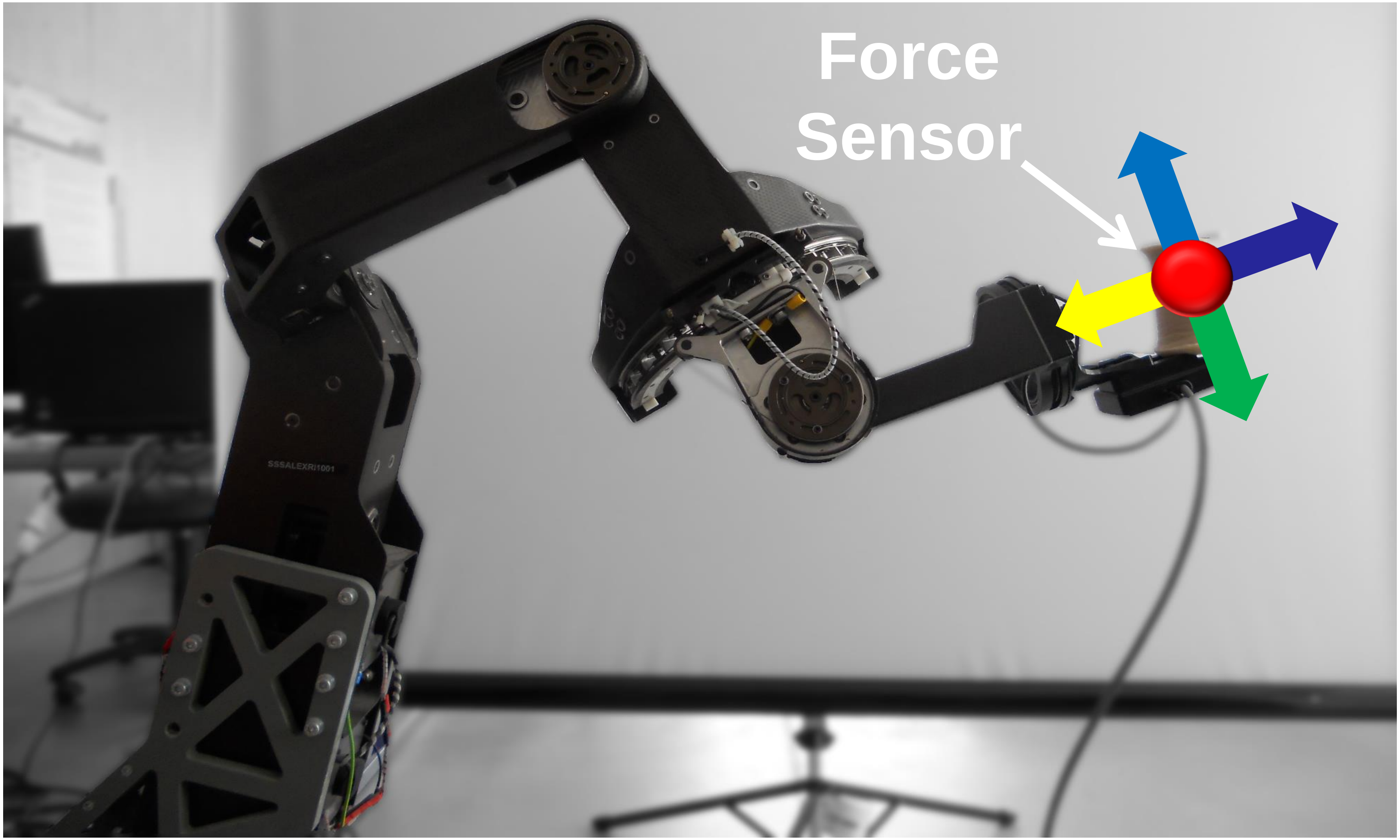
Elbow Muscles
- **BB: long head of Biceps Brachial**
- **TB: long head of Triceps Brachial**



Data Collection



Data Collection



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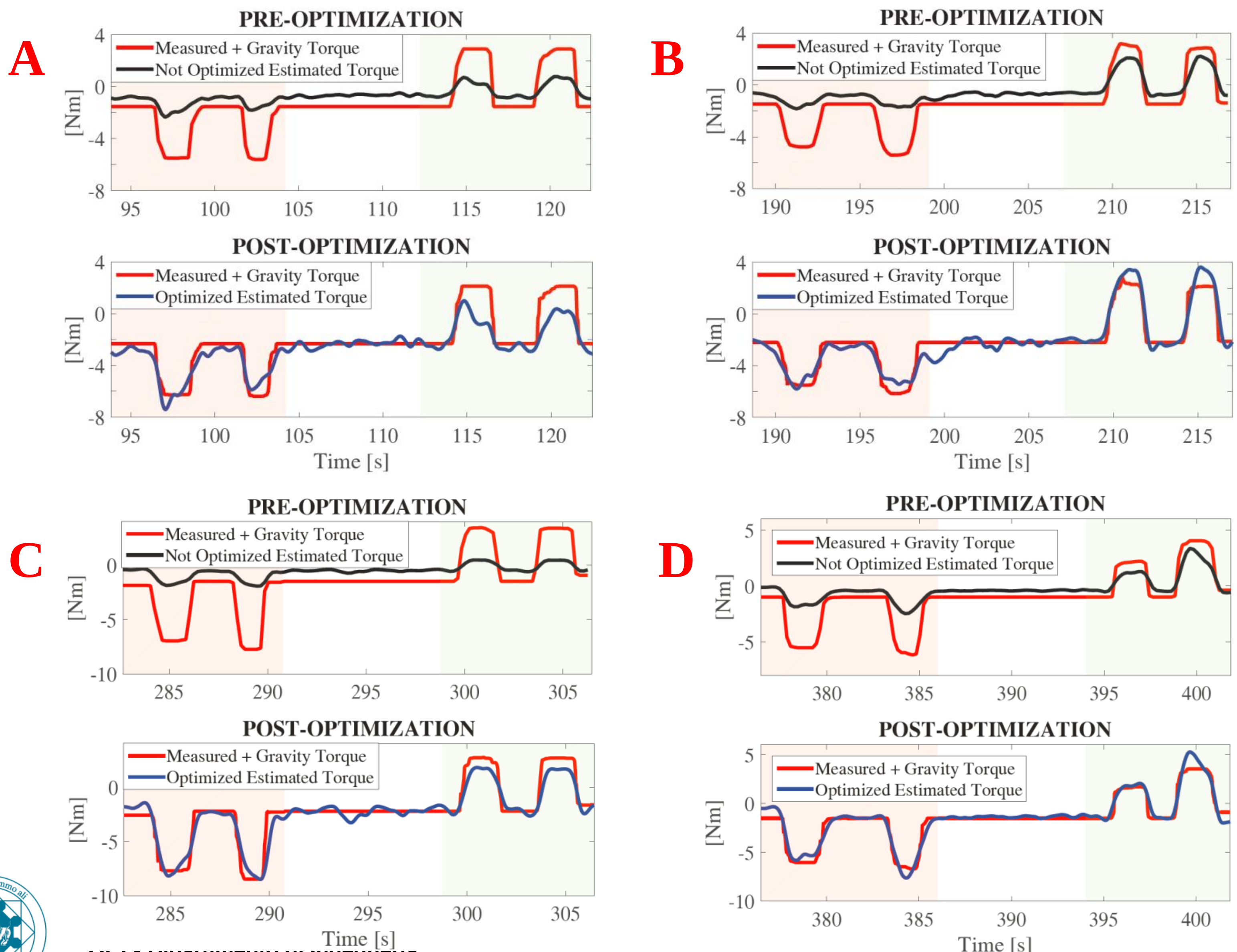
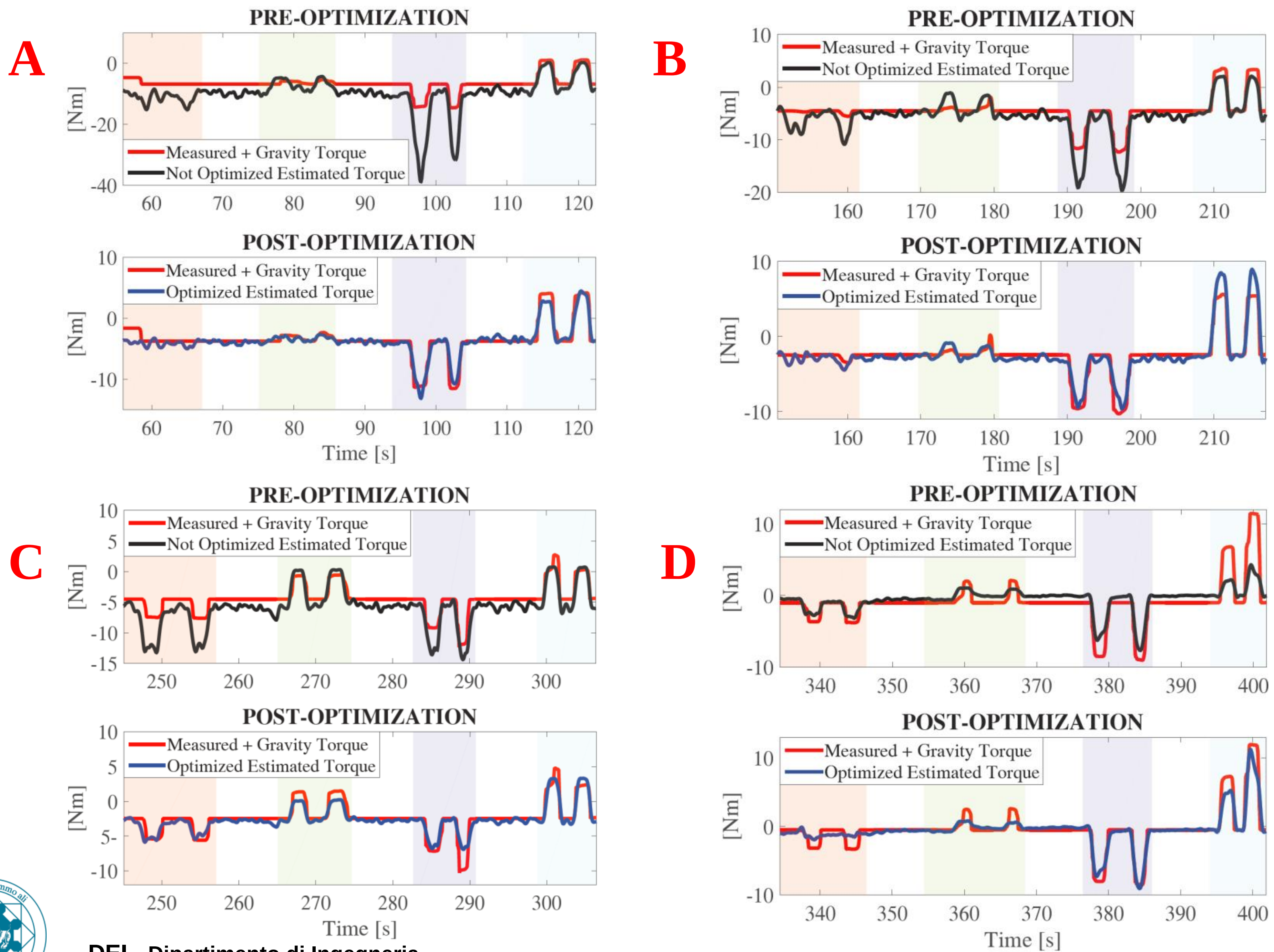
Elbow Model Performance



Shoulder Model Performance



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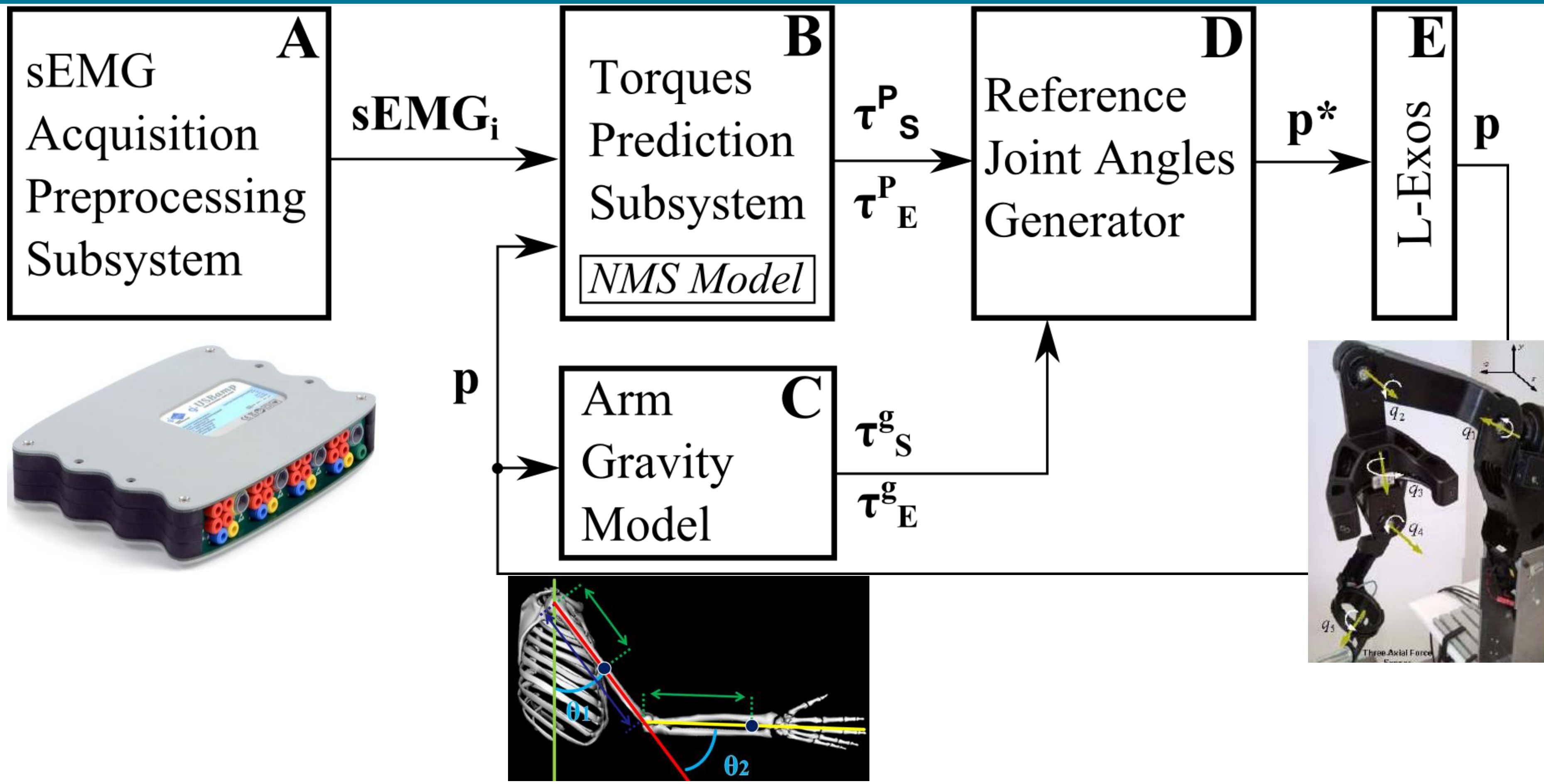
Myoelectric Control Diagram



NMS Model: NeuroMusculoSkeletal Model

$\tau^P_{S(\text{or } E)}$: Predicted torques at shoulder and at elbow
$\tau^g_{S(\text{or } E)}$: Gravity torques at shoulder and elbow
p: Current pose of the exoskeleton
p*: Desired pose of the exoskeleton

Reference Joint Angles Generator

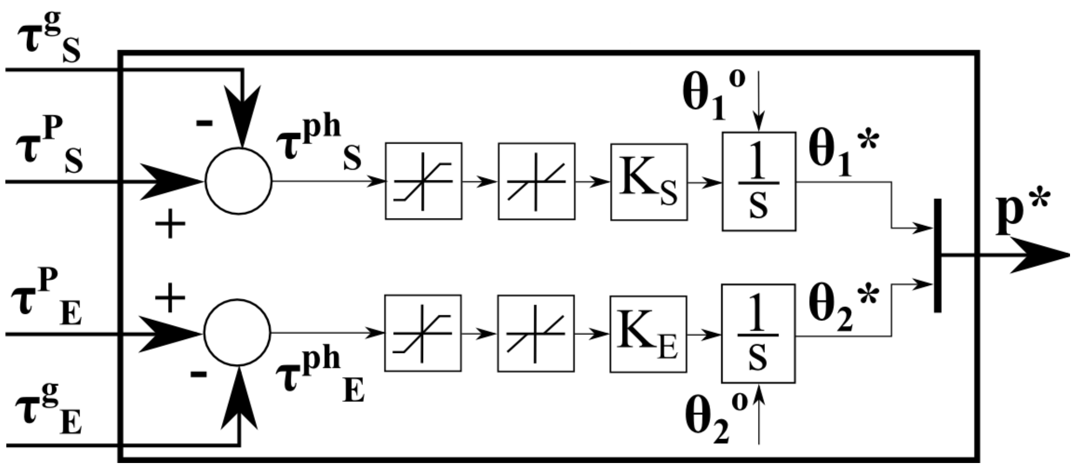
$$\tau_{joint}^{P} = \tau_{joint}^{g} + \tau_{joint}^{ph}$$

Predicted torque

Tonic component (Gravity torque)

Phasic component

The subject supports his arm during the experiments



$\tau^{ph}_{S(or\ E)}$: Phasic torques

$\tau^{P}_{S(or\ E)}$: Predicted torques

$\tau^{g}_{S(or\ E)}$: Gravity torques

p*: Desired pose of the exoskeleton

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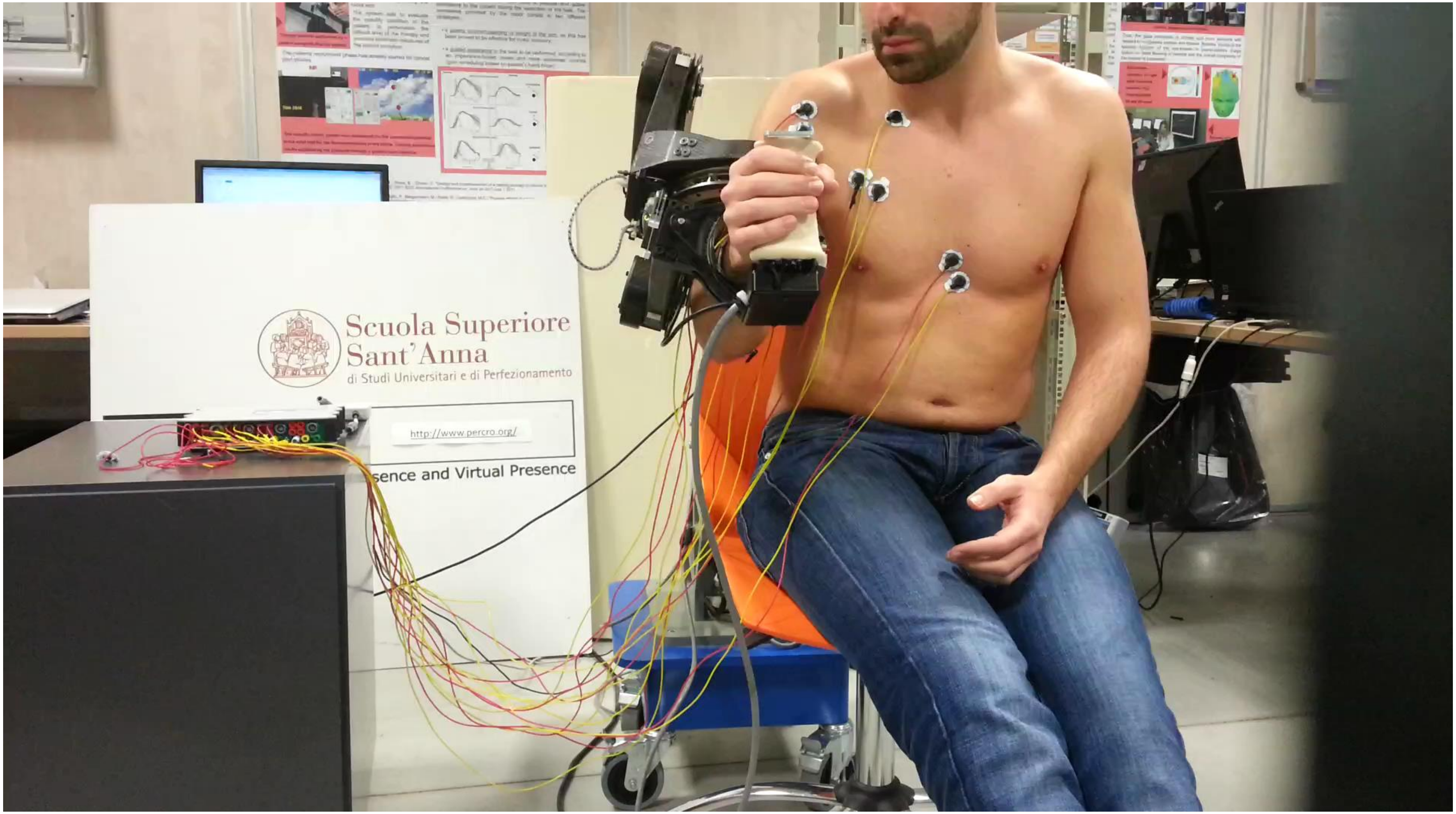
EMG-based control



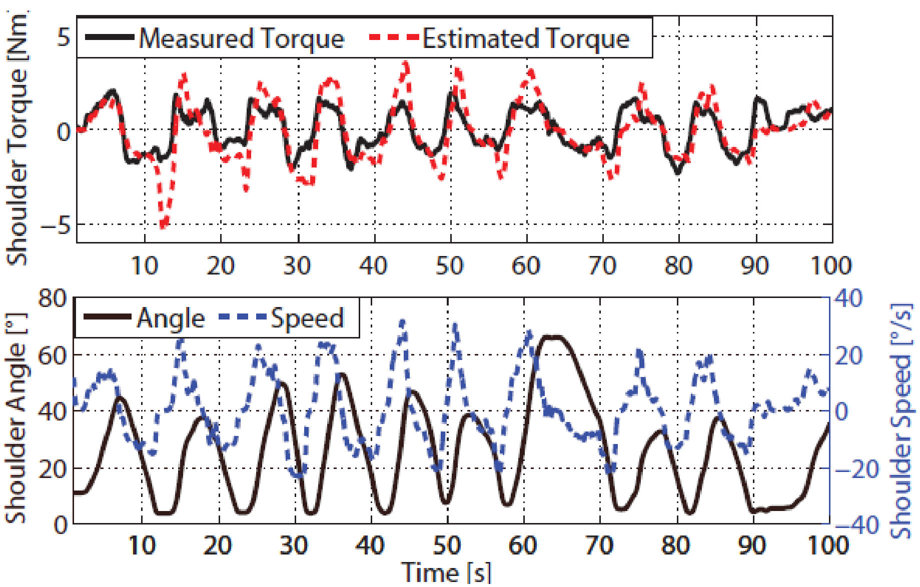
[D. Buongiorno et al. 2015, 2016a]

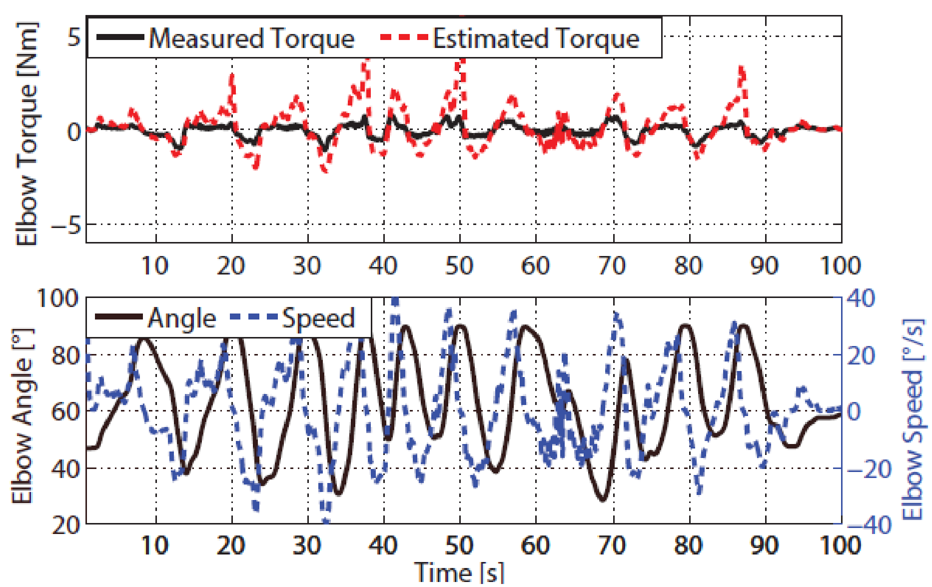
Validation experiment and results

Transparency analysis performing free movements along the pseudo-sagittal plane.

SHOULDER Joint

ELBOW Joint





[D. Buongiorno et al. 2015, 2016a]

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thank you!

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