Bioengineering Department

Neuro**e**ngineering
and
medic**a**l **r**obotics
Lab

DESIGN OF MYOCONTROLLED NEUROPROSTHESES

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Emilia Ambrosini

emilia.ambrosini@polimi.it

Outline

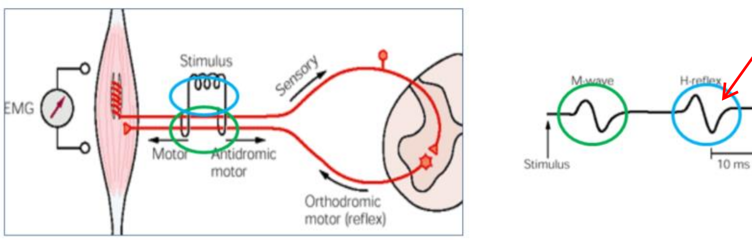
- ✓ Background
- ✓ EMG signals during hybrid muscle contractions
- ✓ Devices for EMG recordings during electrical stimulation
- ✓ Filters to estimate the volitional EMG component
- ✓ Control strategies for myocontrolled neuroprostheses
- ✓ Example of applications on neurological patients
  - *EU project MUNDUS*
  - *EU project RETRAINER*

the signal while we are stimulating is not the usual. Even for recording some adaptations are needed, because of the FES stimulation. So filters. Then C.S.

processing is needed to have an useful EMG + adaptation during the reading

Background

Neuromuscular Electrical Stimulation (NMES) has been used for **assistive** and **rehabilitative** purposes in neurorehabilitation for the last forty-years [Scheffler & Chae, 2007].



stimulation on afferent fibers

NMES induces muscle contractions through the depolarization of motor axons (**peripheral recruitment**) and sensory axons (**central recruitment**). [Bergquist, 2011].

H-reflex

stimulation of efferent and afferent fibers. FES induces MC with 2 mechanism: peripheral and central recruitment. If the muscle is not completely off, you can use EMG as signal of timing/intensity of stimulation. You basically amplify his intention using FES.

Background

When muscles are not completely paralyzed, **EMG signals of the paretic limb can be used to control** the timing and the intensity of the **stimulation** [Jiang, 2010]

You need residual capability of the muscle

WHY SUCH A CONTROL SCHEME IS ACTRACTIVE?

EMG: detect signal, then amplify it's movement

1) *ASSISTIVE PURPOSES* [*RESTORATION]

Myocontrolled NMES augments the force of the paretic muscles allowing the users to directly control the execution of the movements [Pedrocchi, 2013].

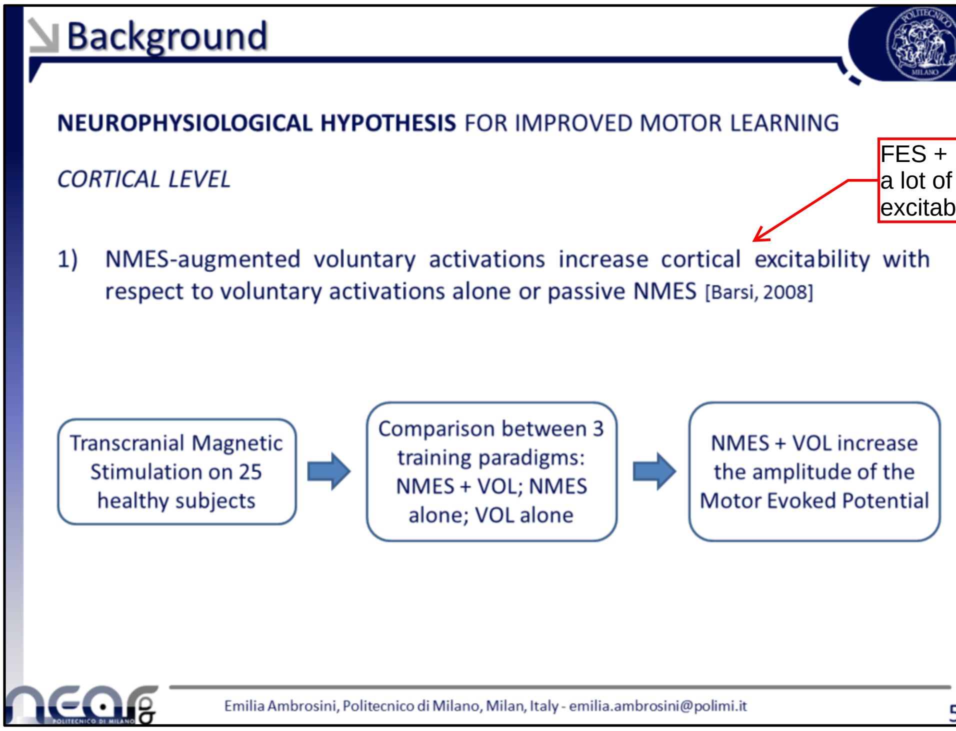
the sync between voluntary action + FES maximes motor RE-LEARNING

2) *THERAPEUTIC PURPOSES* [*REHABILITATION]

NMES co-incidental with the voluntary drive enhances motor re-learning [Fujiwara, 2009; Shindo, 2011].

So this is interesting for both assistive and therapeutic devices

The sync between two actions maximize the motor learning process. So the myocontrolled assistive/therapeutic idea is really interesting.



FES + VOLITIONAL => a lot of cortical excitability

With different technique (tMS, fMRI etc.) we have seen increase of excitability with FES + volitional contraction, instead of FES during passive movements.

Background

NEUROPHYSIOLOGICAL HYPOTHESIS FOR IMPROVED MOTOR LEARNING

CORTICAL LEVEL

FES + VOLITIONAL

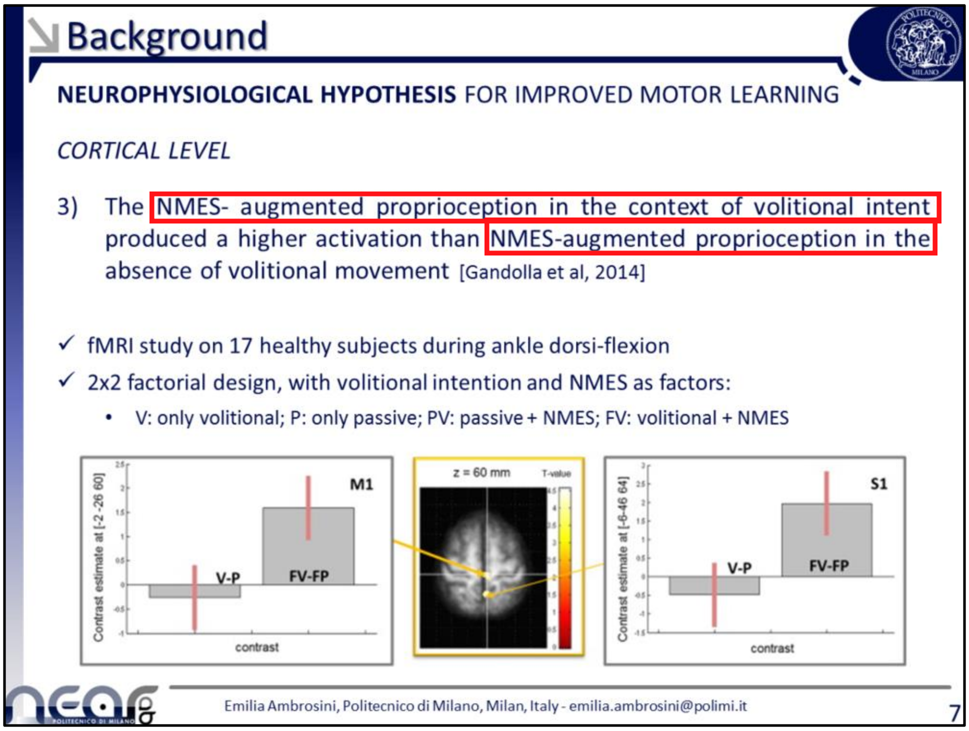
2) NMES combined with voluntary effort improves the prediction of sensory consequences of motor commands [Iftime-Nielsen, 2012]

Migliora il forward model

NMES + VOL

↑ cerebellar activity compared to NMES alone → prediction of sensory consequences of the movements

↓ bilateral activity in the secondary somatosensory areas compared to VOL alone → better match between the internal model and the actual sensory feedback



The authors demonstrated that the positive interaction was seen in both primary motor cortex (M1) and primary somatosensory cortex (S1);

FES-AUGMENTED

in other words, the effect of augmented proprioception depends on volitional movement in both M1 and

S1. The interaction between FES and voluntary effort could be therefore the mechanism by

which FES leads to a clinically meaningful carryover effect in neurological patients.

With different technique we have seen increase of excitability with FES + volitional. It has seen that the activation in the M1 and S1 (Sensory cortical area) has increased activation when FES is combined with volitional. So FES WAY BETTER with volitional ideas rather than passive activation.

Brain activity with fMRI. The activation both in motor area M1 and S1 sensory cortal area, there's an increase of activation when FES is combined with volitional contraction. Instead this is not here during passive movements.

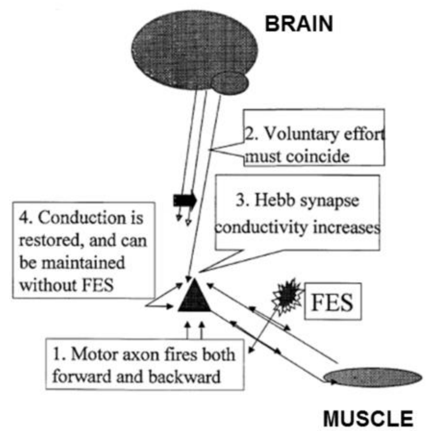
Background

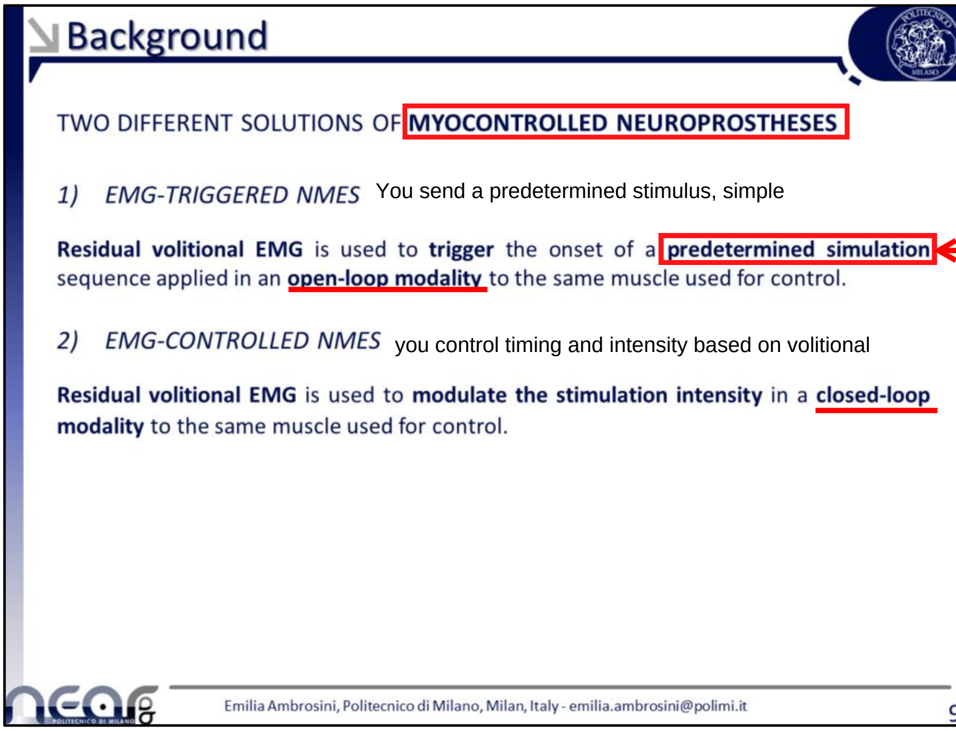
NEUROPHYSIOLOGICAL HYPOTHESIS FOR IMPROVED MOTOR LEARNING

SPINAL LEVEL

NMES antidromic impulses combined with coincident voluntary effort synchronize pre-synaptic and post-synaptic activity of the anterior horn cells

Restorative synaptic modifications at spinal level [Rushton, 2003]





1. **EMG triggered NMES**: you use EMG to trigger the activation, you send a predetermined stimulation just triggered by the volitional
   a. In this case you don't have to record while stimulating, you don't have the problem of filtering + stimulation artifacts. But you have no guarantee about sync (maybe the sbj has stopped to contract?). You dont know if aterwards the subject was not contracting anymore and the FES was doing all the job.

2. **EMG controlled NMES**: online in closed loop you control time and intensity based on volitional contraction.
   a. Real sync: if you don't go on with the contraction the FES stops

Background

TWO DIFFERENT SOLUTIONS OF **MYOCONTROLLED NEUROPROSTHESIS**

	EMG-TRIGGERED NMES	EMG-CONTROLLED NMES
PROS	Simple to implement → EMG signal is measured only before NMES starts	Assure the synchronization between NMES and voluntary effort
CONS	No guarantees about the synchronization between NMES and voluntary effort	More complex technological solutions are needed for the design

EMG signals during hybrid muscle contractions

Hybrid muscle activations: muscle contractions both volitional and electrically induced [Langzam, 2006]

Different from standard EMG signal!

Stimulation artifact: spike lasting few ms due to the electric field generated by the stimulation current

M-wave: compound action potential due to the synchronous firing of the electrically elicited muscle fibers (some mV)

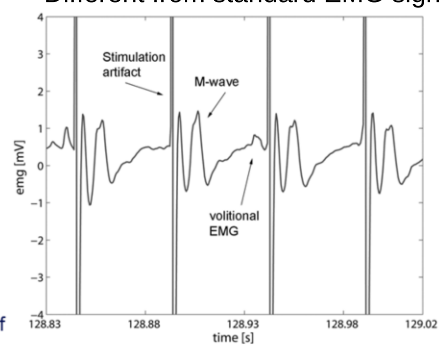
due to sensory fibers

H-reflex: second waveform determined by the orthodromic sensory volley

F-wave: small second compound action potential due to the antidromic efferent stimuli

Volitional EMG: stochastic signal with an amplitude of at least one magnitude less than the M-wave

these things: time variant signals (?)



Stimulation frequency = 20 Hz

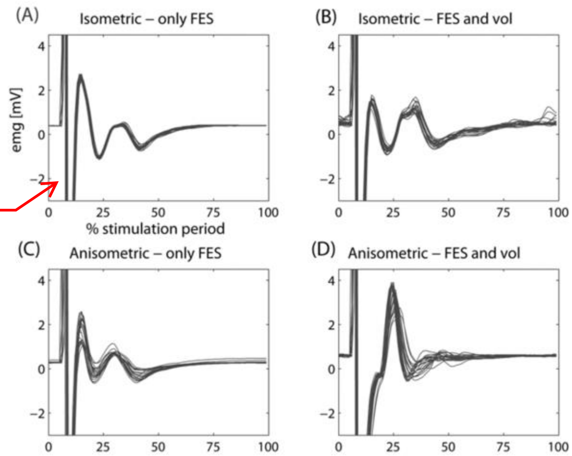
EMG signal during hybrid muscle contraction (volitional + electrical contribution):
-Stimulation artifacts (due to spike sent by the FES). They comes every xms => freq of stimulus It's HUGE to respect the signal usual acquired. Has to be cancaled.
-M-Wave: sync of muscle fibers firing. Again bigger than volitional contraction
-"Little noise": volitional EMG
-Others contribution: H-relflex, F-wave

EMG signals during hybrid muscle contractions

Differences between **isometric** and **anisometric** muscle contractions

passive movement: M wave is deterministic

here we could just substract



20 inter-pulse periods in each panel

Biceps muscle

Stimulation parameters

Current = 18 mA

Pulse Width = 300 us

Frequency = 20 Hz

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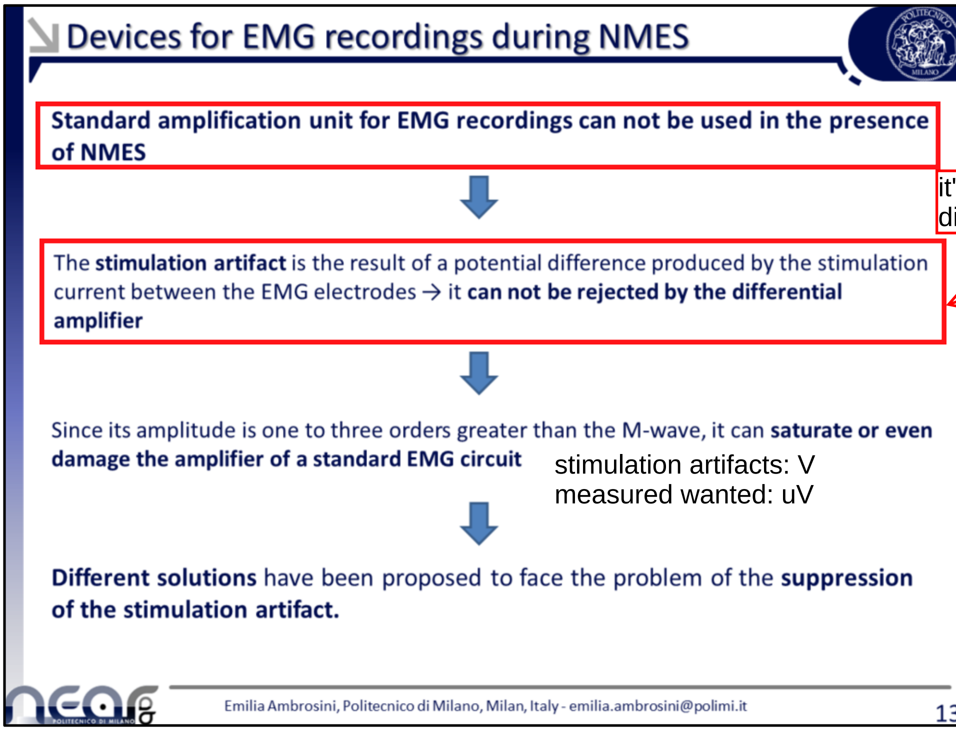
Isometric/anisometric contractions: during isometric contraction (in short time, 20 consecutive) the signal is almost perfectly overlapped (FES). Anisometric: we have movement of muscles and relative to electrodes, M-wave is changing, it’s difficult to filter in this way. In the first case we could just substract with the stimulus effect.

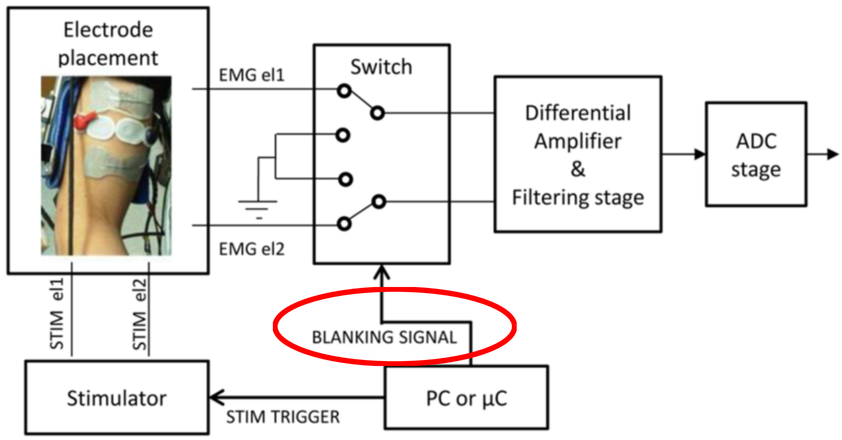


it's already a differential signal!

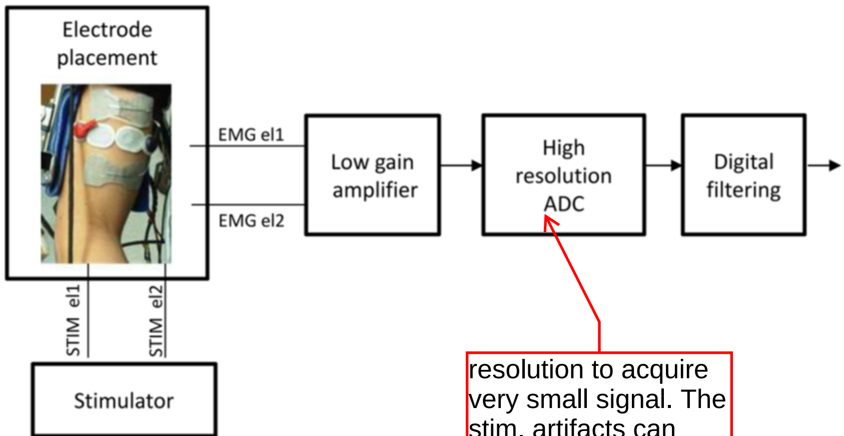
stimulation artifacts: V
measured wanted: uV

The stimulation artifacts (due to FES stimulation) could break the amplifiers which also have an huge gain and are made for really small signal. Solution:
-Blanking circuits: tipo scolleghi l’amp quando stimoli
-Very low gain + ADC (23bits) => acquire very small signals. The stimulation can saturate the amp, but it can recover very fast because it has low gain, and you have time to see the volitional.

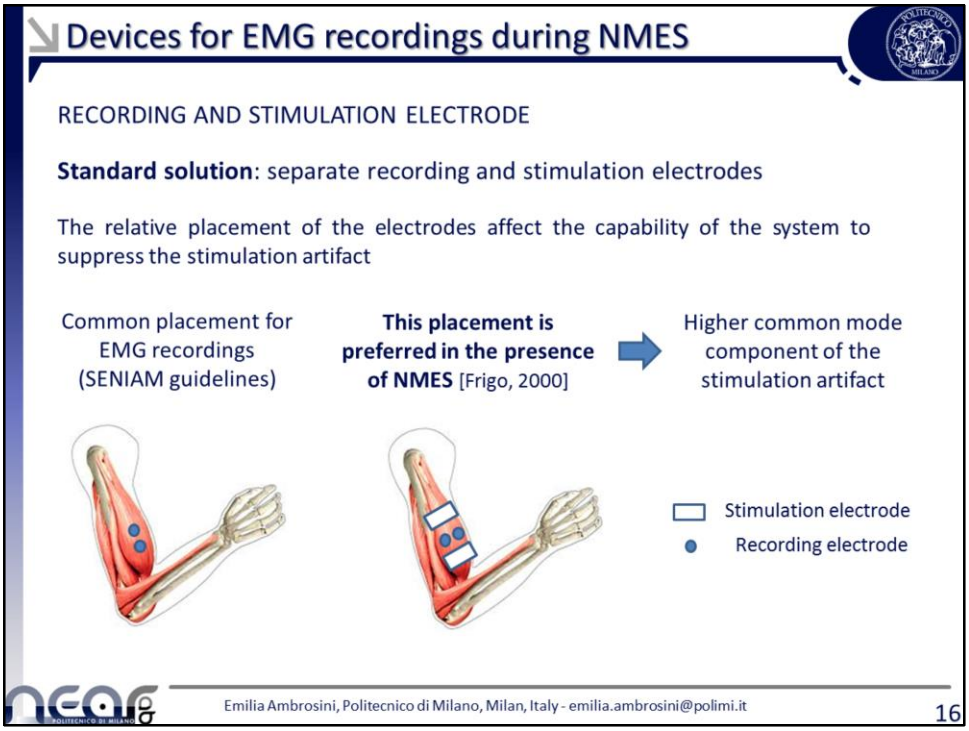
Devices for EMG recordings during NMES



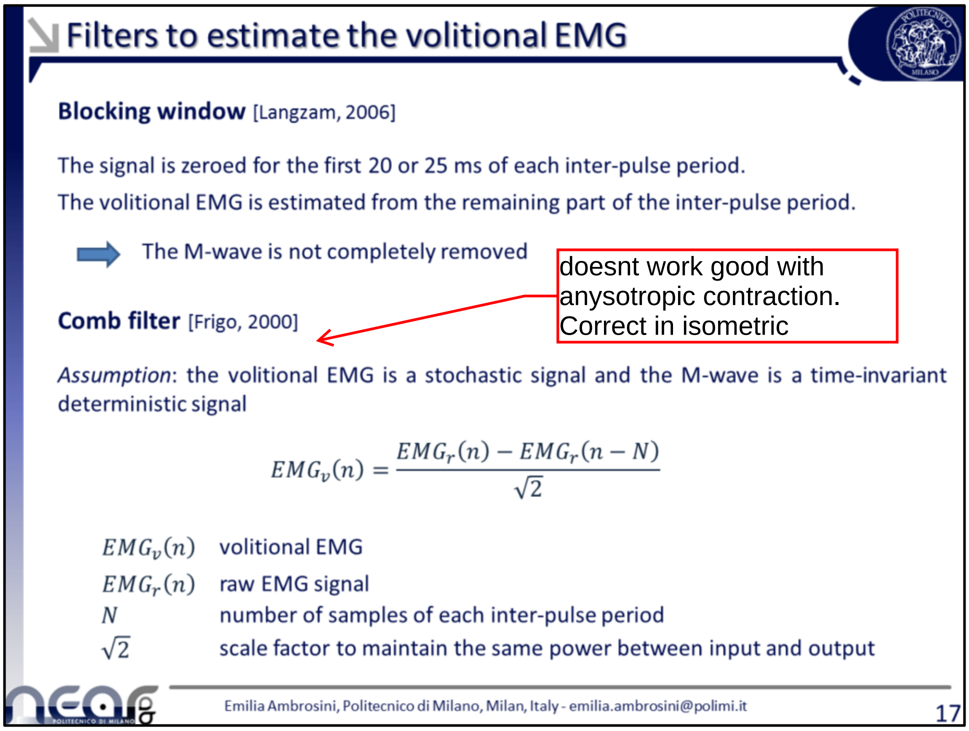
Devices for EMG recordings during NMES



resolution to acquire very small signal. The stim. artifacts can saturate it, but it recover very fast because it has low gain



we are doubling the electrodes, 2 for stim, 2 for recordin. In clinics you have to increase the number of el, and for small muscles is difficult to place all of these electrodes. There are some works to integrate the two in the same electrodes, but nothing commercially available.



Filter volitional EMG: different solution.
-**Blocking window**, cancel the first half then just take the second half of the window. You remove a lot of signal.
-**Comb filter**: you do a subtraction between the actual window and the last window.
-**High pass filter**: the high freq component in the second half is correlated to the volitional EMG. While the M-wave is low freq.
-**Linear prediction adaptive filter**. It’s a difference, but also with a linear combination of a number of previous intervals.

Filters to estimate the volitional EMG

High-Pass filter [Muraoka, 2002; Schauer, 2004]

Assumption: 20-30 ms after the stimulation pulse, only low-frequency electrically-induced components superpose the volitional EMG

Blocking window + high-pass filter with a cut-off frequency between 200 and 330 Hz

Linear Prediction Adaptive filter [Sennels, 1997]

Assumption: the volitional EMG is a band-limited Gaussian signal and the M-wave is time-variant

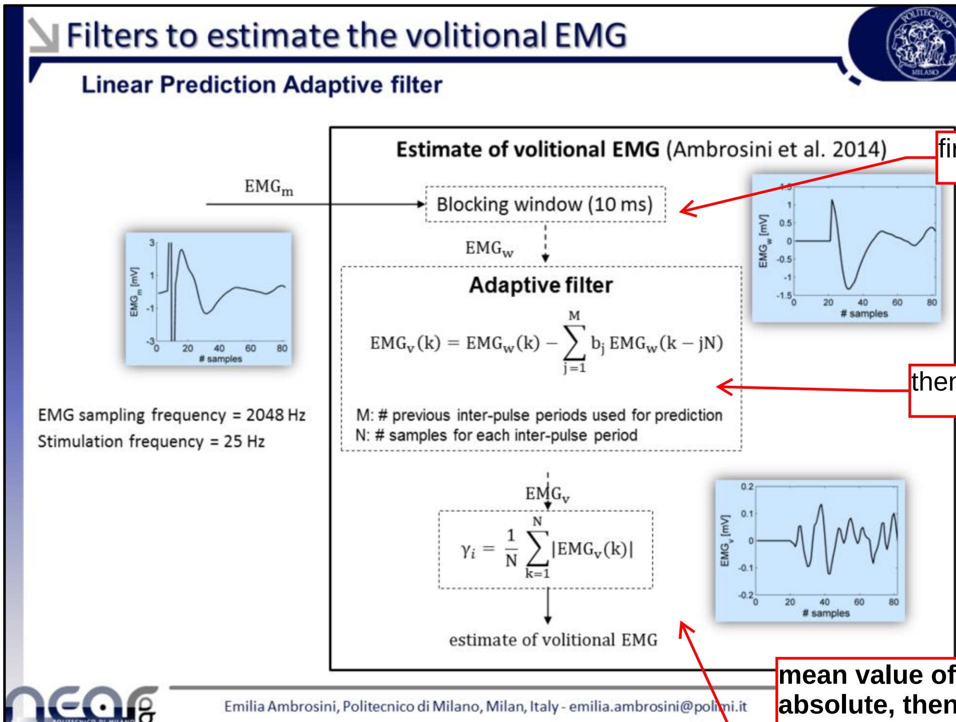
$$EMG_v(n) = EMG_r(n) - \sum_{i=1}^{M} b_j EMG_r(n - jN)$$

linear comb. of a number of previous intervals (6), b coefficients obtain by LSQ.

M number of previous inter-pulse periods used for prediction (6)

b_j filter coefficients computed by solving a least square algorithm that minimizes the output energy of the current inter-pulse period

b_j are updated at a rate equal to the stimulation frequency



first blocking window

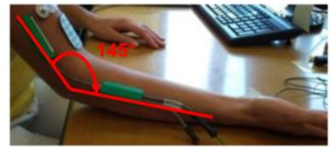
then adaptive filter

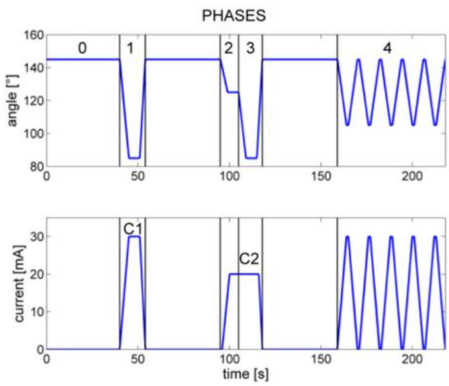
mean value of the absolute, then we have one signal every stimulation, so one sample at the stimulation pulse

Filters to estimate the volitional EMG

HOW TO IDENTIFY THE BEST FILTER ?

Comparison between a time-domain (**adaptive filter**) and a frequency-domain method (**high-pass filter**) on dynamic EMG signals acquired on **healthy subjects** (N=10) and **neurological patients** (N=8)

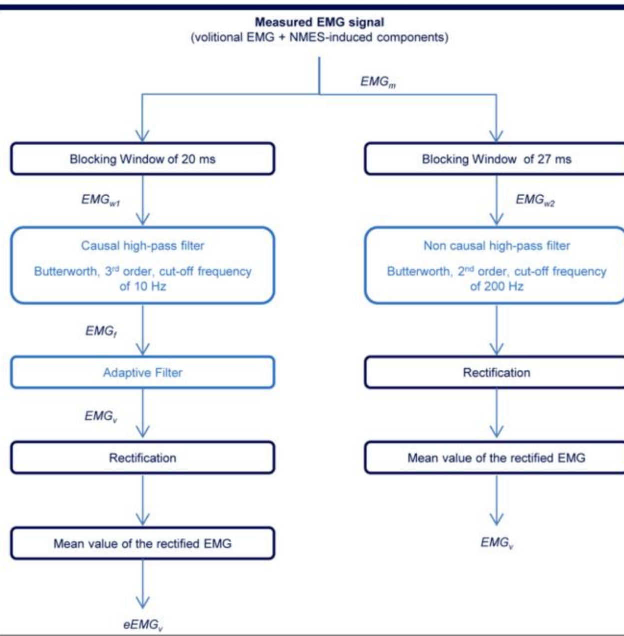




phase 0: rest
phase 1: stimulation C1, no volitional
phase 2: stimulation C2, no volitional
phase 3: stimulation C2 plus volitional
phase 4: variable stimulation, no volitional

[Ambrosini et al, *JEK*, 2014]

Filters to estimate the volitional EMG



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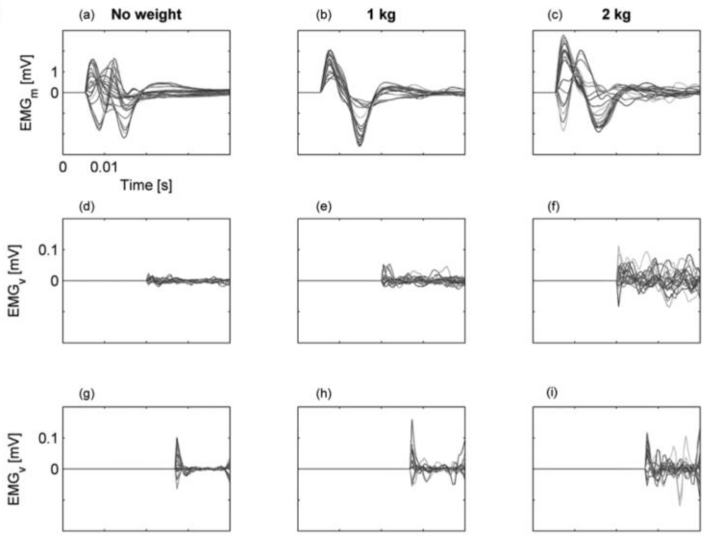
Filters to estimate the volitional EMG

Stimulation of the biceps brachii

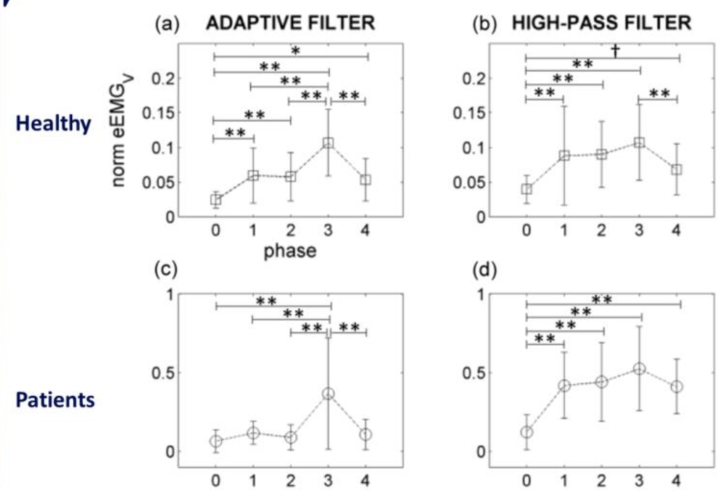
current = 15 mA
PW = 300 µs
frequency = 25 Hz



ADAPTIVE FILTER

HIGH-PASS FILTER

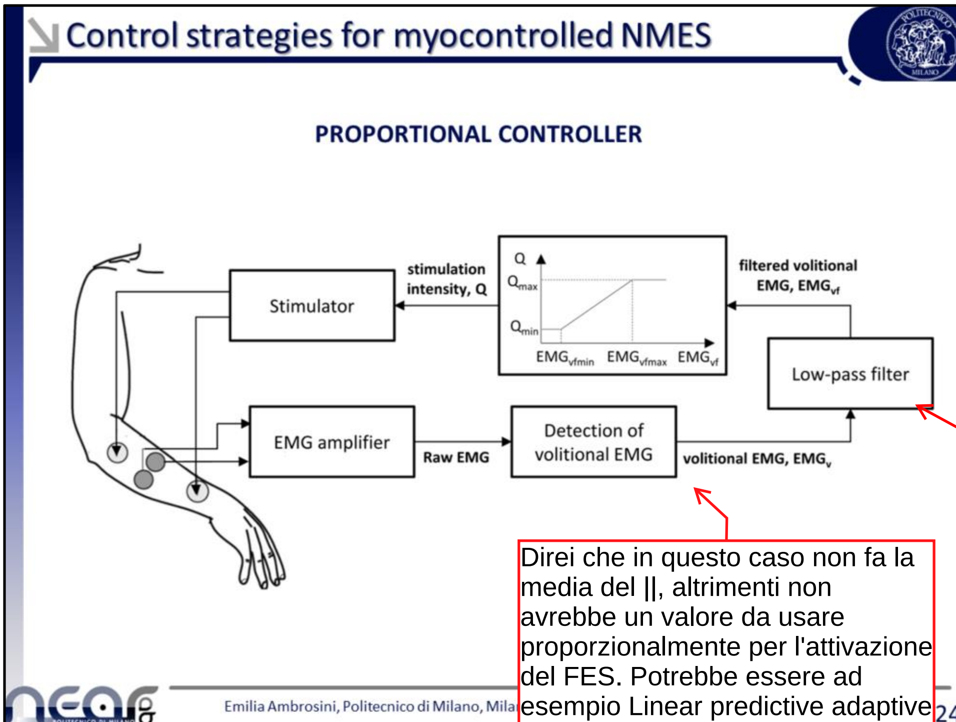
Filters to estimate the volitional EMG



ph0: rest
ph1: stim , no vol
ph2: stim, no vol
ph3: stim + vol
ph4: variable stim, no vol

Two-factors repeated measures ANOVA
** p=0.002; † p=0.015; ** p<0.001.*

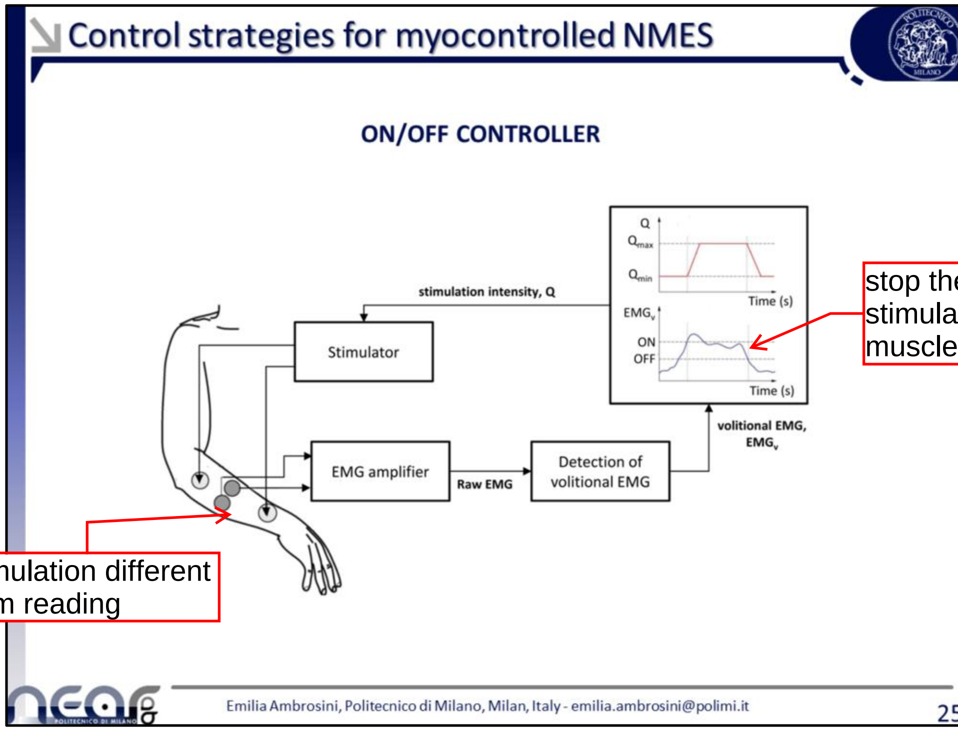
Ambrosini et al, JEK 2014



to avoid noises

Direi che in questo caso non fa la media del ||, altrimenti non avrebbe un valore da usare proporzionalmente per l'attivazione del FES. Potrebbe essere ad esempio Linear predictive adaptive filter

Control strategies (*dell'EMG controlled, non triggered):
-Proportional controlled. **Drawbacks mainly due to the fact that the patient cant really do a smooth contraction and modulate their activity. Usually the patient has a very low activity and to use it the controller may be really unstable.**
-On/off controlled with double threshold [Trigger di schmidth] This just controls the timing and not amplitude



stop the FES from stimulating the muscle

stimulation different from reading

the subject can trigger the start and stop!But the amplitude of stimulation is not controlled, it's precalibrated. He's just controlling the timing.

Example of applications on patients

Only few clinical applications of EMG-controlled neuroprostheses exist.

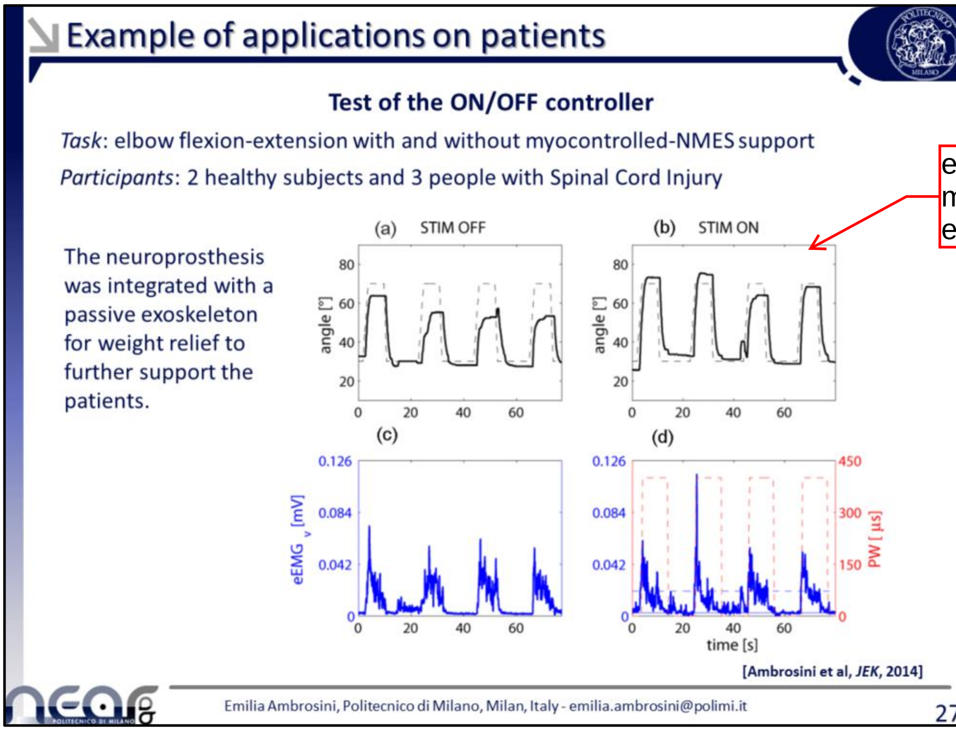
1) EMG-proportional controller supports hand functions during daily life activities in people with Spinal Cord Injury [Thorsen 1999, 2001, 2006]

   ➡ assistive system
   stimulation of a muscle closed to the one used for control

2) EMG-proportional controller improves hand functions in post-stroke patients [Fujuwara 2009; Shindo 2011]

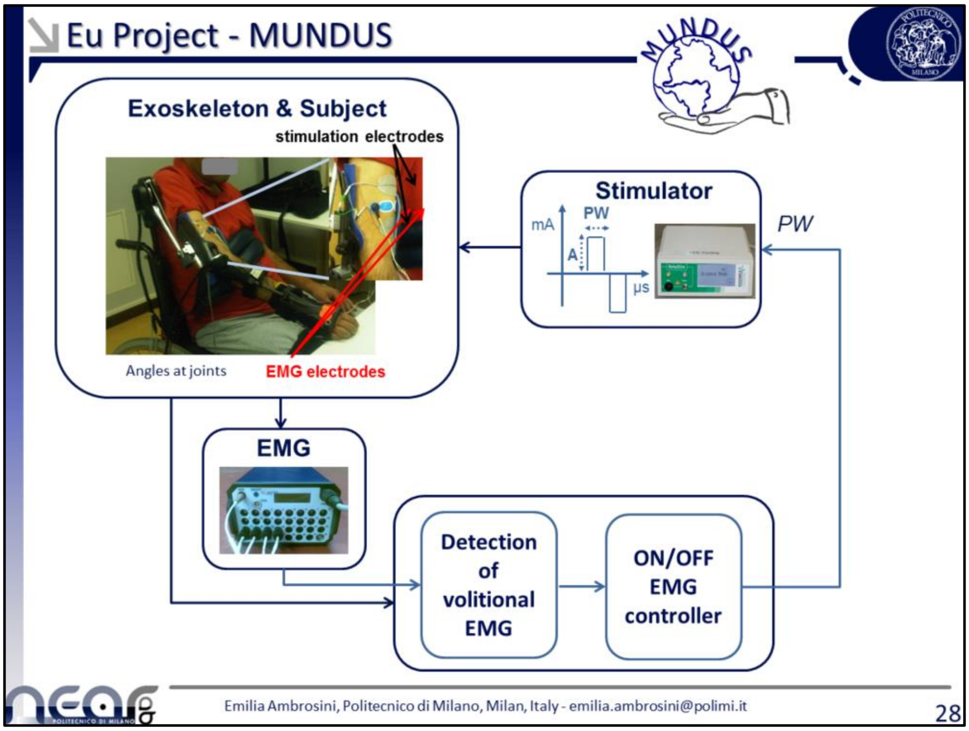
   ➡ rehabilitative purposes
   same electrodes for stimulation and recordings
   stimulation of the same muscle used for control

this was on mundus, so there was also an exoskeleton passive



elbow angle measured with the encoder of joint

BTW in this case not FES alone but with integration of an exoskeleton in order to alleviate the gravity. FES alone couldn’t achieve movement. Also a button can be used for locking a position after a movement.


Eu Project - MUNDUS
MUNDUS
Exoskeleton & Subject
stimulation electrodes
Angles at joints
EMG electrodes
Stimulator
mA
PW
A
μs
PW
EMG
Detection of volitional EMG
ON/OFF EMG controller
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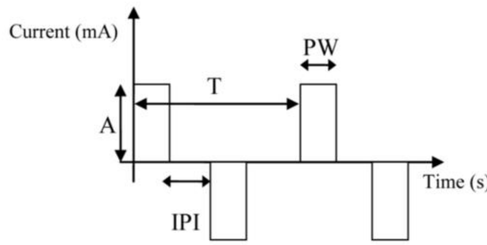
Eu Project - RETRAINER

8-CHANNEL CURRENT CONTROLLED-STIMULATOR



- Pulse amplitude (A): 10-120 mA
- Pulse duration (PW): 100-500 µs

Number of recruited fibers: *Spatial summation*

- Stimulation frequency (f): 20-60 Hz

Rate at which the fibers fire: *Temporal summation*

Eu Project - RETRAINER

Multi-channel EMG AMPLIFIER

Technical specification

- Gain 20 x
- Input Impedance > 10^{12} Ohm
- Common Mode Rejection Ratio > 100 dB
- Sampling frequency (fs) up to 2048 Hz
- High resolution ADC (22 bit)
- Range ±3 V
- Quantization step = $\frac{6}{20}$ x $\frac{1}{2^{21}} = 71.5\ nV$
- Low – pass filter, cut-off frequency of 0.27*fs to avoid aliasing
- Active shielded-cables to avoid cable movement artifacts

Eu Project - RETRAINER

Upper limb exoskeleton

Technical specification

- 3 degrees of freedom
- humeral rotation fixed
- forearm prono/supination, wrist flexion/extension, and wrist deviation mechanically fixed at subject-specific positions
- adjustable weight support
- Electromagnetic DC brakes to lock each DOF
- weight = 2.2 kg

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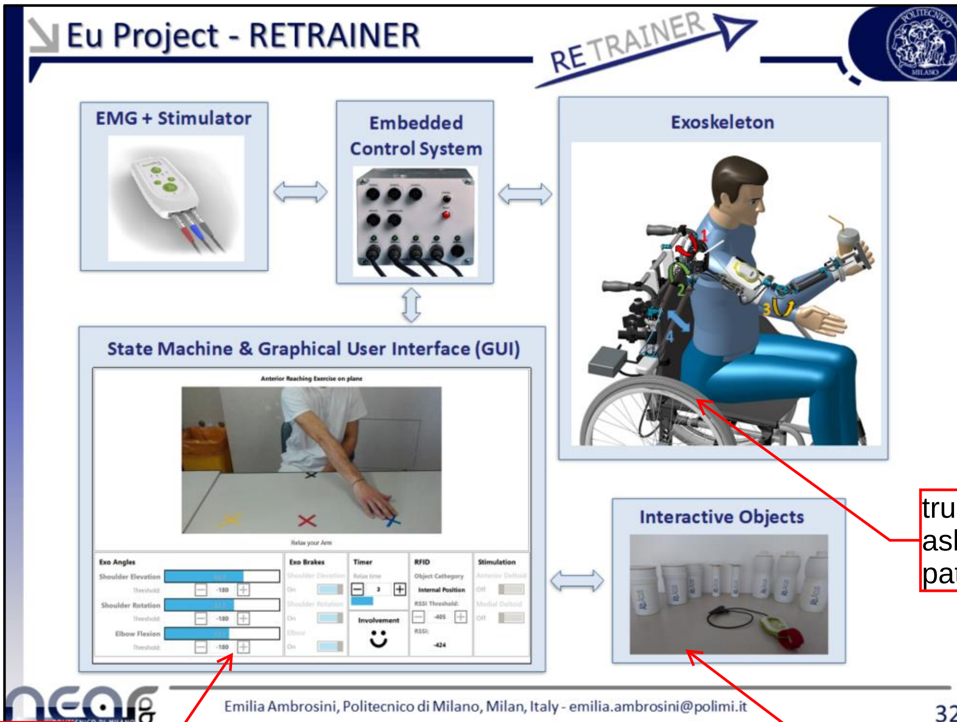
equipped with breaks that locks dof, using a button.

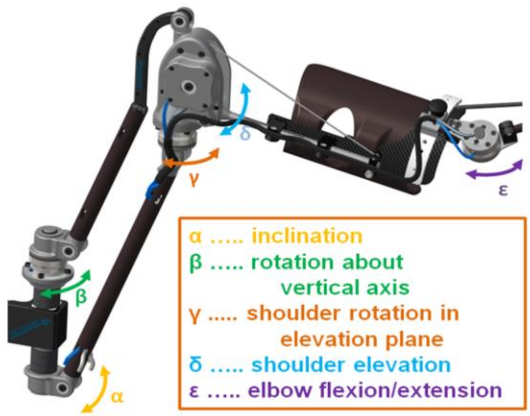


trunk movement! asked by the patients

on surface pro, used by therapist to configure, + subject visual feedback about envolvement. It shows angles, breaks..

this objects have an RFID, antenna on the exoskleton, used to automatically reconize target position. We do the exercise of taking the object, with the rfid reader integrated with the angles we record automatically the target position, then instead of having to press a button, the stimulation automatically switches off.

Eu Project - RETRAINER



Inclination (α)	40°…65°
Rotation about vertical axis (β)	0°….300°
Shoulder elevation (δ)	0°…120°
Shoulder rotation in elevation plane (γ)	0°…110°
Elbow flexion/extension (ε)	0°…120°

Eu Project - RETRAING

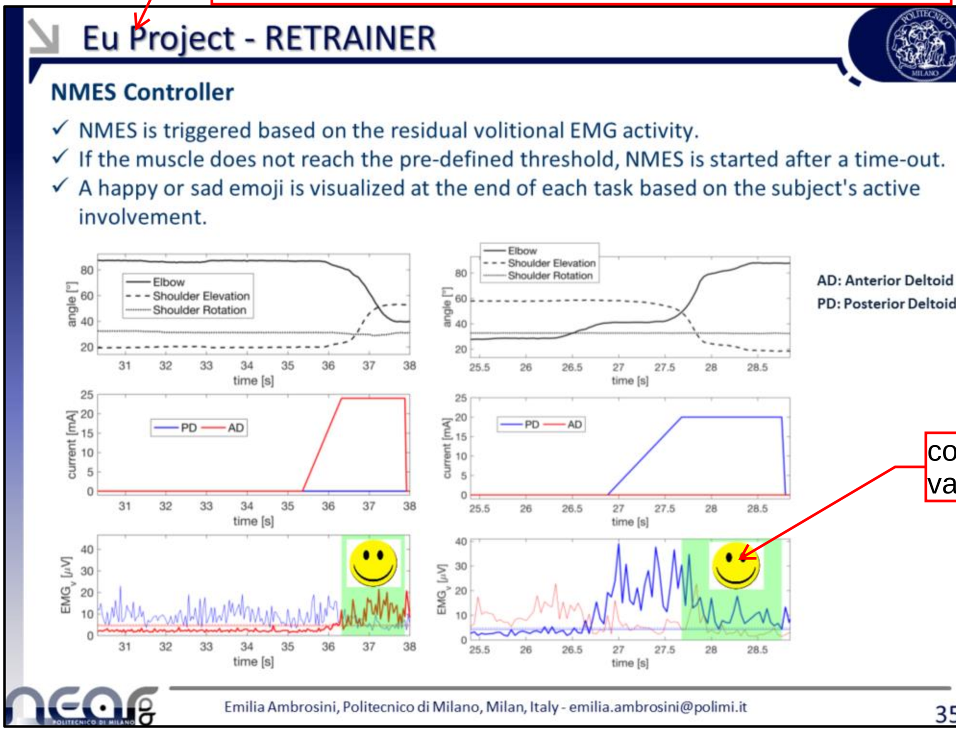
REHAMOVE-PRO STIMULATOR

- ✓ Miniature Size, lightweight, ergonomic casing
- ✓ 4 Stimulation channels, 2 of them with EMG-measurement function
- ✓ USB-connection to the Embedded Target
- ✓ Adjustable stimulation waveform
- ✓ Current: 0-150mA; resolution of 0.5mA
- ✓ Stimulation frequency: with 4 channels active up to 190Hz

HASOMED
HARD- UND SOFTWARE FÜR DIE MEDIZIN

integrating EMG + stimulating

we were using on/off, with two threshold. If EMG is very low is hard to recognize 2 thrshodl, where one should be at least the double of the other to have a stable controller.



continuiamo a valutare

A. The subject was not able to trigger FES to the Anterior Deltoid and FES was triggered after a time-out of 5s; however, when FES was switched on the subject was able to actively participate in the movement.

B. The subject was able to trigger FES of the Posterior Deltoid based on the volitional effort (lower panel) and to maintain the active involvement during the task execution.

For patients not able to start stimulation (Very very low emg activity), we switched to a triggered EMG. But we still measure EMG during stimulation, and provide visual feedback about the voluntary activity. We still know if the subject is just passive.. and we promote him to be active! But the actual control is just done by a trigger. After a time elapsed it starts automatically, and it sort of made the user remember a bit. Some stroke patients at the beginning of therapy dont have residual EMG.