Drucksachenkategorie

A preliminary study in EMG-based Upper-Limb Stroke Rehabilitation

Roberto Perretta

Institut für Robotik und Mechatronik	BJ.: 2011 IB.Nr.: 572-11-20

DIPLOMARBEIT

A PRELIMINARY STUDY IN EMG-BASED UPPER LIMB STROKE REHABILITATION

Freigabe: Der Bearbeiter: Unterschriften

Roberto Perretta

Betreuer:

Claudio Castellini

Der Institutsdirektor

Prof. Dr. G. Hirzinger

Dieser Bericht enthält 96 Seiten

Ort: Oberpfaffenhofen	Datum:	Bearbeiter:	Zeichen:

UNIVERSITÀ DEGLI STUDI DI NAPOLI

FEDERICO II

FACOLTÀ DI INGEGNERIA

CORSO DI LAUREA IN

INGEGNERIA DELL'AUTOMAZIONE

TESI DI LAUREA

A preliminary study in EMG-based Upper Limb Stroke Rehabilitation

RELATORE
Ch.mo Prof.
Bruno Siciliano

CANDIDATO
Roberto Perretta
Matricola 322/77

SUPERVISORE
Dr.
Claudio Castellini

Anno Accademico 2010/2011

Ai miei Genitori*,*
che mi hanno permesso di arrivare fin qui
grazie ai loro sacrifici e sostenendomi nei momenti più duri
A mio Fratello Stefano*,*
che ha sempre creduto in me
e assieme a me gioisce per i miei successi
A mio Fratello Massimiliano*,*
che è con me,in giro per il mondo,
mi assiste e consiglia ogni giorno
sussurrandomi all'orecchio,
a te dedico tutto me stesso,
a te che sei il mio angelo che mi protegge dall'alto
Ai miei più cari Amici*,*
che nei momenti di sconforto e debolezza
in loro ho sempre ritrovato il sorriso

Contents

Chapter I

Stroke Rehabilitation

The aim of my Master Thesis is to develop a concept regarding the field of "Stroke Rehabilitation" that takes into account the use of a technique called "Surface Electromyograpy" and that has to be conducted by a Robotic device able to achieve the recovery of a stroke patient in an autonomous way, changing in the course of the therapy his assistance according with the muscular activity retrieved by non-invasive sensors applied on the skin of the patient.

I.1 Why Stroke

Stroke is the third leading cause of death after cardiovascular diseases and cancer, and represents the greatest cause of severe disability and impairment in the industrialized world.

Every year in the U.S. and Europe there are 200 to 300 new stroke cases per 100.000, the 30% of whom survive with severe invalidity and marked limitations in daily activities, mainly deriving from impaired motor control and loss of dexterity in the use of the arm. [1]

High blood pressure is the number one risk factor for strokes. The following also increase the risk for stroke:

- Arterial fibrillation
- Diabetes
- Family history of stroke
- Heart disease

- High cholesterol
- Alcohol use
- Drugs
- Cigarettes

The incidence grows progressively with the elderly, reaching the maximum percentage with people over eighty years old.

Due to population aging, this trend is going to grow further in the next decades.

Age	% Population	% Stroked People
0-44	56,1	0,065
45-54	13,3	0,410
55-64	11,9	1,275
65-74	10,3	4,500
75-84	6,2	8,796
≥85	2,2	16,185
Tot.	100,0	1,603

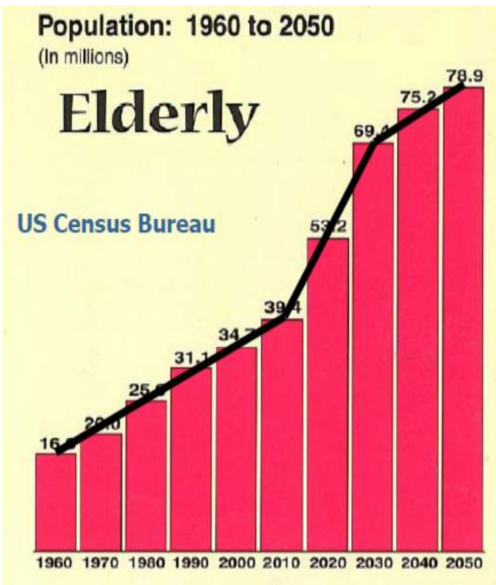


Figure I.1 - (Left) Census in Italy in 2001 - (Right) Elderly growth estimation in USA

I.2 Stoke : what is it? [2,3,4]

Stroke is a neurological deficit of cerebrovascular cause that persists beyond 24 hours or is interrupted by death within 24 hours [1].
The 24-hour limit divides stroke from transient ischemic attack, which is a related syndrome of stroke symptoms that resolve completely within 24 hours.

Strokes can be classified into two major categories:

1. **Ischemic** (~80% of the cases): occurs when a blood vessel that supplies blood to the brain is blocked by a blood clot. This may happen in two ways:

    - A clot may form in an artery that is already very narrow. This is called a thrombus. If it completely blocks the artery, it is called a *thrombotic stroke*.

    - A clot may break off from another place in the blood vessels of the brain, or some other part of the body, and travel up to the brain to block a smaller artery. This is called an embolism. It causes an *embolic stroke*.

    Ischemic strokes may result from clogged arteries, a condition called atherosclerosis. This may affect the arteries within the brain or the arteries in the neck that carry blood to the brain. Fat, cholesterol, and other substances collect on the wall of the arteries, forming a sticky substance called plaque. Over time, the plaque builds up. This often makes it hard for blood to flow properly, which can cause the blood to clot.

    Ischemic strokes may also be caused by blood clots that form in the heart or other parts of the body. These clots travel through the blood and can get stuck in the small arteries of the brain. This is known as a cerebral embolism.

2. **hemorrhagic** (~20% of the cases): Hemorrhagic stroke occurs when a blood vessel in part of the brain becomes weak and bursts open, causing blood to leak into the brain. Some people have defects in the blood vessels of the brain that make this more likely. The flow of blood that occurs after the blood vessel ruptures damages brain cells.

The symptoms of stroke depend on what part of the brain is damaged. In some cases, a person may not even be aware that he or she has had a stroke.

Symptoms usually develop suddenly and without warning, or they may occur on and off for the first day or two. Symptoms are usually most severe when the stroke first happens, but they may slowly get worse.

Some of the symptoms regards changes in hearing or tasting, confusion or loss of memory, difficulty swallowing, difficulty writing or reading ,loss of balance, loss of coordination, muscle weakness in the face or arm or leg, numbness or tingling on one side of the body, problems with eyesight, including decreased vision, double vision, or total loss of vision.

In most cases, the symptoms affect only one side of the body. Depending on the part of the brain affected, the defect in the brain is *usually* on the opposite side of the body. Moreover, depending on which side of the brain is affected, the effects are different.

I.3 The importance of the Rehabilitation

Stroke rehabilitation is the process by which patients with disabling strokes undergo treatment to help them return to normal life as much as possible by regaining and relearning the skills of everyday living. It also aims to help the survivor understand and adapt to difficulties, prevent secondary complications and educate family members to play a supporting role.

Rehabilitation of sensory and cognitive function typically involves methods for retraining neural pathways or training new neural pathways to regain or improve neuro-cognitive functioning that has been diminished by disease or traumatic injury. [5]
The aim is helping the brain to reorganize itself with physical therapy, which in turn helps the stroke survivor to recover functions lost after brain injury, thanks to the property that the brain have to be “plastic”.

The term “neuro-plasticity” is used to describe the ability of neurons and neuron aggregates to adjust their activity and even their morphology to alterations in their environment or patterns of use. The term encompasses diverse processes, as from learning and memory in the execution of normal activities of life. Refer to hypothetical mechanisms that may underlie spontaneous functional recovery after neural injury and can now be studied in humans through such techniques as functional imaging (PET) and functional magnetic resonance imaging (fMRI), electrical and magnetic event-related (EEG), evoked potentials (Eps), and magneto-encephalography (MEG) and non invasive brain stimulation in the form of transcranial magnetic or electrical stimulation (TMS and transcranial direct current stimulation, tDCS). [4]

A rehabilitation is provided by a team that is usually multidisciplinary as it involves staff with different skills working together to help the patient. These include nursing staff, physiotherapy, occupational therapy, speech and language therapy, and usually a physician trained in rehabilitation medicine. Some teams may also include psychologists, social workers, and pharmacists since at least one third of the patients manifest post stroke depression.

Three are the most important processes during a stroke rehabilitation:

1. **Physical Therapy**
2. **Occupational Therapy**
3. **Speech-language Therapy**

Physical Therapy focuses on joint range of motion and strength by performing exercises and re-learning functional tasks such as bed mobility, transferring, walking and other gross motor functions. Physiotherapists can also work with patients to improve awareness and use of the hemiplegic side. Rehabilitation involves working on the ability to produce strong movements or the ability to perform tasks using normal patterns. Emphasis is often concentrated on functional tasks and patient's goals. One example: **physiotherapists employ to promote motor learning involves constraint-induced movement therapy**.

Through continuous practice the patient relearns to use and adapt the hemiplegic limb during functional activities to create lasting permanent changes.

Occupational Therapy is involved in training to help relearn everyday activities known as the Activities of daily living(ADLs) such as eating, drinking, dressing, bathing, cooking, reading and writing, and toileting.

Speech and language therapy is appropriate for patients with the speech disorders: dysarthria and apraxia of speech, aphasia, cognitive-communication impairments and/or dysphagia (problems with swallowing).

According with the physical therapist Brunnstrom, seven are the stages of the stroke recovery:

- **Stage 1:** Flaccidity - capable of no voluntary movement on the most affected side.
- **Stage 2:** Spasticity appears - capable of movement only in synergy patterns, and usually not voluntary (spasticity).
- **Stage 3:** Spasticity increases - gaining voluntary control of movement in synergy patterns.
- **Stage 4:** Spasticity decreases - voluntary movement without synergy patterns begins.
- **Stage 5:** Spasticity continues to decline - capable of more complex natural movements.
- **Stage 6:** Spasticity disappears, except for when fatigued movement of individual joints is almost normal.
- **Stage 7:** Normal movement.

Treatment of spasticity often involves early mobilizations, commonly performed by a physiotherapist, combined with elongation of spastic muscles and sustained stretching through various positioning. Gaining initial improvements in range of motion is often achieved through rhythmic rotational patterns associated with the affected limb.

After full range has been achieved by the therapist, the limb should be positioned in the lengthened positions to prevent against further contractures, skin breakdown, and disuse of the limb with the use of splints or other tools to stabilize the joint. Cold in the form of ice wraps or ice packs have been proven to briefly reduce spasticity by temporarily dampening neural firing rates. Electrical stimulation to the antagonist muscles or vibrations has also been used with some success

Stroke rehabilitation should be started as quickly as possible and can last anywhere from a few days to over a year. Most return of function is seen in the first few months, and then improvement falls off with the "window" considered officially by U.S. state rehabilitation units and others to be closed after six months, with little chance of further improvement. However, patients have been known to continue to improve for years, regaining and strengthening abilities like writing, walking, running, and talking. Daily rehabilitation exercises should continue to be part of the stroke patient's routine. Complete recovery is unusual but not impossible and most patients will improve to some extent: proper diet and exercise are known to help the brain to recover.

Some current therapy methods include the use of virtual reality and video games for rehabilitation. These forms of rehabilitation offer potential for motivating patients to perform specific therapy tasks that many other forms do not. Many clinics and hospitals are adopting the use of these off-the-shelf devices for exercise, social interaction and rehabilitation because they are affordable, accessible and can be used within the clinic and home.

Is possible to classify the rehabilitation strategy used under the Physical Therapy in the following macro-groups:

1. **Assistive strategy**
2. **Challenge-based strategy**
3. **Simulating normal tasks**

Active assist exercise uses external, physical assistance to aid participants in accomplishing intended movements. Physical and occupational therapists manually implement this technique in clinical rehabilitation on a regular basis, for both lower and upper extremity training. Assistive strategy is common during the first stages of the therapy, when the patient is weak and not able to move on his own.

Active assist exercise interleaves effort by the participant with stretching of the muscles and connective tissue. Effort is thought to be essential for provoking motor plasticity and stretching can help prevent stiffening of soft tissue and reduce spasticity, at least temporarily [25,26].

Physically assisting movements can also help a participant to perform more movements in a shorter amount of time.

On the other hand, there is also a history of motor control research that suggests that physically guiding a movement may actually decrease motor learning for some tasks. Guiding the movement also reduces the burden on the learner's motor system to discover the principles necessary to perform the task successfully.

Challenge-based is focused on movement tasks more difficult or challenging. This kind of therapy is common in advanced stages of stroke recovery, when the patient is able to move on his own and has acquired strength and part of control into the muscles.

Resistive exercise refers to the therapeutic strategy of providing resistance to the participant's hemiparetic limb movements during exercise, an approach that has a long history in clinical rehabilitation and clinical rehabilitation devices.
In literature two are the therapy used under the challenge-based concept.
The first concern is ***"Constraint-induced strategies"***. These strategies refers to a family of rehabilitation techniques in which the unimpaired limb of the patient is constrained to encourage use of the impaired limb.
The second concern is "***Error-amplification strategies".*** Researchers have proposed therapies that amplifying movement errors rather than decreasing them. Amplifying curvature errors during reaching by persons with chronic stroke with a force field caused participants to move straighter, at least temporarily, when the force field was removed, compared to reducing curvature errors during training.

From one perspective, also moving against gravity can be considered as a variant of the resistive approach, considering that gravity applies a force to the participant's limbs.

Simulation of normal tasks concern the last stages of rehabilitation, when the patient has regained most of the lost functionality, and needs to relearn task of normal life like eating, dressing, drinking.

I.4 Robotic Rehabilitation after Stroke

The goal of robotic therapy control algorithms is to control robotic devices designed for rehabilitation exercise, so that the selected exercises to be performed by the participant provoke motor plasticity, and therefore improve motor recovery. Currently, however, there is not a solid scientific understanding of how this goal can best be achieved. Robotic control algorithms have therefore been designed on an ad hoc basis, usually drawing on some concepts from the rehabilitation, neuroscience, and motor learning literature.

According with the rehabilitation paradigms, also the robotic control algorithms can be classified in the same way, and for each group different implementations have been developed.

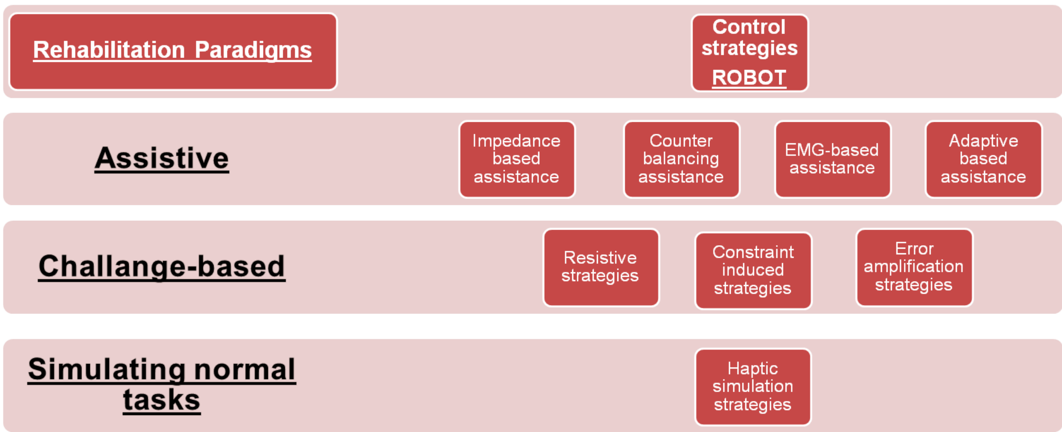


Figure I.2 – Robotic and Usual rehabilitation strategies.

Impedance-based control underlie the idea that when the participant moves along a desired trajectory, the robot should not intervene, and if the participant deviates from the desired trajectory, the robot should create a restoring force, which is generated using an appropriately designed impedance.

Counter balancing control provides partially or total weight counterbalance to a limb.

EMG based assistance use signals recorded from selected muscles as an indicator of effort generation to trigger assistance. The assistance is triggered when the processed EMG signals increase above a threshold in a kind of "proportional myoelectric control".

Adaptive control is based on adaptation of assistance according on the performance of some task parameter as movement timing or participant slacking in response to assistance.

Resistive robotic device apply constant resistive forces to the affected limb. Many of these robotic devices introduce resistance-based training just as one of the multiple therapy options of the robotic device, usually for participants with a low level of impairment.

Constraint induced control essentially only allows the participant to move if force generation it toward the target.

Haptic simulation devices can be used as interfaces for interacting with virtual reality simulations of activities of daily living, such as manipulating objects or walking across a street. The simulator realize adaptive, interactive and stimulating environment where the patient can perform the usual movements but in a virtual world.

In order to quantify the success of a rehabilitation technique, proper scales of evaluation have been realized [7,9] :

Abbreviation	Outcome measure
AMAT	Arm Motor Ability Test
ARAT	Action Research Arm Test
AS	Ashworth Scale
BBT	Box and Block Test
BI	Barthel Index
CAHAI	Chedoke Arm and Hand Activity Inventory
CMSA	Chedoke-McMaster Stroke Assessment
EMG	Electromyogram
EQ-5D	EuroQol Quality of Life Scale
FAT	Frenchay Arm Test
FIM	Functional Independence Measure
FIM motor	Functional Independence Measure motor subscale
FM	Fugl-Meyer scale
FM motor	Fugl-Meyer motor subscale
fMRI	Functional Magnetic Resonance Imaging
MAS	Modified Ashworth Scale
MFT	Manual Function Test
Motor AS	Motor Assessment Scale
MRC	Medical Research Council
MSS	Motor Status Score
NHPG	Nine-Hole Peg Test
NSA	Nottingham Sensory Assessment
RLAFT	Rancho Los Amigos Functional Test
RMA	Rivermead Motor Assessment
ROM	Range of Motion/Movement
SCT	Star Cancellation Test
SIS	Stroke Impact Scale
TUG	Timed Up and Go
TCT	Trunk Control Test
UMAQS	University of Maryland Arm Questionnaire for Stroke
VAS	Visual Analogue Scale
WMFT	Wolf Motor Function Test

Figure I.3 – Outcome measures in stroke rehabilitation

In red we have the most common used scales:

- **FIM**: assesses physical and cognitive disability.
- **FM**: It is designed to assess motor functioning, balance, sensation, joint range of motion, joint pain.
- **MAS**: measures muscle hypertonia instead of spasticity.
- **MRC**: assessment of muscle power/muscle weakness.
- **MSS**: evaluation of upper limb motor outcomes; expands the measurement provided by the FM score.

The progress of the researchers about robotic rehabilitation and the scientific challenge that also institutions and hospitals took in order to believe that in a not so far future the interaction of the robots in the daily life will be more strict, is opening a way to these devices to exploit their potentiality.

Around the World even more hospitals and clinics are adopting robotic solution to help people in recovering after stroke, and for this reason is necessary to prove the efficacy of robots in rehabilitation. Because of this, in the last decade also the robotic assistance efficacy is measured with the same scales used by physicians during the “human to human” therapy.

In the next graph is possible to see which are the robotic devices that are assessing their efficacy with the outcome measures introduced before.

Robot device	Reference	*n*	Type of patients	FM motor	MSS	MAS	MRC	FIM	Kinematic assessments
MIT MANUS	Lo et al., 2010 (31)	127	Chronic	+		+			
	Posteraro et al., 2009 (32)	20	Chronic		+	+			
	Krebs et al., 2008 (33)	47	Chronic	+					
	Rabadi et al., 2008 (34)	30	Subacute	+	+		+	+	
	Fasoli et al., 2003 (35)	20	Subacute	+	+	+	+		
	Volpe et al., 2000 (36)	56	Subacute	+	+		+	+	
	Aisen et al., 1997 (37)	20	Subacute	+			+	+	
Bi Manu track Arm trainer	Hesse et al., 2008 (38)	54	Subacute	+		+	+		
	Hesse et al., 2005 (39)	44	Subacute	+		+	+		
	Hesse et al., 2003 (13)	12	Chronic			+			
MIME	Lum et al., 2006 (40)	23	Subacute	+	+		+	+	
	Lum et al., 2002 (10)	27	Chronic	+				+	Reach extent
	Burgar et al., 2000 (41)	21	Chronic	+					
NeReBot	Masiero et al., 2007 (42)	35	Subacute	+		+	+	+	
	Rosati et al., 2007 (43)	24	Subacute	+	+		+	+	
BATRAC	Luft et al., 2004 (11)	21	Chronic	+					
	Whitall et al., 2000 (17)	14	Chronic	+					
GENTLE	Coote et al., 2008 (22)	20	Chronic	+		+			
ReoGo	Bovolenta et al., 2009 (15)	14	Chronic	+		+	+	+	
BdF	Squeri et al., 2009 (44)	4	Chronic	+					
Reo Therapy	Treger et al., 2008 (45)	10	Subacute	+					
HWARD	Takahashi et al., 2008 (20)	13	Chronic	+		+			
BFIAMT	Chang et al., 2007 (12)	20	Chronic	+		+			Peak speed, Time, Jerk
Therajoy/ drive	Johnson et al., 2007 (46)	16							+
REHAROB	Fazekas et al., 2007 (47)	30	Mixed	+		+		+	
REHA-SLIDE	Hesse et al., 2007 (48)	2	Subacute	+		+	+		
ARM Guide	Kahn et al., 2006 (49)	19	Chronic						Range, Smoothness, Path length

Figure I.4 – Robotic devices and outcome measures [7] . “n” is the number of studies done.

The report brings out the fact that research groups are strictly involved in robotic rehabilitation , a lot of case studies have been done and almost all the evaluating scales are used to assess the efficacy.

Especially the “MIT-Manus” device is the one more involved in robotic rehabilitation and an important clinical trial has been conducted from 2005 until 2010 in order to compare the usual rehabilitation with the robotic ones.

The results are showed in the next figures:

Outcome	Robot-Assisted Therapy vs. Usual Care		
	Robot-Assisted Therapy (N=25)	Usual Care (N=27)	Mean Difference (95% CI)
Change in score on Fugl-Meyer Assessment	1.11±1.01	−1.06±1.00	2.17 (−0.23 to 4.58)
Change in time on Wolf Motor Function Test‡	3.13±2.96	7.54±2.97	−4.41 (−11.52 to 2.70)
Change in score on Stroke Impact Scale	4.61±2.36	−3.03±2.34	7.64 (2.03 to 13.24)
Change in score on pain scale‡	−0.81±0.39	0±0.38	−0.81 (−1.73 to 0.11)
Change in score on Modified Ashworth Scale‡	−0.03±0.11	−0.04±0.11	0.01 (−0.25 to 0.26)

Outcome	Robot-Assisted Therapy vs. Intensive Comparison Therapy		
	Robot-Assisted Therapy (N=47)	Intensive Comparison Therapy (N=46)	Mean Difference (95% CI)
Change in score on Fugl-Meyer Assessment	3.87±1.05	4.01±1.06	−0.14 (−2.94 to 2.65)
Change in time on Wolf Motor Function Test‡	−3.96±3.00	−4.89±3.00	0.93 (−7.03 to 8.89)
Change in score on Stroke Impact Scale	6.31±1.68	5.77±1.67	0.54 (−3.87 to 4.94)
Change in score on pain scale‡	−0.61±0.29	0.24±0.30	−0.84 (−1.62 to −0.06)
Change in score on Modified Ashworth Scale‡	−0.07±0.09	0.12±0.09	−0.19 (−0.42 to 0.04)

Figure I.5 – Comparison between Robotic assistance and usual/intensive therapy, within 12 months therapy [7]

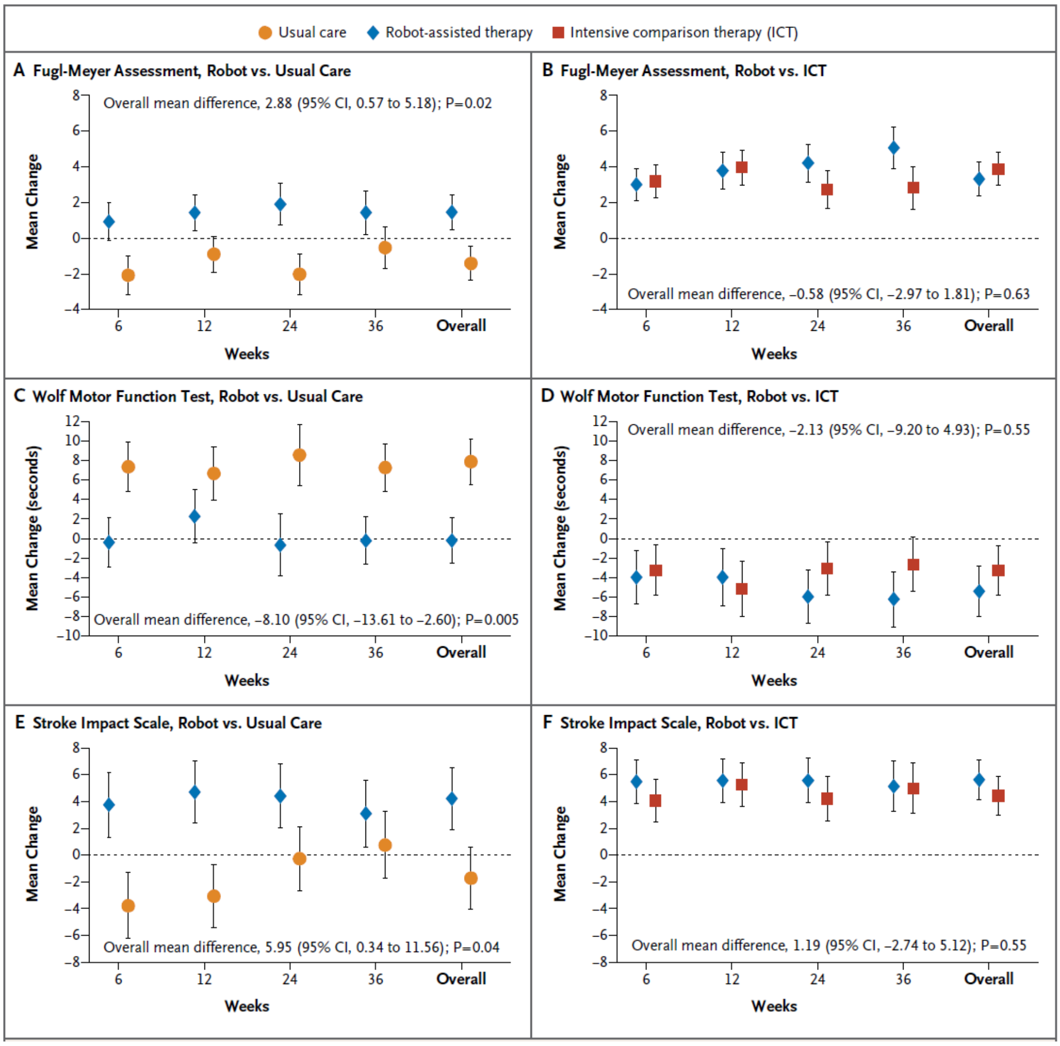


Figure I.6 – Comparison between Robotic assistance and usual/intensive therapy, within 36 months therapy [7]

Is possible to observe that within 12 months of therapy there is a more remarkable improvement of Robotic assistance rather than Usual therapy, but the difference between Robotic and Intensive rehabilitation is weak.

During the 36-week period, patients receiving robot-assisted therapy had significantly better performance than those receiving usual care on the Fugl-Meyer Assessment and the Wolf Motor Function Test, but the between-group difference on the Stroke Impact Scale was not significant (P>0.022). Differences between patients receiving robot-assisted therapy and those receiving intensive comparison therapy (ICT) were not significant for any of the three tests.

This important result remarks that Robotic rehabilitation is a novel reality, and despite the good results obtained we need a long time before Robots can substitute completely the work of a human physician, but at least can give a substantial contribute during the therapy thanks to their affordability, and the possibility to repeat thousand of time a movement unlike a human therapist do.

Following are presented the most used Robotic systems in rehabilitation.

System	Manufacturer/developer	Rehabilitation science principles	Joints	Movement characteristics
Act 3D	Northwestern University	- Addresses inefficient synergies - Gravity mitigated or enhanced	Shoulder, elbow	- Passive, active assistive, resistive - Unilateral
ARMin	Hocoma Medical Engineering, Inc. & University Hospital Balgrist	- Massed practice with target - Audio, visual and tactile feedback - Gravity mitigation (exoskeleton)	Shoulder, elbow	- Passive, active assistive
ARM-GUIDE	Rehabilitation Institute of Chicago & University of California at Irvine	- Massed practice with target endpoint - Reaching in any plane - Addresses learned nonuse - Gravity mitigated	Shoulder,elbow	- Passive, active assistive, resistive - Unilateral
AutoCITE	University of Alabama at Birmingham & VA Richmond	- Constraint-induced movement therapy - Unilateral - Addresses learned nonuse - Functional tasks practiced	Shoulder, elbow, wrist, hand	- Unilateral - ADL
Bi-Manu-Track	Department of NeuroRehab at Klinik-Berlin/Charité Hospital	- Addresses learned nonuse - Mirror movement	Forearm, wrist	- Passive, active assistive, resistive - Bilateral - Mirror movement
Driver SEAT	Rehab Research & Development Center at VA, Palo Alto, CA/ Birmingham VA Medical Center	- Bilateral training - Functional ADL practiced	Shoulder, elbow, wrist, hand	- Bilateral - ADL
GENTLE/s	University of Reading	- Massed practice with target pathway - Addresses learned nonuse - Visual and haptic motor feedback	Shoulder, elbow	- Passive, active assistive, resistive -Trajectory fork (decision making) - Unilateral
InMotion² (MIT-MANUS)	Interactive Motion Technologies, Inc.	- Massed practice with target endpoint - Addresses learned nonuse	Shoulder, elbow	- Passive, active assistive, resistive - Unilateral - Planar movement
PneuWrex	University of California at Irvine	- Functional task training - Gravity mitigation (exoskeleton)	Shoulder, elbow	- Passive, active assistive
MIME	Rehab Research & Development Center at VA, Palo Alto, CA	- Massed practice with target endpoint - Mirror movements - Addresses learned nonuse	Shoulder, elbow	- Passive, active assistive, resistive - Unilateral/ bilateral

Figure I.7 - Robotic rehabilitation systems in use for clinical research or therapy [9]

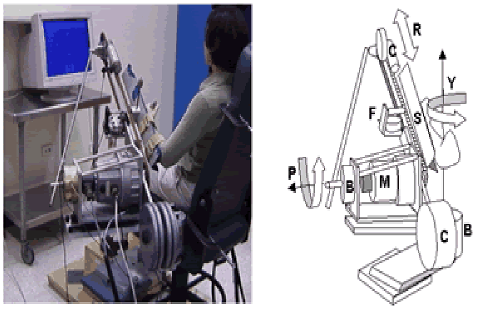


Figure I.8 - **ARM Guide**

Linear slide mechanism allows straight line movements. Vertical and horizontal orientation of the path can be altered manually.

Figure I.9 - **MIT–MANUS**

2 DoF planar motion. An additional wrist add on (InMotion3) allows three DoF to be controlled at the wrist.

Figure I.10 - **Act 3D**

HapticMaster providing three DoF, with single point of attachment at wrist. In paper, planar motion is used with 3rd DoF altering the apparent weight of the arm

Figure I.11 - **Gentle/s system**

Modified HapticMaster provides three dimensional workspace at wrist. Upper arm support using a passive suspension system.

Figure I.13 - **Mime**

2 DoF planar motion but there is an ability to alter the angle of the plane. Systems can use unaffected arm for bi-manual training.

Figure I.14 - **Bi-manu-track**

2×1 DoF allow bimanual wrist flexion/extension or forearm pronation/supination.

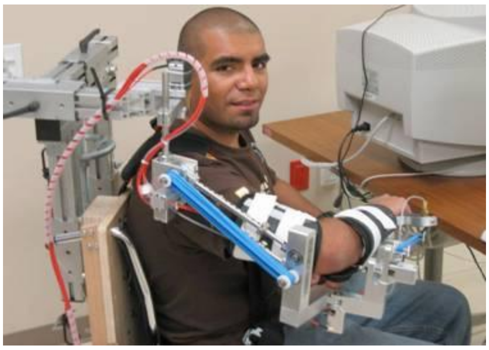


Figure I.15 - **Pneu-Wrex**

5 DoF. Four at shoulder and one at elbow. Supported at upper arm and wrist.

Figure I.16 - **ARMin**

4 active DoF: three rotations around the shoulder and then rotation of the elbow.

Figure I.17 - **RUPERT**

Pneumatic-Engine Exoskeleton

Figure I.18 - **HAL**

Electric-Engine Exoskeleton

I.5 The raw idea

The idea is to use the unimpaired side of the body as a “teacher” for the impaired one in a way that the rehabilitation of the patient could be possible autonomously with the assistance of the Robot without the presence of a physician.
The idea comes also from a specific rehabilitation strategy called “bilateral therapy” where a patient have to perform a movement using both the arms in a mirror-way. **Resulting data suggest that combined unilateral/bilateral therapy may reduce abnormal synergies and allow motor-cortex activation more than unilateral therapy alone** [10,11].

A first concept of a novel rehabilitation therapy has been developed. This therapy takes into account the progress of the patient using the ***“Surface ElectroMyography”*** (sEMG) to assess how much the muscle have been rehabilitated and this is connected with how the brain has restored the connection with the muscles. EMG sensors are applied on the skin over specific muscles and the muscular activity is retrieved during a movement.
The patient is asked to do a movement with the unimpaired arm and EMG signals are recorded. In this way for each movement is possible to understand the muscular synergy activation.
When the patient is asked to perform the same movement with the impaired arm, we expect that a similar muscular synergy activity is revealed by the EMG sensors. Because of the brain injury, any electrical signal, or in a disordered way, are sent by the brain to the muscle. After a period of training the patient is able to reach different level of recovery and to accomplish more movements. EMG activity is useful to supervise the differences between the two arms during a specific movement.

The patient is asked to perform, for example, a circle with the unimpaired arm, and EMG sensors are retrieving a certain muscular activity that involve the muscle of the shoulder. These muscles are activated with a certain level of strength and with a specific pattern.

When the patient is asked to perform the same movement, with the impaired arm, and in a mirror-way, we expect that the same muscles are activated.

Obviously, because of the injury the level of strength would be different like also the pattern activation, but what we would expect at least is that the muscular synergy should be similar. In other worlds, we expect that for a determined movement, the same muscles from both the arms should be activated. In the beginning of the therapy we expect some abnormality, and of course a lower level of strength from the impaired arm, but during the rehabilitation and with a lot of training we wish that the muscles of both the arms are activated in a similar way.

This concept has been implemented during my thesis work at Deutsches Zentrum für Luft- und Raumfahrt (DLR) in Germany. No tests have been performed on stroke patients, but according with a physician that was supporting my work, a "simulation" of stoke has been performed by non-injured subjects.

A virtual game has been developed in Matlab, and experiments on normal subjects have been conducted. In order to test this concept an acquisition card, an EMG setup and a position tracker have been used.

In the next chapter will be discussed about how to simulate a stroke patient and about the hardware system used to achieve the training.

Chapter II

Surface Electro Myography

II.1 EMG acquisition system

In order to acquire the muscular activity, a proper acquisition system have been used. It consists in:

- An acquisition board.
- EMG sensors.

The EMG acquisition board

The hardware used is a **NI WLS-9205** board from *National Instruments*.[12]

The board consists of three separate modules. The first is the analog device apt to acquire the signals, and the second is a WI-FI carrier where the analog device is mounted inside in order to send the EMG signals to a PC host.

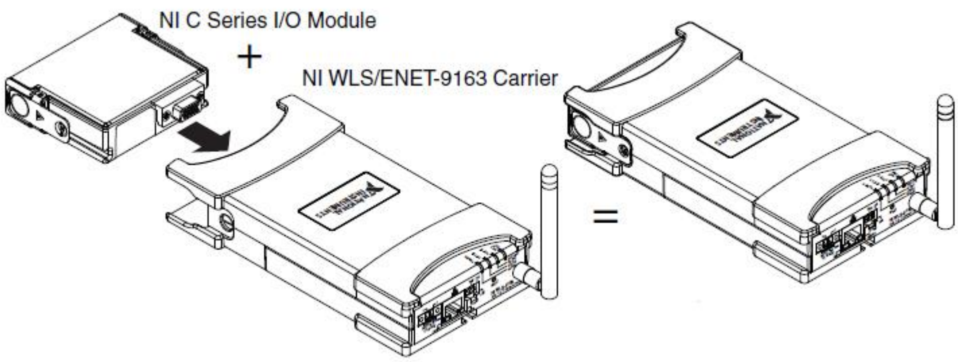


Figure II.1 – EMG device setup

The third module is an adapter that allow the connection of the EMG electrodes to the board.

The acquisition module

The NI 9205 is a 32-channel single-ended (or 16-channel differential) 16-bit analog input module. It provides also one digital input channel, one digital output channel, one COM, and one AI SENSE channel. The sample rate is up to 1000Hz.

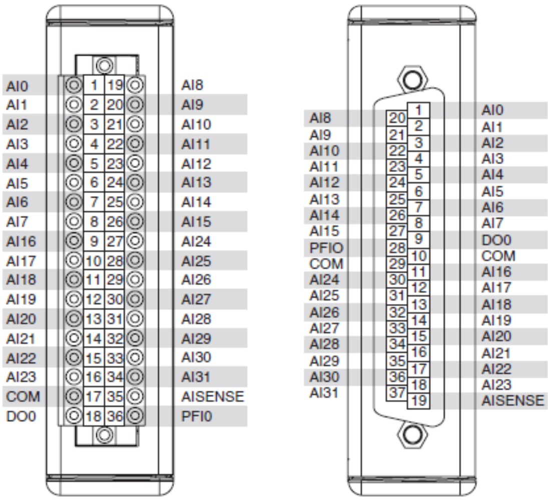


Figure II.2 – Acquisition module

Analog Input Characteristics:

- Conversion time
  - R Series Expansion chassis:4.50 µs (222 kS/s)
  - All other chassis:4.00 µs (250 kS/s)
- Input coupling: DC
- Nominal input ranges: ±10 V, ±5 V, ±1 V, ±0.2 V
- Minimum overrange
- (for 10 V range) : 4%
- Maximum working voltage for analog inputs: ±10.4 V
- Input bias current : ±100 pA

- Crosstalk (at 100 kHz)
    - Adjacent channels: –65 dB
    - Non-adjacent channels : –70 dB
- Analog bandwidth: 370 kHz
- Overvoltage protection
- AI channel (0 to 31): ±30 V (one channel only)
- AISENSE : ±30 V
- CMRR (DC to 60 Hz): 100 dB

The acquisition module is mounted inside a wireless carrier, NI WLS-9163, that is apt to send the signal to the computer in two ways: [13]

- **Wireless**
    - Radio mode: IEEE 802.11b, 802.11g
    - Wireless mode: Ad-Hoc and Infrastructure
    - Frequency range: 2.412–2.462 GHz
    - Channel: 1–14
- **Ethernet**
    - Network interface: 100 Base-TX, full-duplex;
    - Network protocols: TCP/IP, UDP
    - Network ports used: HTTP:80, TCP:31415, UDP:44515
    - Network IP configuration: DHCP + Link–Local, DHCP, Static, Link–Local
    - Communication rates: 10/100 Mbps, auto-negotiated

EMG electrodes

In order to measure the muscular activity, EMG electrodes from *Otto boch GmbH* have been used.

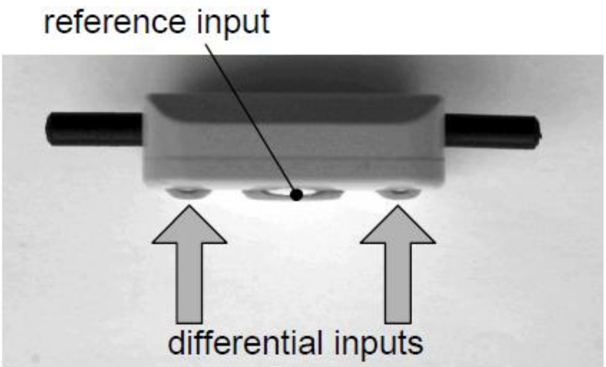


Figure II.3 – EMG sensor

These electrodes have the important property to be differential.

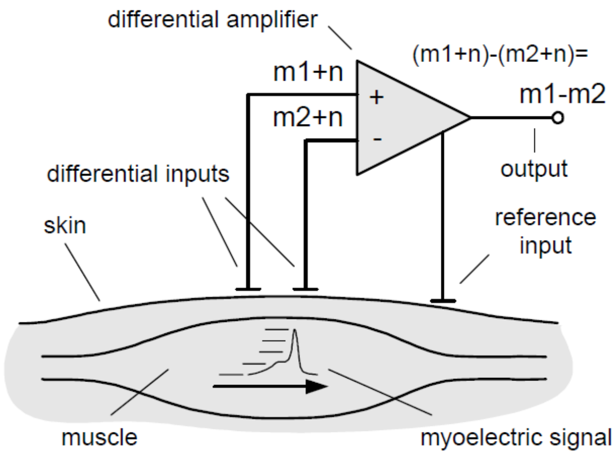


Figure II.4 – Differential acquisition

The signal is detected at two sites, electronic circuitry subtracts the two signals and then amplifies the difference. As a result, any signal that is "common" to both detection sites will be removed and signals that are different at the two sites will have a "differential" that will be amplified. Any signal that originates far away from the detection sites will appear as a common signal, whereas signals in the immediate vicinity of the detection surfaces will be different and consequently will be amplified. Thus, relatively distant power lines noise signals will be removed and relatively local EMG signals will be amplified. This explanation requires the availability of a highly accurate "subtractor". In practice, even with the wondrous electronics of today, it is very difficult to subtract signals perfectly. The accuracy with which the differential amplifier can subtract the signals is measured by the Common Mode Rejection Ratio (CMRR). A perfect subtractor would have a CMRR of infinity. A CMRR of 32,000 or 90 dB is generally sufficient to suppress extraneous electrical noises. Current technology allows for a CMRR of 120 dB, but there are at least three reasons for not pushing the CMRR to the limit:1) Such devices are expensive. 2) They are difficult to maintain electrically stable, and 3) the extraneous noise signals may not arrive at the two detection surfaces in phase, and hence they are not common mode signals in the absolute sense. [16]

II.2 Electromyography [14,15,16]

Electromyography (EMG) is a technique for evaluating and recording the electrical activity produced by *skeletal muscles* during a voluntary contraction. [12]

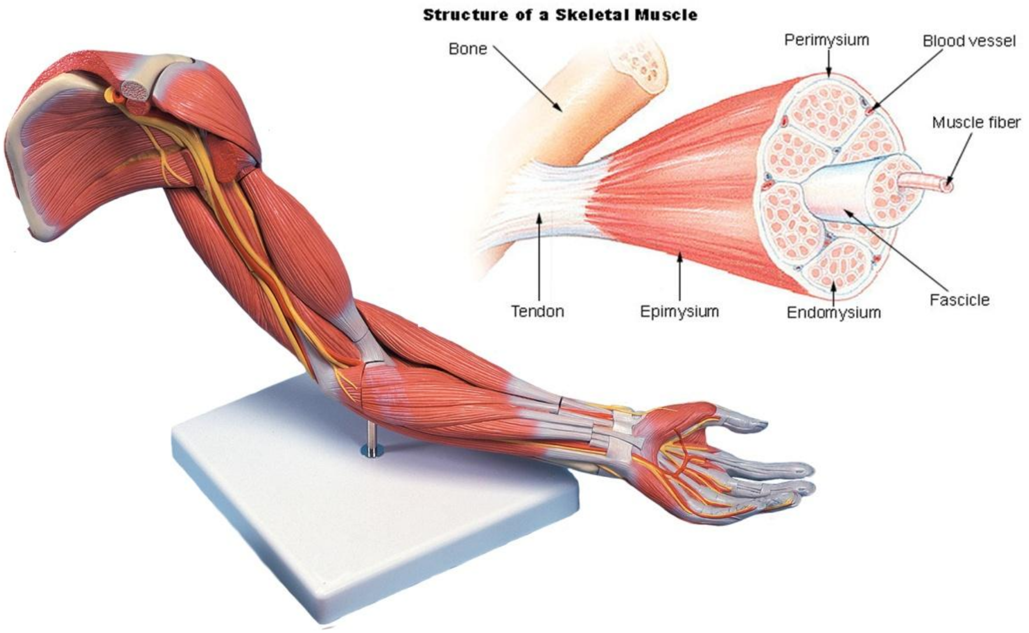


Figure II.5 - Representation of an Arm and the structure of a Skeletal Muscle. Skeletal muscle move the skeleton; they are connected to the bones through the tendons and are activated by the brain (voluntary muscles) with signals that are propagated through the nervous system to the moto-neurons that innervates muscle fibers.

The existence of electrical conduction in the muscle tissues was discovered by Francesco Redi in 1660 before , and then demonstrated in "*De viribus electricitatis in motu musculari"* written by Luigi Galvani in the late 1791.

This science have found great interest in the medicine, thanks to its capability in asserting muscular abnormalities, activation level or analyze the biomechanics of human movements.

Nowadays EMG has been adopted also in Engineering like in moving artificial prosthesis, to assert the level of muscular rehabilitation after a brain injury, to control an electrical wheelchair or even a Robot.

In order to retrieve the muscle activity , two are the common ways:

- **Intramuscular EMG:** allow to get more precise information about muscular characteristics, but require to insert thin needle electrodes or needles containing two fine-wire electrodes, through the skin into the muscle tissue. In some application this methodology could be inefficient because is able to record the activity of only few muscle fibers.
- **Surface EMG (sEMG):** is a non-invasive and painless methodology. Gives a general picture of muscle activation obtained from positioning an electrode on the skin above the interested muscle. This is the general methodology commonly used also because doesn't require the intervention of any professional unlike the intramuscular EMG.

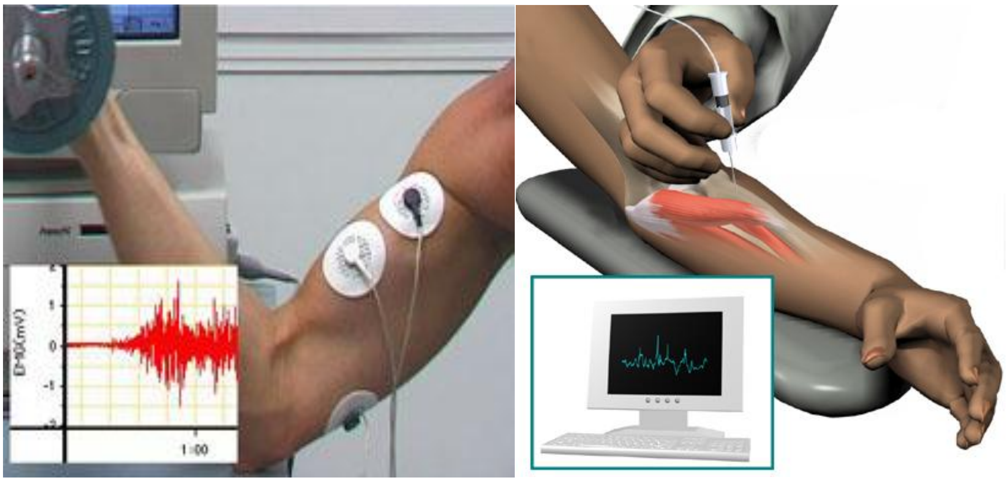


Figure II.6 - Surface EMG (Left figure) , Intramuscular EMG (Right figure)

II.3 Characteristics of the EMG signal [14][15]

When the brain sends a signal to a specific muscle in order to move it, a weak electrical signal is propagated on the skin over the muscle. This is due to the property that muscle tissues have to conduct electrical potentials similar to the way nerves do, and the name given to these electrical signals is *muscle action potential*. Surface EMG is a method of recording the information present in these muscle action potentials.

When EMG is acquired from electrodes mounted directly on the skin, the signal is a composite of all the muscle fiber action potentials occurring in the muscles underlying the skin. These action potentials occur at random intervals. So at any one moment, the EMG signal may be either positive or negative voltage.
The combination of the muscle fiber action potentials from all the muscle fibers of a single motor unit is the motor unit action potential (MUAP).

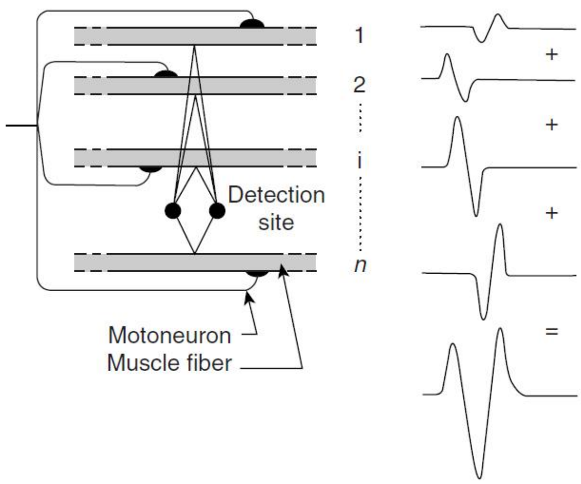


Figure II.7 - Combination of the signals from the muscle fiber action potentials

The amplitude of the EMG signal is stochastic (random) in nature and can be reasonably represented by a Gaussian distribution function. The amplitude of the signal can range from 0 to 10 mV (peak-to-peak) or 0 to 1.5 mV (rms). The usable energy of the signal is limited to the 0 to 500 Hz frequency range, with the dominant energy being in the 50-250 Hz range due to the inherent noise present during the acquisition.

When detecting and recording the EMG signal, there are two main issues of concern that influence the fidelity of the signal. The first is the signal-to-noise ratio. That is, the ratio of the energy in the EMG signals to the energy in the noise signal. The other issue is the distortion of the signal, meaning that the relative contribution of any frequency component in the EMG signal should not be altered.

EMG signal acquires noise while traveling through different tissues. Moreover, the EMG detector, particularly if it is at the surface of the skin, collects signals from different motor units at a time which may generate interaction of different signals.

Three are the most significant aspect of noise during the EMG acquisition:

- Ambient Noise
- Transducer Noise
- Motion artifacts

Ambient noise is generated by electromagnetic devices such as computers, force plates, power lines etc. Essentially any device that is plugged into the wall A/C outlet emits ambient noise. This noise has a wide range of frequency components, however, the dominant frequency component is 50Hz or 60Hz, corresponding to the frequency of the A/C power supply (i.e. wall outlet).

Transducer noise is generated at the electrode – skin junction. Electrodes serve to convert the ionic currents generated in muscles into an electronic current that can be manipulated with electronic circuits and stored in either analog or digital form as a voltage potential.

SEMG electrodes typically are passive (i.e., they are simple conductive surfaces requiring low skin resistance). They can, however, be active, incorporating preamplifier electronics that lessen the need for low skin resistance and improve the signal-to-noise ratio.

Motion artifacts: There are two main sources of motion artifact, one from the interface between the detection surface of the electrode and the skin, the other from movement of the cable connecting the electrode to the amplifier. Both of these sources can be essentially reduced by proper design of the electronic circuitry. The electrical signals of both noise sources have most of their energy in the frequency range from 0 to 20 Hz.

II. 4 Acquisition of the EMG signal [15,16,17]

The EMG process consists in:

1. Signal acquisition and conditioning
2. Signal processing
3. Feature extraction

The first stage consist to acquire the EMG signal directly from the muscle during a movement, using a surface electrode.
The signal is acquired thanks an acquisition board, and so is converted in a digital form with a fixed sample frequency.

The signal acquired after the conditioning step is called "Raw signal". This signal contain the information retrieved by a muscle during a contraction, but is not directly interpretable and it needs a successive step of processing

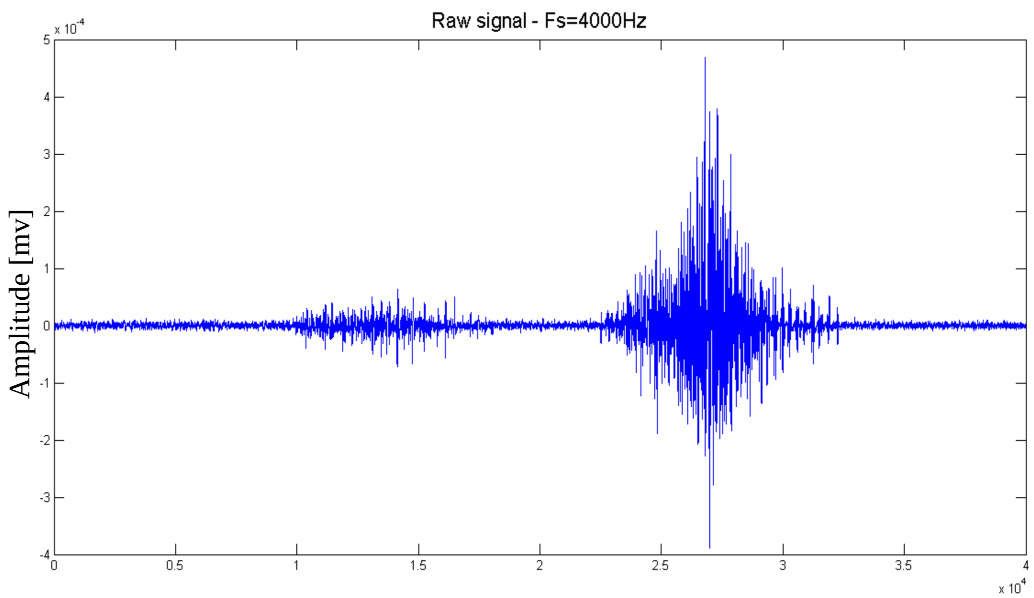


Figure II.8 – Raw Emg signal acquired at 4000Hz with a TRIGNO wireless system

As said before, the EMG signal has the dominant energy between 0-500Hz and this is possible to observe if the Fourier analysis is applied to the raw signal.

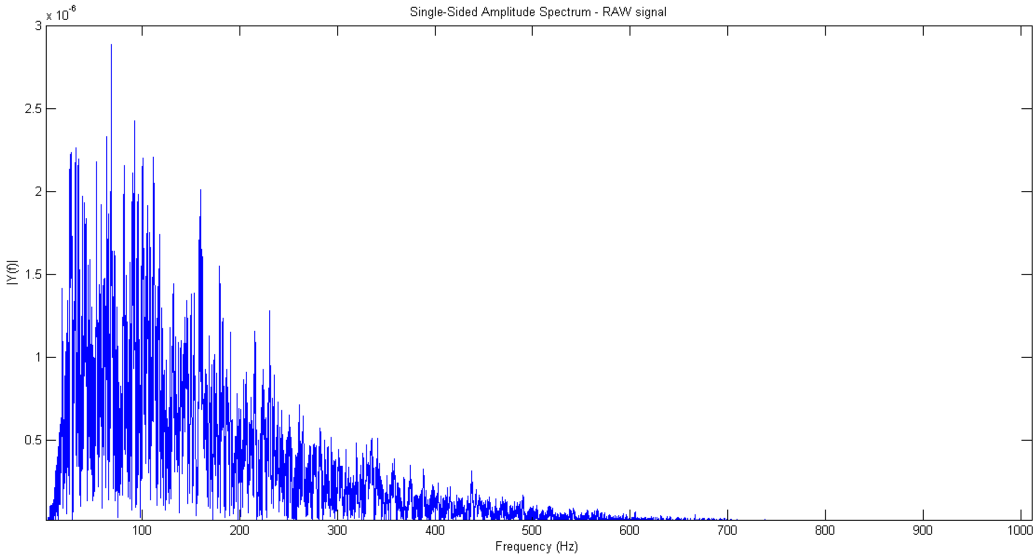


Figure II.9 – Frequency Spectrum of the raw signal acquired before

After the raw EMG signal has been recorded, this has to be processed in order to retrive all the informations regarding the muscle activation during a specified movement.

To clean the raw signal, a band-pass filter has been applied with frequency between 20-300Hz in order to filter the motion artifact at low frequency , and the high frequency disturbances.

Then the signal is rectified.

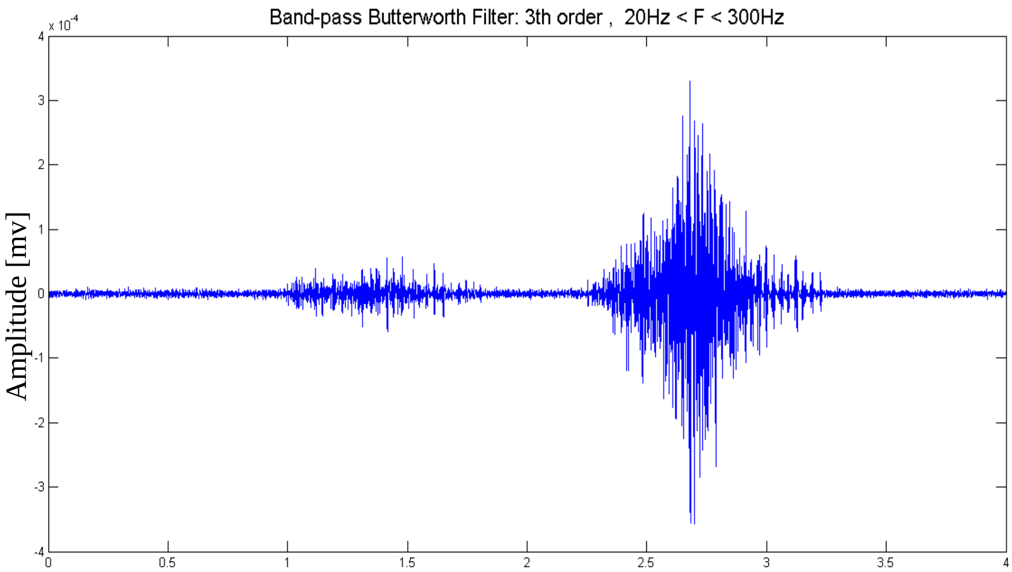


Figure II.10 – EMG signal after the application of a Band-pass filter

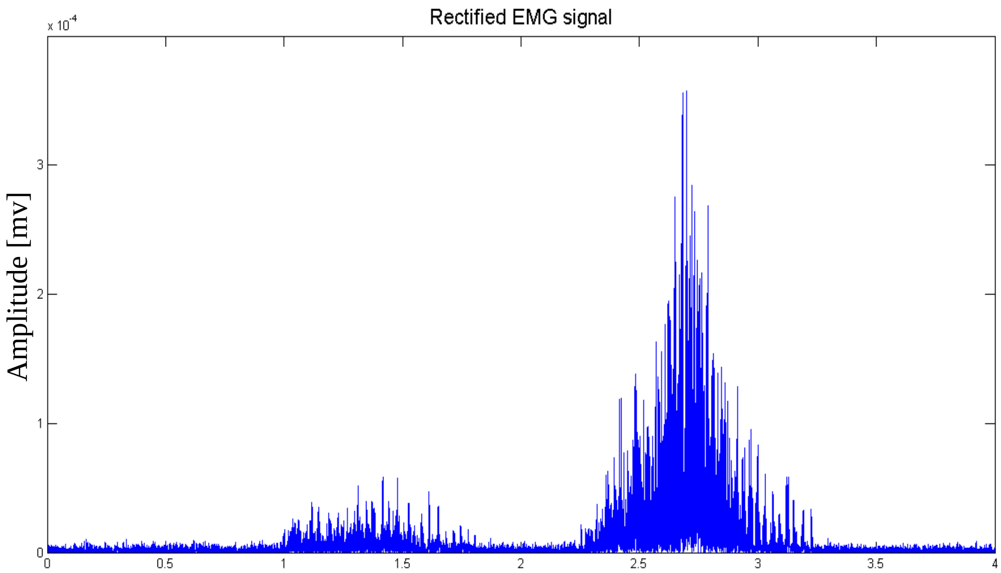


Figure II.11 – Signal rectified

In order to capture the envelope of the signal, the RMS has to be applied. Then an Anti-aliasing filter assure the Nyquist theorem.

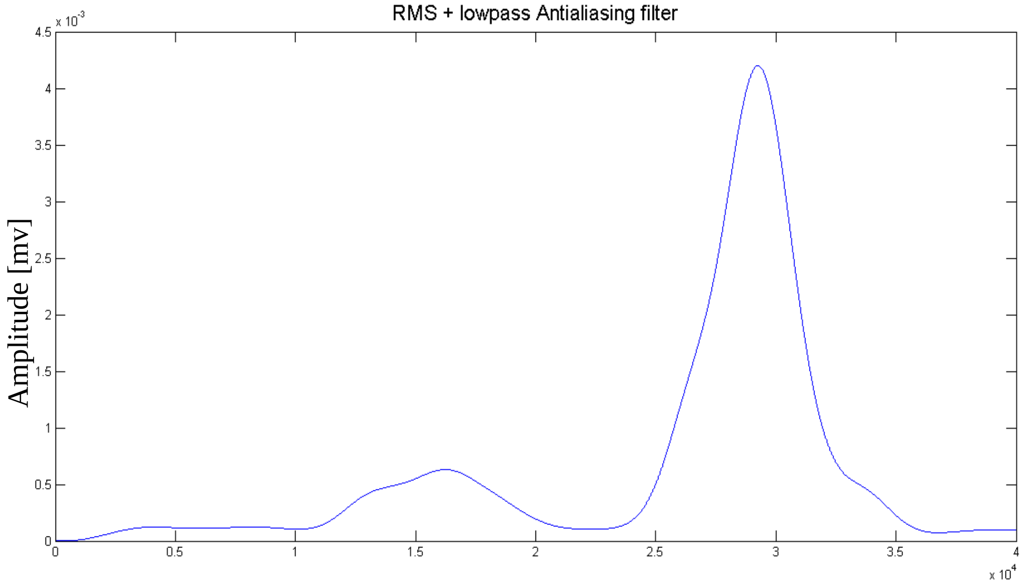


Figure II.12 – Envelope of the EMG signal

Chapter III

Position Tracker

III.1 Position Tracker [18]

In order to interface the user with the software, a position tracker is applied on the hand. The *Flock of Birds* (FOB) is a six degree-of-freedom measuring device that can be configured to simultaneously track the position and orientation of up to thirty sensors by a transmitter.

The FOB determines position and orientation by transmitting a pulsed DC magnetic field that is simultaneously measured by all sensors in the Flock. From the measured magnetic field characteristics, each sensor independently computes its position and orientation and makes this information available to the host computer.

The measurement system is composed by:

- The central logic unit
- The magnetic field transmitter
- The sensor

The sensor has been fixed on a special wearable glove in order to be used with both the hands.

The transmitter is positioned on the desk, in front of the user at 50cm in a way that is in the middle of the user in order to have, out of the sign, same position values retrieved with both the arms.

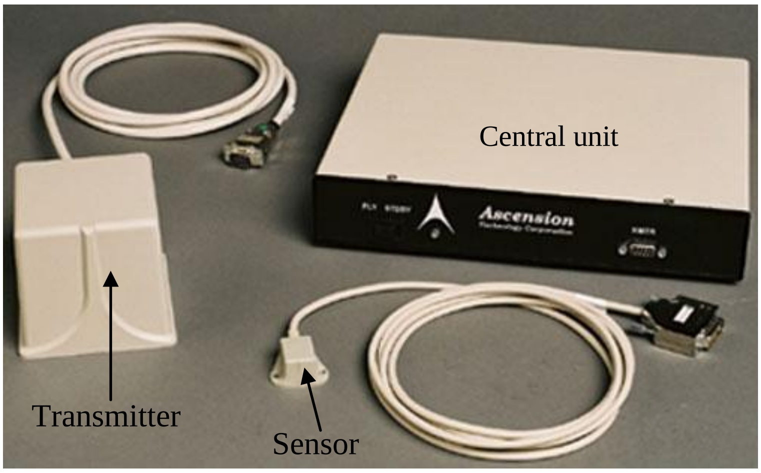


Figure III.1 – The device

The Central Unit contain two independent serial interfaces RS-232. The first is for communicate with a host computer; the second is a dedicated RS485 interface for communications between the Flock members.

The FOBs can be configured to suit the needs of many different applications: from a standalone unit consisting of a single transmitter and sensor to more complex configurations consisting of various combinations of transmitters and sensors.

SPECIFICATIONS

Physical:

- **Transmitter:** 9.5cm cube (mounted inside enclosure or external) with 25.4cm cable.
- **Sensor:** 2.54 x 2.54 x 2cm with 25.4cm cable
- **Central Unit:** 24 x 29 x 6.6cm

Technical:

- **Positional range:** ± 121.9cm in any direction
- **Angular range:** ± 180° Azimuth & Roll , ± 90° Elevation
- **Static positional accuracy:** 0.3cm RMS averaged over the translational range
- **Positional resolution:** 0.1cm @ 30.5cm
- **Static angular accuracy:** 0.5° RMS averaged over the translational range
- **Angular resolution:** 0.1° RMS @ 30.5cm
- **Update rate:** 100 measurements/sec
- **Outputs:** X, Y, Z positional coordinates and orientation angles, rotation matrix, or quaternion
- **Interface:** RS232: 2,400 to 115,200 baud
  RS485: 57,600 to 500,000 baud
- **Format:** Binary
- **Modes:** Point or Stream (RS232 only)

Electrical:

- **Power requirements:**
  +5 VDC @ 2.45 amps avg., 3.85 amps peak
  +12 VDC @ 0.53 amps avg., 0.63 amps peak
  -12 VDC @ 0.34 amps avg., 0.46 amps peak

III.2 Communication PC-Central Unit over RS232

RS232 SIGNAL DESCRIPTION

The RS-232C interface conforms to the Electronic Industries Association (EIA) specifications for data communications. The FOB requires connections only to pins 2, 3 and 5 of the 9-pin interface connector.

The Bird's 9-pin RS-232C connector is arranged as follows:

PIN	RS232 SIGNAL	DIRECTION
1	Carrier Detect	Bird to host
2	Receive Data	Bird to host
3	Transmit Data	host to Bird
4	Data Terminal Ready	host to Bird
5	Signal Ground	Bird to host
6	Data Set Ready	Bird to host
7	Request to Send	host to Bird
8	Clear to Send	Bird to host
9	Ring Indicator	No connect

RS232 TRANSMISSION CHARACTERISTICS

The host computer must be configured for the following data characteristics:

Baud Rate: 2400 - 115,200 (as set by Bird dipswitch.)
Number of data bits: 8
Number of start bits: 1
Number of stop bits: 1
Parity: none
Full duplex

RS232 Transmission Description

There are two ways in order to communicate with the FOB over RS232.
The first consist to create a "serial object" and using direct serial commands
Each RS232 command consists of a single command byte followed by N command data bytes, where N depends upon the command. A command is an 8 bit value which the host transmits to The Bird using the format shown below.

The RS232 command format is as follows:

	MS bit									LS bit
	Stop	7	6	5	4	3	2	1	0	Start
RS232 Command	**1**	**BC7**	**BC6**	**BC5**	**BC4**	**BC3**	**BC2**	**BC1**	**BC0**	**0**

where, BC7-BC0 is the 8 bit command value (see RS232 Command Reference) and the MS BIT (Stop = 1) and LS BIT (Start = 0) refers to the bit values that the UART in your computer's RS232 port automatically inserts into the serial data stream as it leaves the computer.

This way is faster but needs to operate bitwise, it means that for each received command by the FOB, each command have to be converted and operated.

Another way to communicate with the device is to implement the communication routine in C/C++ using a specific library that gives to the user an interface that makes him transparent from all the bitwise operations.

In the next chapter will be discussed in detail in which way take place the communication.

RS232 COMMAND SUMMARY

Following there are all the commands is possible to send to the device:

<u>**Command Name**</u>

ANGLES: Data record contains 3 rotation angles.

ANGLE ALIGN: Aligns sensor to reference direction.

BORESIGHT: Aligns sensor to the reference frame

BORESIGHT REMOVE: Remove the sensor BORESIGHT

BUTTON MODE: Sets how the mouse button will be output.

BUTTON READ: Reads the value of the mouse button pushed.

CHANGE VALUE: Changes the value of a selected Bird system parameter.

EXAMINE VALUE: Reads and examines a selected Bird system parameter.

FACTORY TEST: Enables factory test mode.

FBB RESET: Resets all of the Slaves through the FBB.

HEMISPHERE: Tells Bird desired hemisphere of operation.

MATRIX: Data record contains 9-element rotation matrix.

METAL: Outputs an accuracy degradation indicator.

NEXT TRANSMITTER: Turns on the next transmitter in the Flock.

POINT: One data record is output for each B command from the selected Flock unit. If GROUP mode is enabled, one record is output from all running Flock units.

POSITION: Data record contains X, Y, Z position of sensor.

POSITION/ANGLES: Data record contains POSITION and ANGLES.

POSITION/MATRIX: Data record contains POSITION and MATRIX.

POSITION/QUATERNION: Data record contains POSITION and QUATERNION.

QUATERNION: Data record contains QUATERNIONs.

REFERENCE FRAME: Defines new measurement reference frame.

REPORT RATE: Number of data records/second output in STREAM mode.

RS232 TO FBB: Use one RS232 interface connection to talk to all Birds.

RUN: Turns transmitter ON and starts running after SLEEP.

SLEEP: Turns transmitter OFF and suspends system operation.

STREAM: Data records are transmitted continuously from the selected Flock unit. If GROUP mode is enabled then data records are output continuously from all running Flock units.

STREAM STOP: Stops any data output that was started with the STREAM command.

SYNC: Synchronizes data output to a CRT or your host computer.

XON: Resumes data transmission that was halted with XOFF.

XOFF: Halts data transmission from The Bird.

III.3 The communication routine

In order to communicate with the FOB, the following procedure have to be followed:

1. **Initialization:** ask to the device if is already waked, and if not, wake up the device.
2. **System configuration:** after waking the device, is possible to change the system parameters.
   Is possible to set the following parameters:
   - current system status
   - error code flagged by server or master bird
   - number of devices in system
   - number of servers in system
   - transmitter number
   - crystal speed in MHz
   - measurement rate in frames per second
   - chassis number
   - number of devices within this chassis
   - number of first device in this chassis
   - software revision of server application or master bird
   - status of all devices in flock, indexed by bird number
3. **Device configuration:**
   - device status
   - device ID code
   - software revision of device
   - error code flagged by device
   - setup information
   - data format
   - rate of data reporting, in units of frames
   - full scale measurement, in inches

- hemisphere of operation
- bird number
- transmitter type
- filter constants
- reference frame of bird readings
- alignment of bird readings

4. After that the configuration is complete is possible to retrieve the position or orientation of the sensor. Two are the common way, the first is to "stream" the data and the second is to ask each time a single frame. In both the cases, after get the data, this has to be converted from inches to cm.

5. When the device finish to work it needs a specific command, "Shutdown", to stop the acquisition.

Chapter IV

The Training Software

IV.1 The Training Software

The software has been developed in Matlab on a desktop Pc. The computer has the following characteristics:

- Windows Xp 32 bit OS
- 2 GHz quad core processor
- 4 Gbyte ram
- 28” Monitor in order to have a better view

The software consists in a training game and the user have to perform different movements in the space. In particular the user have to follow a red cross projected on the screen and two different movements have been implemented. In the first the red target is moving along a “circle”. In the second is moving along an “eight”.

Has been assumed that the right arm of the user is the “unimpaired arm”, instead the left arm is the “impaired” arm that has to be rehabilitated.

According with the literature, repeated movements can improve the ability of the patient to use again that part of the brain has been damaged during the stroke event [24,25,26]. Thanks to the use of a virtual game, the patient is more involved and interested rather than the usual therapy done at the hospital with a physician.[27]

The training consists in repeating 10 times the movement with the unimpaired arm , evaluate the behaviour and compare each repetition of the impaired arm with the results of the unimpaired one in order to understand if there are significantly improvements. Later will be discussed more in detail how to compare the behaviour of the two arms.

In order to simulate a physical disease , it has been assumed that the movement of the right arm is the reference for the left arm. In this way the user is called to perform the movement with the right arm before, and in the meanwhile the muscular activity is retrieved thanks to the EMG sensors.
The radius of the figure for the right arm is fixed to 15cm for both the figures.

Then the user is called to perform the same movement with the left arm, but in three different ways:

1. The first time the user perform the movement, but the radius of the figure is 5cm. In this way is assumed that, due to the impairment, the user has got less strength in the arm, and even if he is able to perform the movement, he can’t reach the same radius of the right arm.
2. Then the user perform the same movement, but the radius is 10cm. It is assumed that, after a period of training, the patient is gaining his abilities and is able to perform a bigger movement.
3. The last case is when the patient is completely rehabilitated and is able to perform the movement with the radius of 15cm as the unimpaired arm has done before.

In order to activate the same muscles in both the arms, the movement from the left and right arm have been performed in a “mirror-like” way. The right arm start from a point above the circle that is specular in respect of the starting point of the left arm. Moreover the right arm do the movement in a anti clockwise way, instead the left arm in a clockwise way.

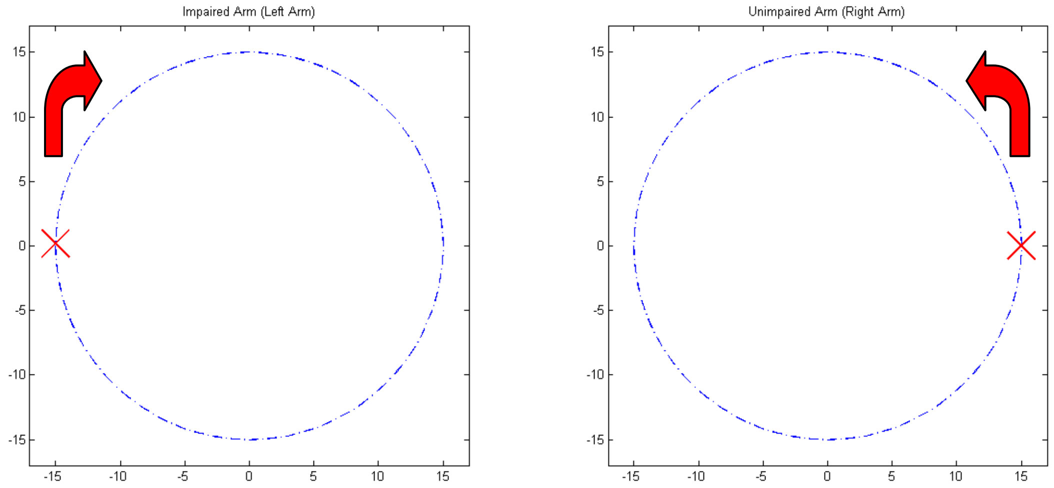


Figure IV.1 – Movement "Circle" in XY plan.

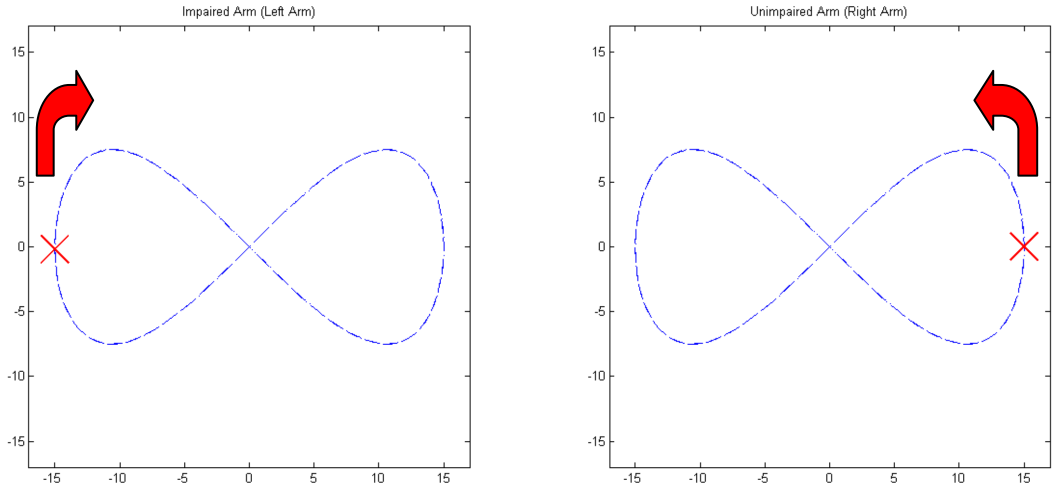


Figure IV.2 – Movement "Eight" in XZ plan

This "simulation of impairment" has been developed accordingly with the different stages of stroke-rehabilitation. The patient, after a first stage of muscular contraction, is "flaccid". This means that he is not able, or at most with few strength, to move the arms. From this concept has came the idea to start from a little radius for the left arm, but during the time of the rehabilitation is expected a regain of the cerebral activity and consequentially a regain of the limb's motion.

IV.2 Electrodes position

The importance of this training is to analyze the muscle activity during the movement of the upper-limbs in order to find out a new rehabilitation technique that take into account the regaining level of the impaired side of the body, retrieved with EMG sensors.

After having chosen the movements to do, the most important step is to investigate which muscles in the arm are more significant for this training.

For this reason EMG electrodes have been attached on the skin above the muscles of fore-arm, arm, shoulder and pectoral.

Using the National-Instrument software “Labview Signal Express” has been possible to visualize the muscular activity in real time, and after performing the two movements mentioned above, the following muscles were chosen because more involved:

- **Biceps brachii**

Electrodes need to be placed on the line between the medial acromion and the fossa cubit at 1/3 from the fossa cubit.

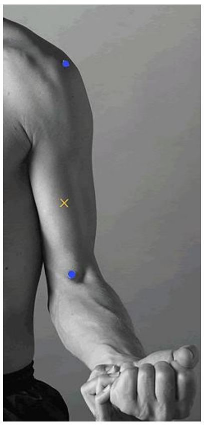


Figure IV.3 – Sensor placement above Biceps brachii

- **Triceps lateral**

Electrodes need to be placed at 50% on the line between the posterior crista of the acromion and the olecranon at two finger width lateral to the line.

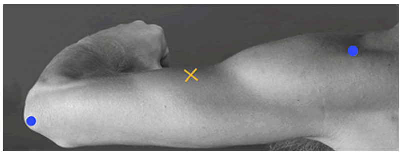


Figure IV.4 – Sensor placement above Triceps lateral

- **Triceps brachii**

Electrodes need to be placed at 50 % on the line between the posterior crista of the acromion and the olecranon at 2 finger widths medial to the line.

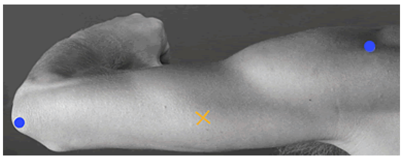


Figure IV.5 – Sensor placement above Triceps brachii

- **Deltoid anterior**

The electrodes need to be placed at one finger width distal and anterior to the acromion.

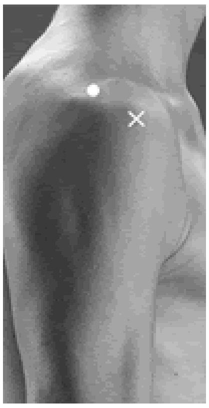


Figure IV.6 – Sensor placement above Deltoid anterior

- **Deltoid medius**

Electrodes need to be placed from the acromion to the lateral epicondyle of the elbow. This should correspond to the greatest bulge of the muscle.

Figure IV.7 – Sensor placement above Deltoid medius

- **Deltoid posterior**

Center the electrodes in the area about two finger breaths behind the angle of the acromion.

Figure IV.8 – Sensor placement above Deltoid posterior

Skin preparation, electrodes location and fixation, were accomplished according to guidelines of the *Surface Electromyography for the Non-Invasive Assessment of Muscles* (SENIAM). [1]
Each sensor were fixed on the skin using two stripes of medical adhesive tape in order to avoid as much as possible the relative movement between the skin and the sensor during the movement, that may affect the signal recording.

In order to proof the correct location of the sensors “Labview Signal Express” has been used. With this software is possible to visualize the signal coming from all the sensors. A preliminary test has been repeated for each subject before starting the experiment. The test consist to perform a maximum contraction for each muscle and on both the arms. In this way is possible to understand if the sensors respond in the same way.
Because one arm is weaker respect to the other, the amplitude of each signal, comparing same muscles on both the arms, are different, but the shape are similar.

During the real experiment instead is much more difficult to understand the differences between two muscles during a movement, because the user doesn’t perform the training using a maximum contraction of the muscle. Later on is discussed in detail this problem.

IV.3 The GUI

The training game consists in a GUI implemented in Matlab.

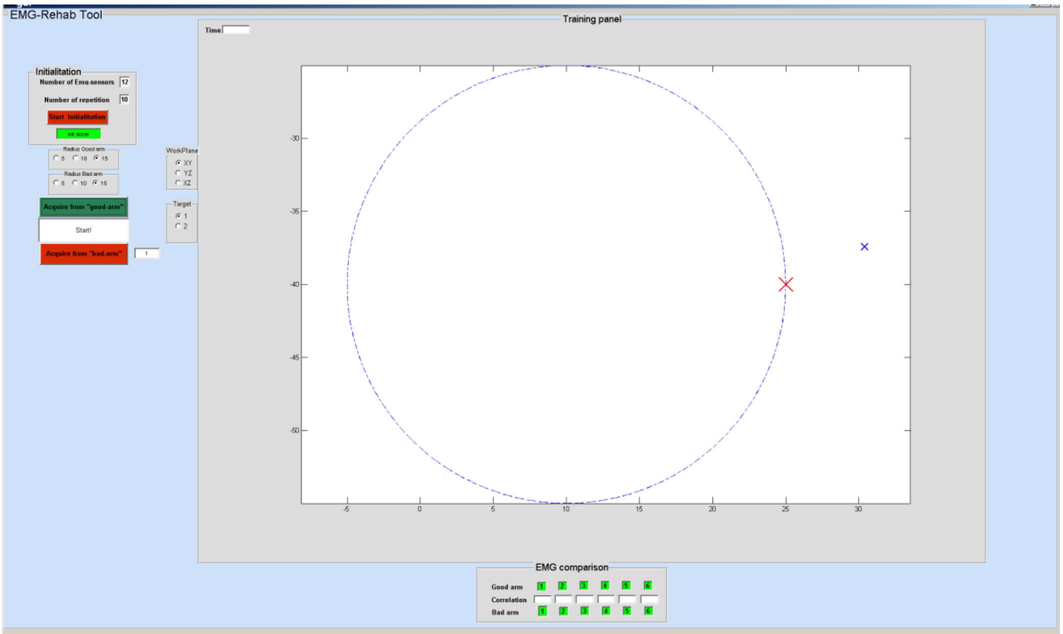


Figure IV.10 – The software

Is possible change the values regarding the initialization:

- Number of EMG sensors.
- Number of repetition (valid for the unimpaired arm).
- Radius of the figure for both the arms: 5,10 or15cm.
- Work plan: XY, XZ or YZ.
- Target: figure “Circle” or “Eight”

In the central part of the GUI is drawn the target has to be followed (a blue cross), and the marker that moves according the position given by the tracker (a red cross).

On the bottom the results of the comparison between the two arms are showed.

To make possible the visualization on the screen, a script has been programmed in Matlab. The cross target that the user has to follow, is moving on the screen accordingly to the parametric equation of the "circle" or of the "eight":

Parametric equation of the "Circle"

$x = r * \cos(t)$

$y = r * \sin\,(\mathrm{t})$

Parametric equation of the "Eight"

$x = r * \cos(t)$

$y = r * \sin(\mathrm{t}) * \cos\,(\mathrm{t})$

Where *r* is the radius, and *t* is the vector of the time that is properly chosen in respect of which arm is working and consequentially which has to be the starting point of the red target above the figure.

Regarding the movement of the blue marker, it moves accordingly to the data coming from the position tracker. In order to communicate with the FOB and getting the proper data, three function in C-language were written using specified library in order to avoid to sending binary commands over RS232 com port:

- **FOB_init.c** : with this function is possible to configure the device.

  With the command `birdRS232WakeUp` is possible to waking up the device, opening the com-port, setup the baudrate (115.2K baud), the read and write timeout (both 2 sec) and the number of devices connected with the central unit.
  With the commands `birdSetSystemConfig` and `birdSetDeviceConfig`

is possible to setup the device with the measurement rate (101.3 Mhz) and the relative position of the user in respect of the magnetic field generator.

- **FOB_getdata.c** : with this function is possible to get the position of the sensor.

There are different possibilities to get the data from the FOB. In this case is asked to the device to get a single frame on demand and not to stream the data. This is needed because we want to visualize in real time the position of the tracker on the screen, so we demand at each time to the device to get a frame, and draw the position of the hand on the screen.
`birdStartSingleFrame` and `birdGetFrame` start the frame and put the information inside an array. When the function is called, the element from the array are pulled out.

- **FOB_shutdown.c** : this function is used to stop the frame reading and close the connection.

In order to integrate the functions mentioned with Matlab, they were compiled in Matlab as “mex functions”.
In order to get the EMG signals from the analog device, the “Data Acquisition Toolbox” of Matlab has been used.
After opening an analog object with the command `analoginput` is possible to setup the object choosing the type of signal (Single Ended) , the rate of acquisition (1000 Hz) and the number of sample for trigger (25000).
With the command `addchannel` is possible then to add the channels act to acquire the EMG signals.
Also in this case is possible to get the data from the device in a streaming mode or get single stream on demanding. But in this case is really important to use a streaming mode, unlike the FOB device, in order to have the highest frame rate is possible.

The two main issues regarding a correct functionality of the system are:

1. **Synchronization**
2. **Frequency of acquisition**

When EMG signals are acquired during the movement, these have to be synchronized with the training game because the EMG signals have to be recorded accordingly with the movement of the target, and even more important, EMG signal from the unimpaired arm have to be synchronized with the ones retrieved from the impaired arm.
To solve this problem has been decided that the acquisition of the muscle activity start only when the user “touch” with the blue cross marker, the red target on the screen.

In this way the user can move the blue marker moving his hand in the space, but no EMG signal are acquired until the target is not moving on the screen. This ensures also the synchronization with the game because no EMG signals are acquired during the time the user attempt to make starting the target, and also ensures the synchronization between the signals retrieved from the right arm and the left arm. Making starting the acquisition only when the target cross is touched, assure that the acquisition is synchronized between the two arms because the starting time point is the same, and there is no need to synchronize the EMG signals afterwards.

The second problem regards the frequency of acquisition.

Ideally the EMG device acquire at 1000Hz and the FOB device at 101.3Hz.
The issue is that we want to integrate the function regarding the record from both the devices inside the for-loop act to visualize the object moving on the screen.
Unfortunately, the velocity of the for-loop is not synchronized with the velocity of the FOB device and the EMG device. Moreover, because there is a further delay

when the functions regarding the acquisition of the data from the two devices attempt opening the connection (Ethernet for the EMG device and COM for the FOB device).

A part from this, another problem is that the graphic engine of Matlab is slow, and when we ask to plot the graphical objects in real time with the movement of the hand, all the system become incredibly slow. A first experiment showed that due to the plotting and the elaboration, the acquisition frequency of the EMG device and the FOB device decreased at circa 10Hz, that is unsustainable.

In order to avoid this problem, the following solution has been implemented:
the acquisition of the FOB data at each time of the for-loop is essential because is needed to plot the position of the hand for each movement of it.

For this reason, in order to get independent the velocity of acquisition of the FOB device, but let the function stay inside the for-loop, a timer has been implemented.
Even if this solution is not completely independent by the velocity of the for-loop, the timer, when activated, ask independently the data to the device and put this data inside a buffer, with a velocity that is possible to setup a priori.
In this way is not the for-loop to activate the *FOB_getdata* function at each time, but the timer is doing it.

At each time the for-loop ask the data to the timer buffer and this give a better result; in fact the acquisition frequency of the FOB device is around 25Hz , but it’s enough for this application because the movement are slow and there is no need of higher frequency.

Instead the acquisition frequency of the EMG device has to be fast, because otherwise would not respect the Nyquist Theorem and then would lose any physical significance.

Unlike the FOB device, there is no need to acquire at each step of the for-loop a EMG stream, because is not request to visualize the muscular activity in real time.
For this reason the command “START” from the Data Acquisition Toolbox has been used. With “START” the device is called to acquire at 1000Hz and for 25000 frame per second.
The device start to acquire when the user touch the target cross on the screen; at this moment also the FOB timer is starting.

When the target makes an entire loop along the figure, both the devices stop to acquire data.

Chapter V

Experiment and results

V.1 Experiment

Five healthy subjects with no history of neurological disorder or any kind of disease were recruited to serve as control. Four man and one girl with mean age of 24,6.
In order to understand better the problem of Stroke Rehabilitation, and how to conduct a “simulation” of stroke patient to perform correct experiments, we were in contact since the beginning of my work with a stroke physician of the “Klinikum rechts der Isar” in Munich.

Before starting the experiment, has been asked to each subject to read and sign an informative paper about the experiment.
The subject have to seat on a comfortable chair and the distance of the chair from the table, where the magnetic field generator is placed, is dependent by the length of the arms.

Six electrodes were applied on the following muscles and in the same spots on both the arms of the subject:

- **EMG sensor #1 :** Biceps brachii
- **EMG sensor #2 :** Triceps brachii
- **EMG sensor #3 :** Triceps lateral
- **EMG sensor #4 :** Deltoid anterior
- **EMG sensor #5 :** Deltoid medius
- **EMG sensor #6 :** Deltoid posterior

Electrodes for each muscle were placed according to guidelines of SENIAM. [19]

After the sensor placement the Labview Signal Express software is useful to understand the correctness of the electrode placement and the functionality of the EMG device.

The subjects were divided in two groups: the first is composed by three subject that were asked to follow the target along the figure “Eight” in the XZ plan, after the position sensor is connected on the hand; the second is composed by two subjects that were asked to follow the target along the figure “Circle” in the XY plan.
Before they have to perform the movement with the right arm, doing ten repetition of the movement with a fixed radius of 15cm.
After the acquisition, the system automatically evaluate the average of the ten repetition in order to find out a “standard profile” for each muscle activity, that will be the reference profile for the left arm.
Then is asked to the subject to perform the same movement with the left arm, in a mirror way respect to the right arm, and with three different radius of the figure: 5,10 and 15cm.

For each radius the subject have to repeat the movement five time.

For every trial, data are collected, analyzed using Matlab, and stored on the hard disk.

Because the acquisition card has already implemented on board an high pass filter and a rectifier, all the data acquired were processed with a low-pass filter (Butterworth 2th order, cutoff 0.3Hz) in order to capture the envelopes of EMG activity.

V.2 Qualitative analysis

With a first qualitative analysis, EMG signals from each sensors on both the arms are compared.

In the next figures is showed the comparison between each muscles and they are repeated five times because it was asked to the subject to repeat with the left arm five times the movement.

The comparison is between each single repetition of the left arm with the mean average of the ten repetition done with the right arm.

The results are repeated three time according with the movement done for the radius of 5, 10 and 15cm.

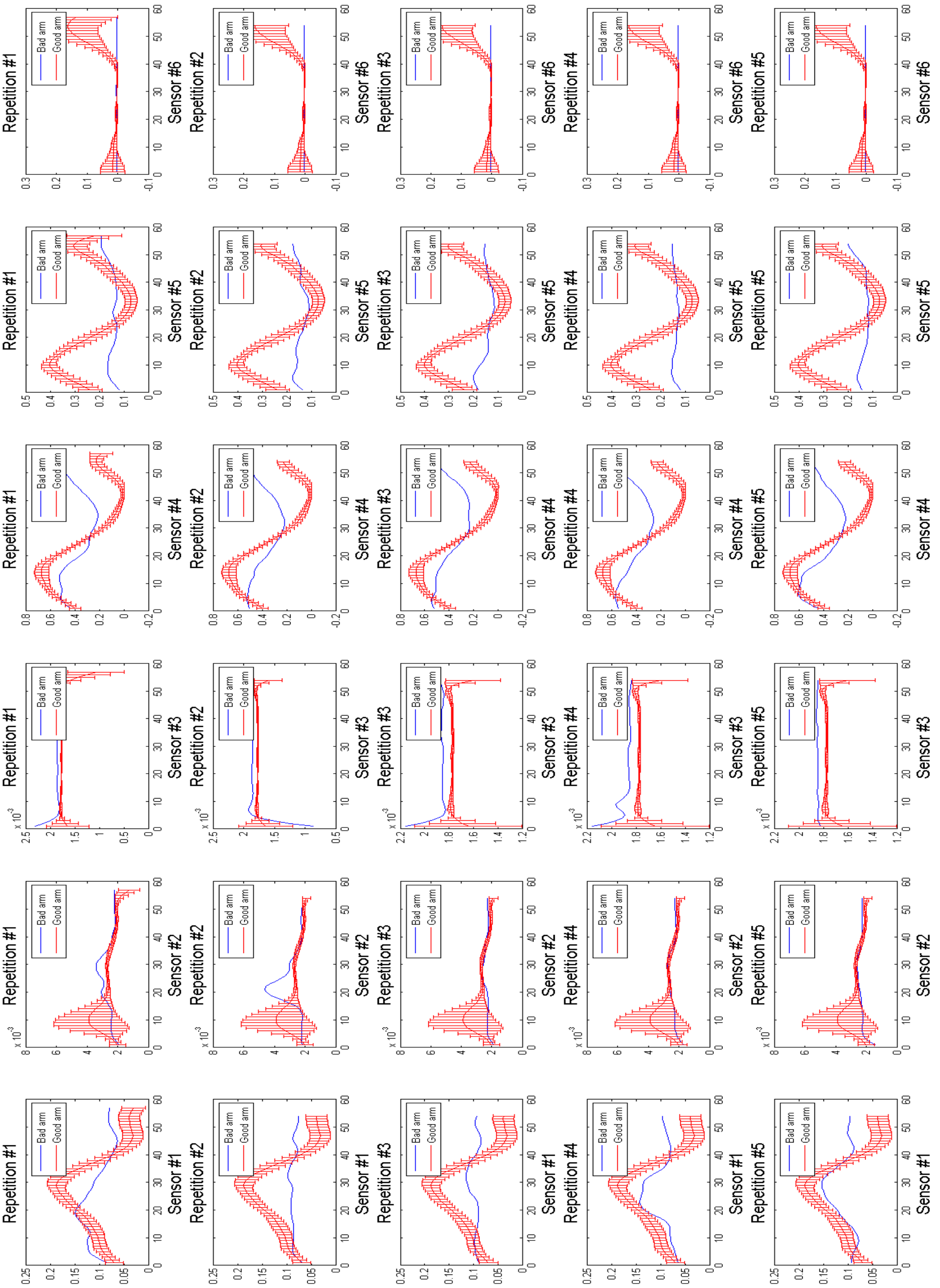


Figure V.1 – Subject n.5, Plan XY, five repetition of the left arm with radius=5cm. In red there is the mean with the standard deviation of the ten repetition of the right arm. In blue there are each repetition of the left arm

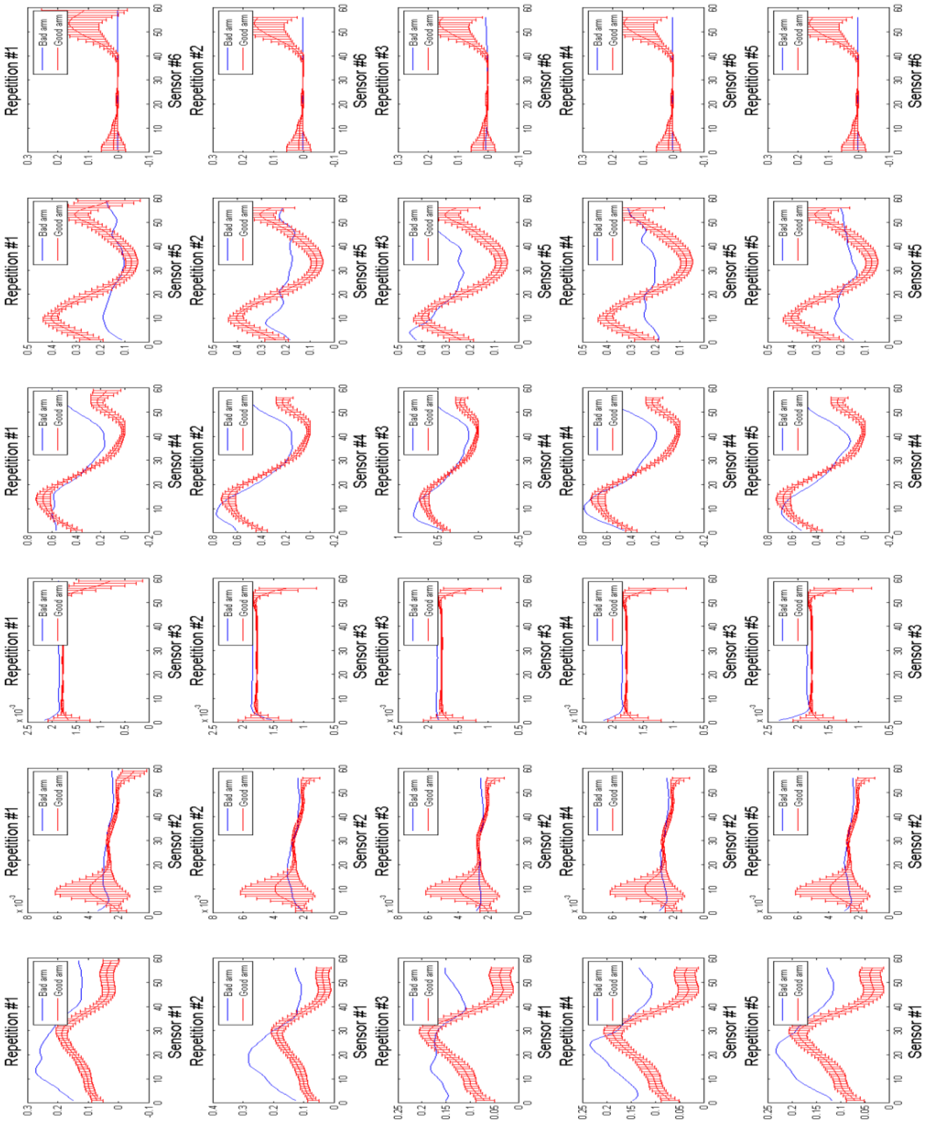


Figure V.2 – Subject n.5, plan XY, five repetition of the left arm with Radius=10cm.

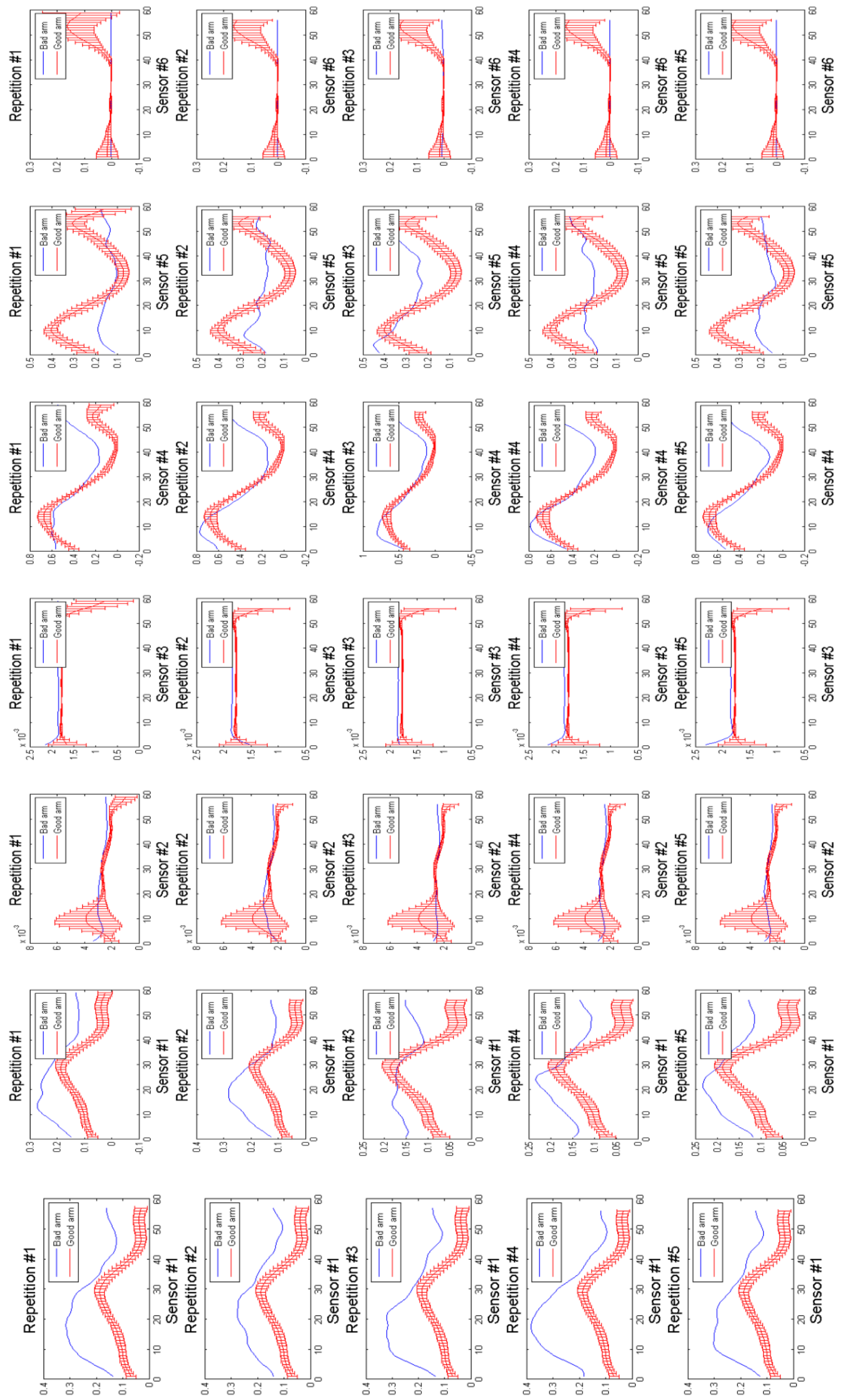


Figure V.3 – Subject n.5, Figure XY, five repetition with radius=15cm

In order to understand better the results, in the next graph is showed for each radius, only one repetition.

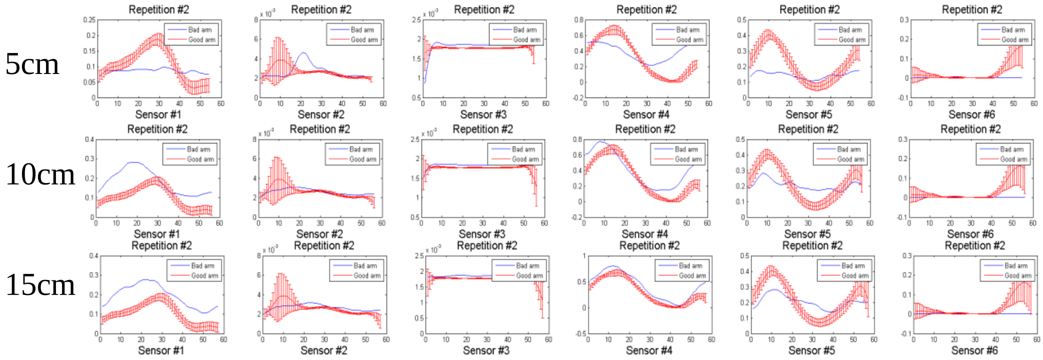


Figure V.4 – Comparison of muscles for 5, 10 and 15cm radius

From the graph is possible to see how the shape of the EMG profile for each muscle of the left arm become more “similar” to those of the right arm as long as the radius of the movement done from the left arm become bigger.
This seems to confirm the thesis that after a training, the left arm is able to do a movement comparable with the one done by the right arm that is the reference.

Analyzing the graphs is moreover obvious that some EMG sensors respond better than the others. For example EMG sensors 3 and 6 give bad results, because the third have an amplitude in the range of 10^{-3} , that is in the spectrum of the noise, and the sixth sensor give different results from the muscles on the two arms.
This problem appears for each subject. After a deep analysis came out that for the movement regarding figure “Circle”, the muscles of the shoulder and the biceps are more involved; instead regarding figure “Eight” only the muscles of the shoulder are more involved. After a quantitative analysis is discussed how to approach at this problem.

This qualitative analysis is repeated for each subject and a common positive trend appears.

V.3 Quantitative analysis

In order to compare in a quantitative way each EMG signal, two numerical instruments have been used:

- **Sample Pearson Correlation Coefficient** [20]
- **Normalized Root Mean Square Error (NRMSE)** [21]

The ***correlation coefficient*** is a measure of the correlation (linear dependence) between two variables *X* and *Y*, giving a value between +1 and −1 inclusive. It is widely used in the sciences as a measure of the strength of linear dependence between two variables.

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}}.$$

The correlation coefficient ranges from −1 to 1. A value of 1 implies that a linear equation describes the relationship between *X* and *Y* perfectly, with all data points lying on a line for which *Y* increases as *X* increases. A value of −1 implies that all data points lie on a line for which *Y* decreases as *X* increases. A value of 0 implies that there is no linear correlation between the variables.

The interpretation of a correlation coefficient depends on the context and purposes. A correlation of 0.9 may be very low if one is verifying a physical law using high-quality instruments, but may be regarded as very high in the social sciences where there may be a greater contribution from complicating factors.

A key mathematical property of the Pearson correlation coefficient is that it is invariant (up to a sign) to separate changes in scale of the two variables.

This property is really important because signals from unimpaired arm are compared with signals retrieved by the impaired arm. Even if one arm is weaker, the “shape” of the EMG signal between two equal muscles of both the arms, should be similar.

Root-mean-square error (RMSE) is a frequently used measure of the differences between values predicted by a model or an estimator and the values actually observed from the thing being modeled or estimated. RMSE is a good measure of accuracy.

RMSE(ϑ_1, ϑ_2)= $\sqrt{\mathrm{MSE}(\theta_1,\theta_2)} = \sqrt{\mathrm{E}((\theta_1-\theta_2)^2)}$

Where: $\theta_1 = \begin{bmatrix} x_{1,1} \\ x_{1,2} \\ \vdots \\ x_{1,n} \end{bmatrix}$ and $\theta_2 = \begin{bmatrix} x_{2,1} \\ x_{2,2} \\ \vdots \\ x_{2,n} \end{bmatrix}$.

The formula becomes: RMSE(ϑ_1, ϑ_2)= $\sqrt{\frac{\sum_{i=1}^{n}(x_{1,i}-x_{2,i})^2}{n}}$.

The ***Normalized Root-Mean-Square Error (NRMSE)*** is the RMSE divided by the range of observed values:

$$\boldsymbol{NRMSE = \frac{RMSE}{x_{max} - x_{min}}}$$

In this application we consider the range of the values observed on the left arm.

With these two mathematical tools, a qualitative analysis has been done. Correlation coefficient and NRMS have been evaluated during the comparison process between the EMG signals of both the arms.

In next pictures has been showed the analysis for each subject.

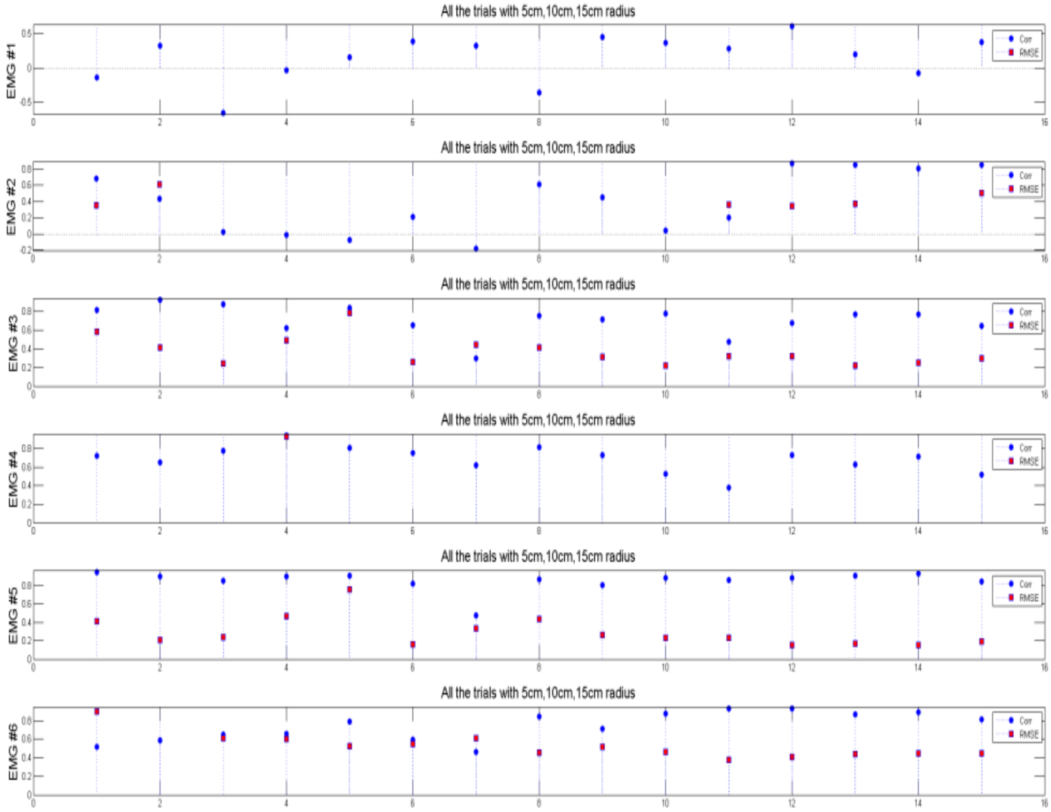


Figure V.5 – Subject n.1 , Plan XZ , Figure "Eight"

In this graph is showed for each EMG sensor, the comparison between each muscle activity of the left and right arm. In blue is the correlation coefficients, and in red the NRMSE results.

All the data are collected from the three trials with 5, 10 and 15cm of the radius.

All the subject were analyzed and the results are showed in the following graphs.

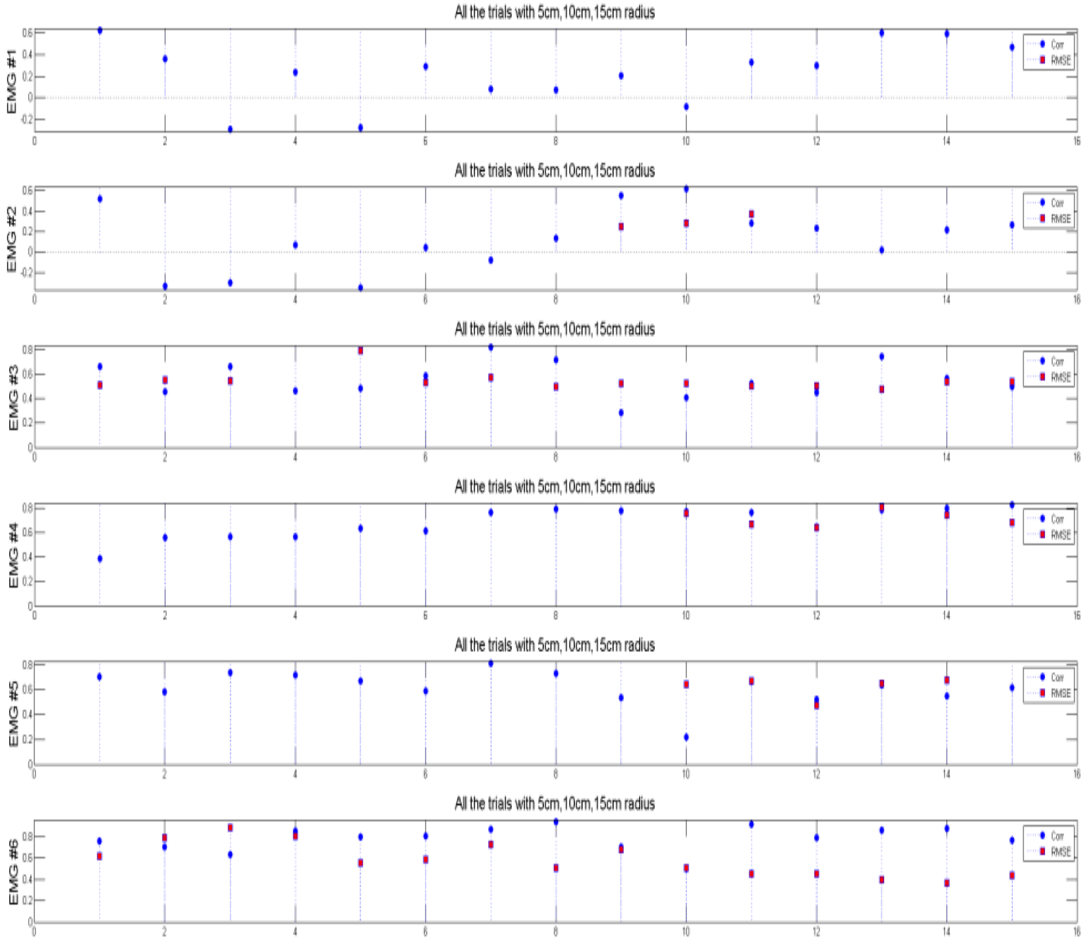


Figure V.6 – Subject 2, Plan XZ , figure “Eight”

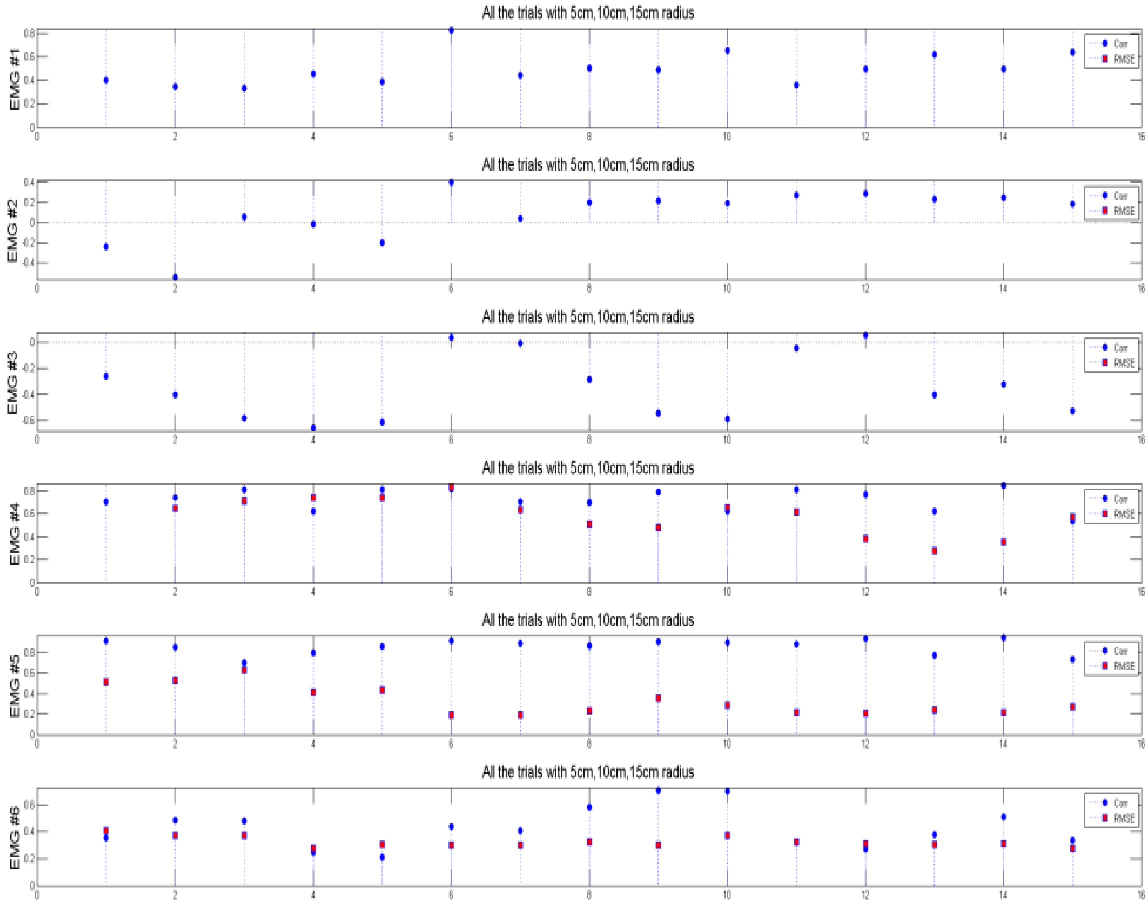


Figure V.7 – Subject 3, Plan XZ , figure “Eight”

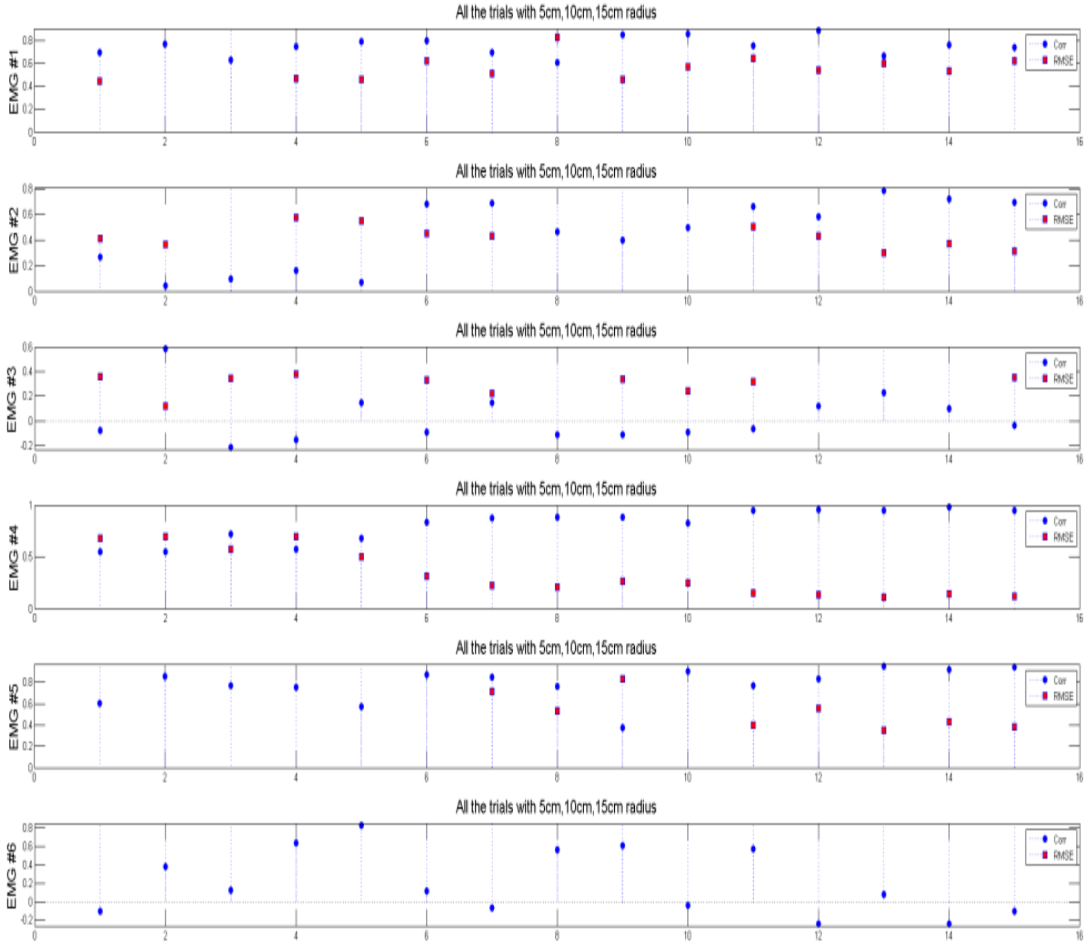


Figure V.8 – Subject 4, Plan XY , figure “Circle”

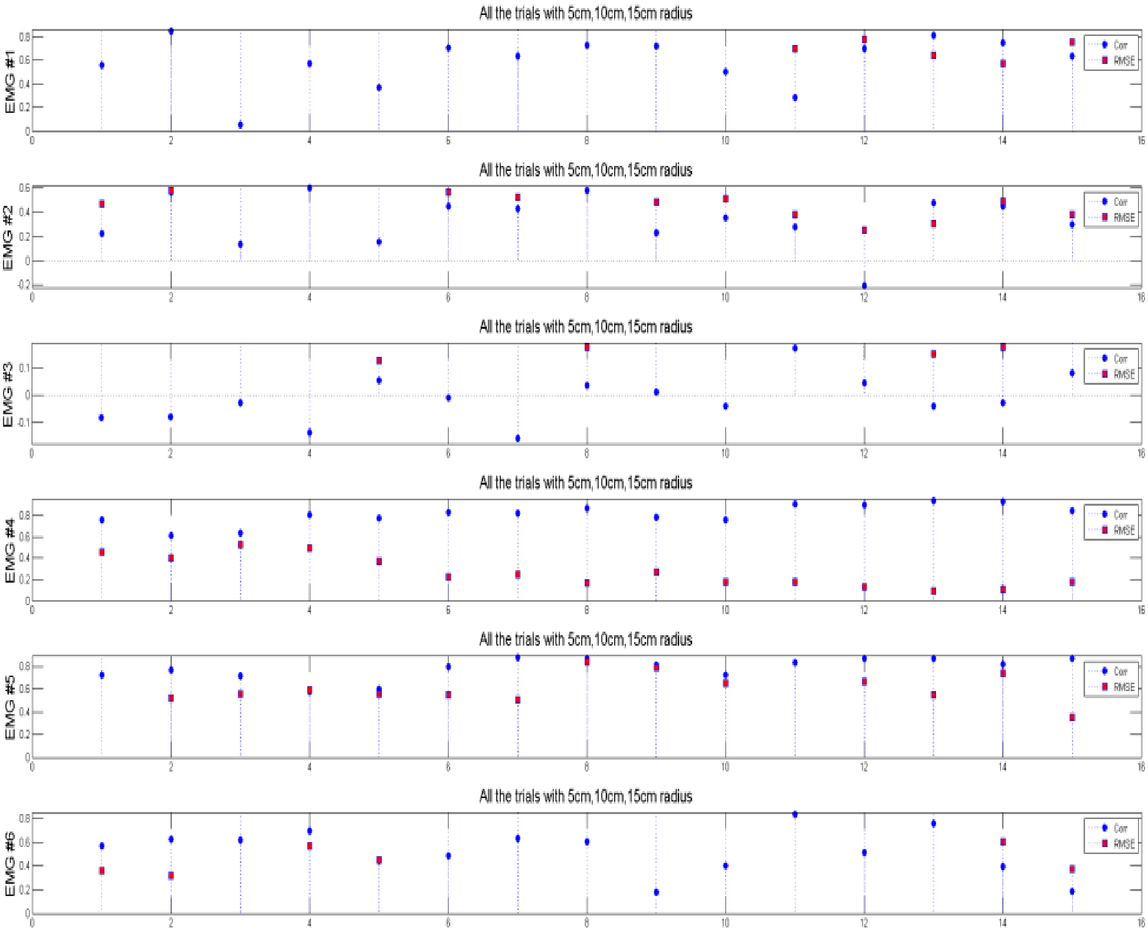


Figure V.9 – Subject 5, Plan XZ , figure “Eight”

Subject n.4 were asked to perform also the movement “Circle” in the XY plan, but unfortunately the results are bad due of a non correct acquisition of the signal. For this reason this experiment is excluded for the analysis. In the next picture is possible to see the result.

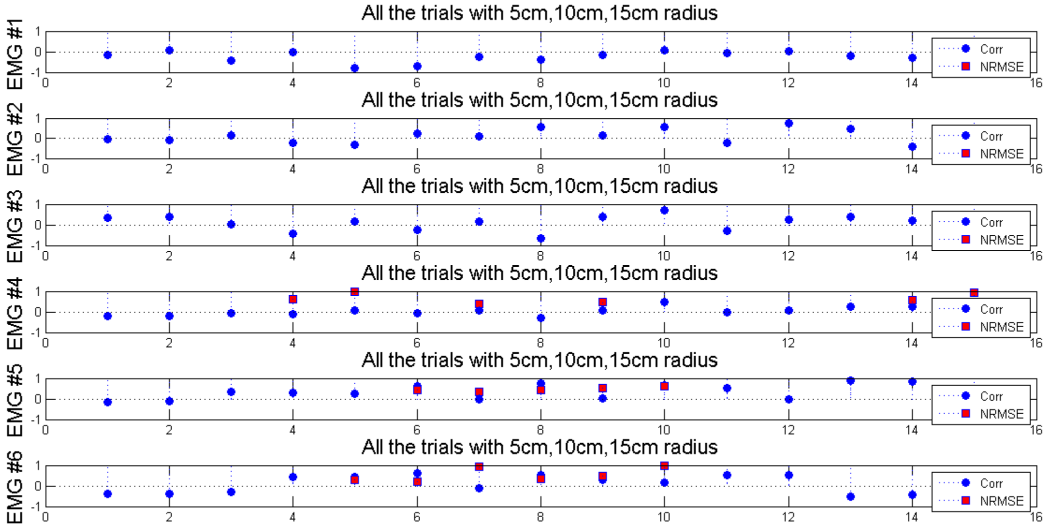


Figure V.10 – Correlation vs. NRMSE for subject n.4

Is obvious to understand that the correlation indexes gives bad results because have an alternative pattern from negative to positive and this is due of a bad acquisition of the EMG signals. Is also possible to observe that the NRMSE coefficients are higher than 1 for all the sensors.

For this reason this trial is not considered.

Thanks to the quantitative analysis it has been possible to understand how to compare two EMG signal. But in order to have a general picture of the quality of this “therapy” is more interesting to merge the results obtained by the six separate sensors.
We want to observe if there is a positive trend during the training, and specifically we want to find out if, taken all the repetitions for each subject and doing a cataloguing according with the repetition done with 5, 10 and 15cm of radius, there is a positive growth of the correlation index.

In order to proceed in this way, for each subject have to be collected all the correlation coefficients from all the EMG sensors at 5cm, then at 10cm and 15cm, in a unique vector.

With the qualitative analysis is possible to recognize that not for all the muscles is possible to have good results and is needed to exclude some sensor for each subject. This because for a particular movement, for example the figure “Eight”, only the muscle of the shoulder are more involved, instead the muscle of the arm are weakly involved. Moreover because the sensor are located not in the precise spot on both the arms, and this cause a non optimal correlation of the EMG signals, or also because the sensor is not properly connected on the skin. Analyzing the previous graphs is possible to write a table where, for each subject, which EMG sensors are included in the next analysis:

	Sensor 1	**Sensor 2**	**Sensor 3**	**Sensor 4**	**Sensor 5**	**Sensor 6**
Subj. 1		**X**	**X**	**X**	**X**	**X**
Subj. 2			**X**	**X**	**X**	**X**
Subj. 3	**X**			**X**	**X**	
Subj. 4	**X**	**X**		**X**	**X**	
Subj. 5	**X**			**X**	**X**	**X**

The results for each subjects:

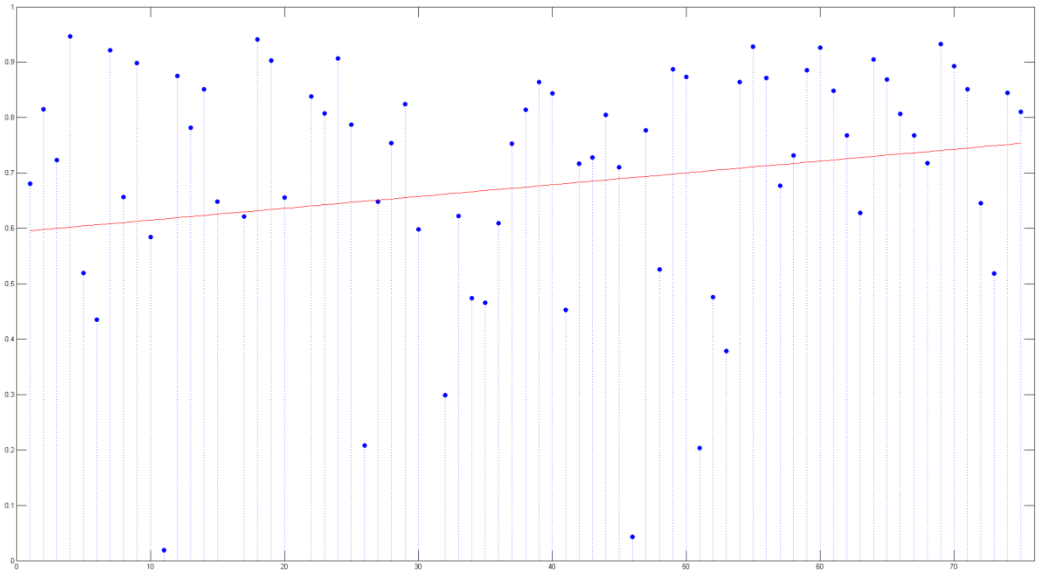


Figure V.11 – Subject n.1 , Correlation coefficients for all the included sensors grouped for 5, 10 and 15cm of the radius

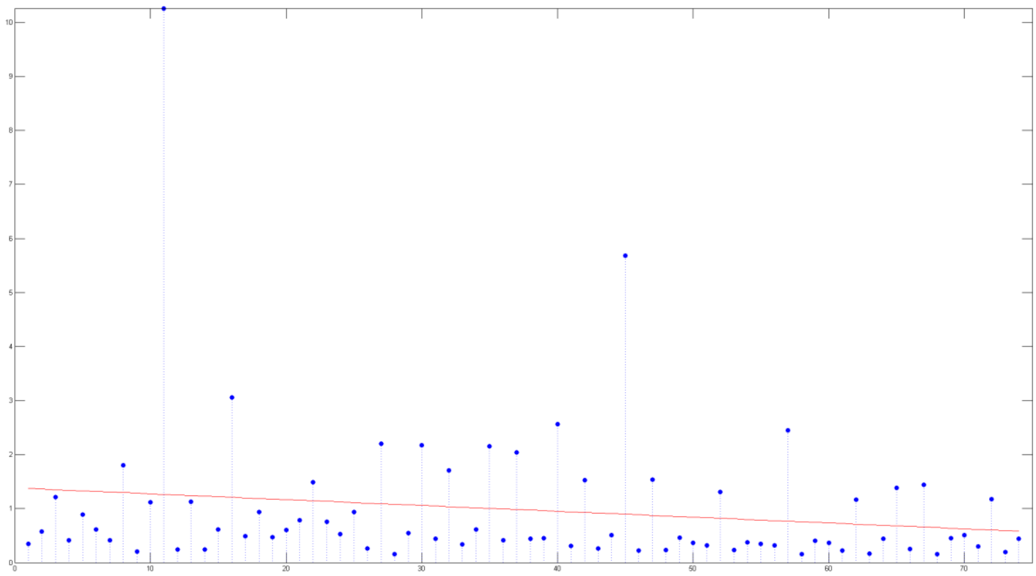


Figure V.12 – Subject n.1 , NRMSE coefficients for all the included sensors grouped for 5, 10 and 15cm of the radius

The red line in the graphs is the linear regression line obtained with a 1th order polynomial that fits the data in a least squares sense, using the command "POLYFIT" in Matlab.

The slope of the line depends on how the data inside the three groups of 5, 10 and 15cm are sorted. To have a more detailed picture of the efficacy of this experiment, is necessary to plot also the fitting line that go across the mean of each groups for the Correlation Index and for the NRMSE coefficients.

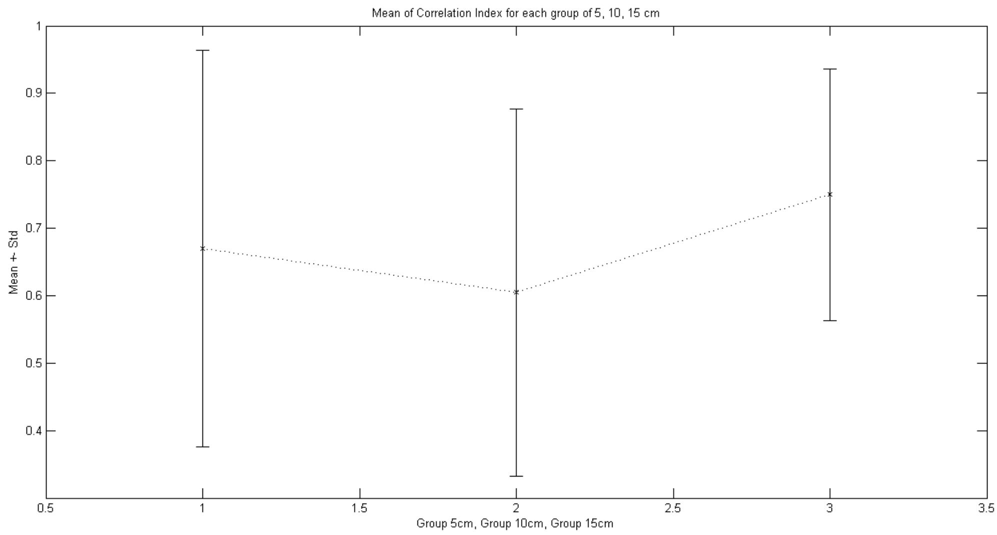


Figure V.13 – Subject n.1 , Correlation index, mean ± std of group 5, 10 and 15cm

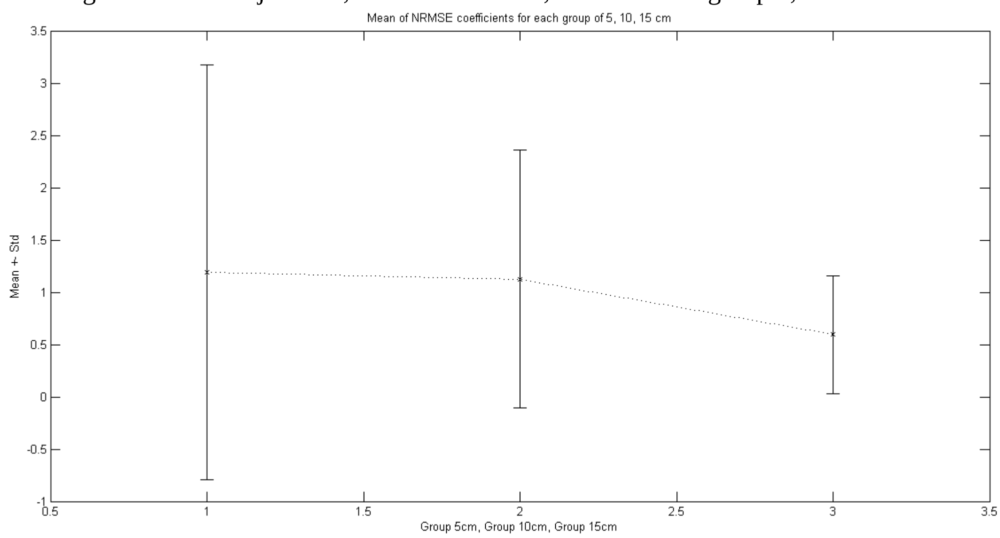


Figure V.14 – Subject n.1 , NRMSE coefficients, mean ± std of group 5, 10 and 15cm

The same is repeated for each subjects.

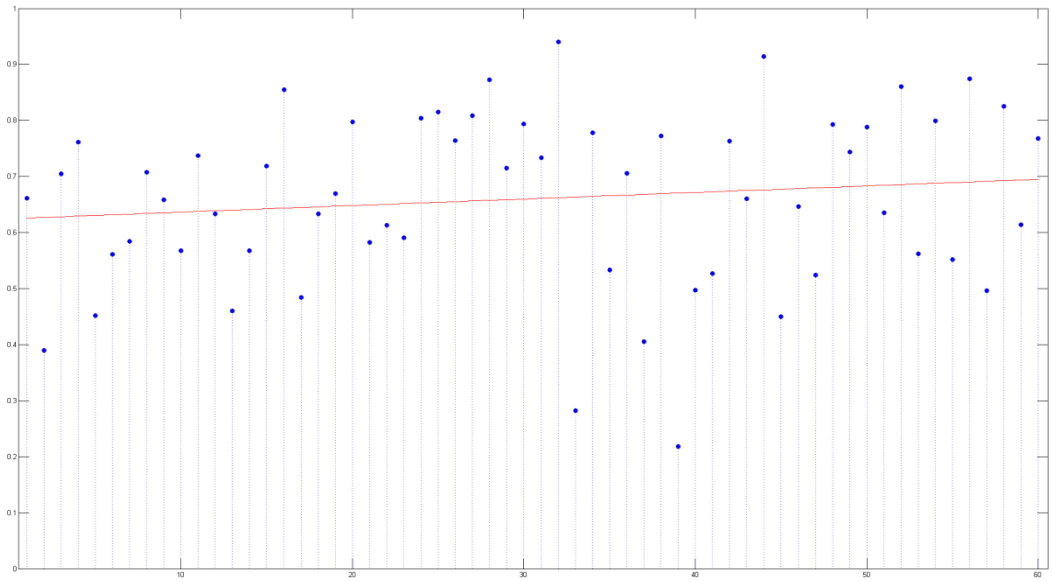


Figure V.15 – Subject n.2 , Correlation coefficients for all the included sensors grouped for 5, 10 and 15cm of the radius

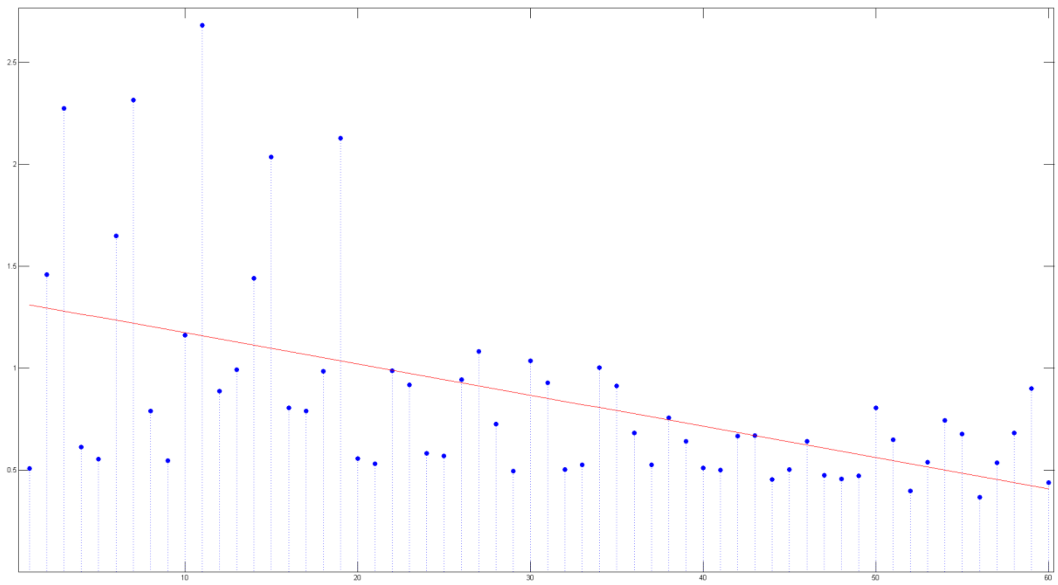


Figure V.16 – Subject n.2 , NRMSE coefficients for all the included sensors grouped for 5, 10 and 15cm of the radius

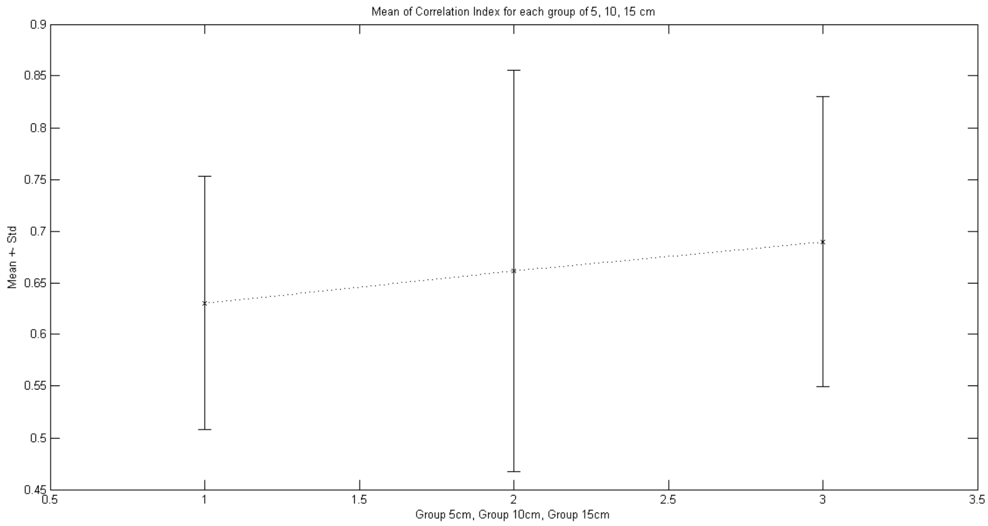


Figure V.17 – Subject n.2 , Correlation index, mean ± std of group 5, 10 and 15cm

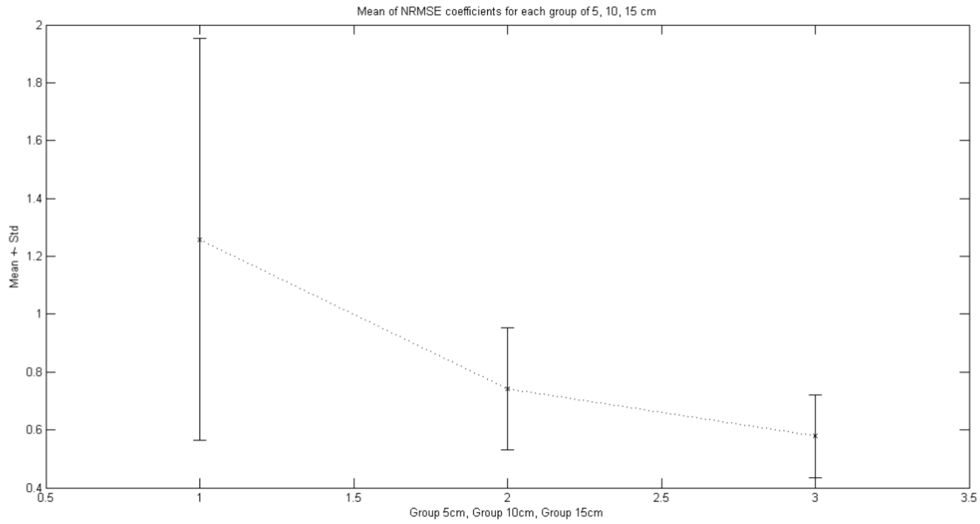


Figure V.18 – Subject n.2 , NRMSE coefficients, mean ± std of group 5, 10 and 15cm

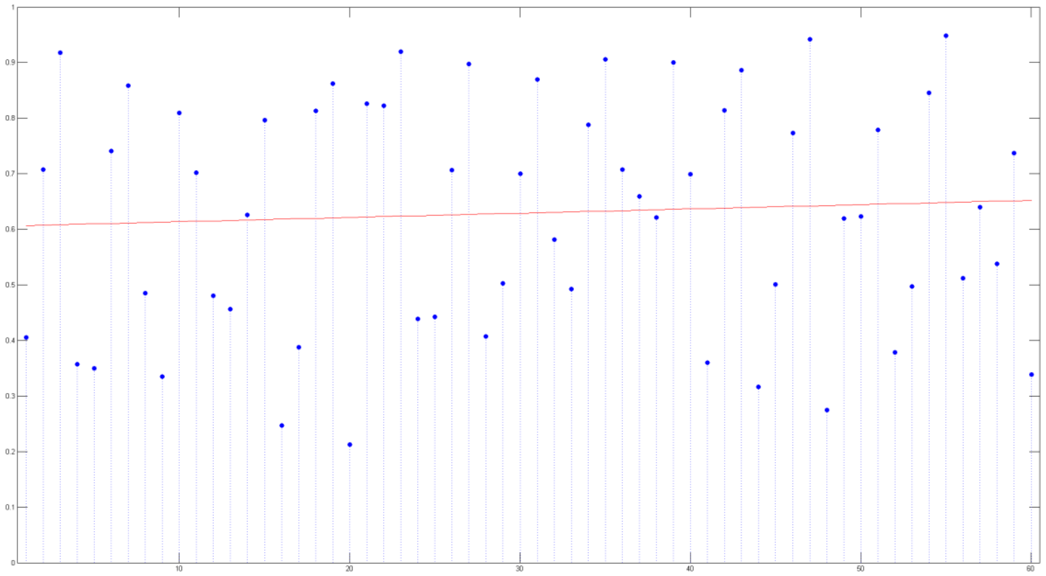


Figure V.19 – Subject n.3 , Correlation coefficients for all the included sensors grouped for 5, 10 and 15cm of the radius

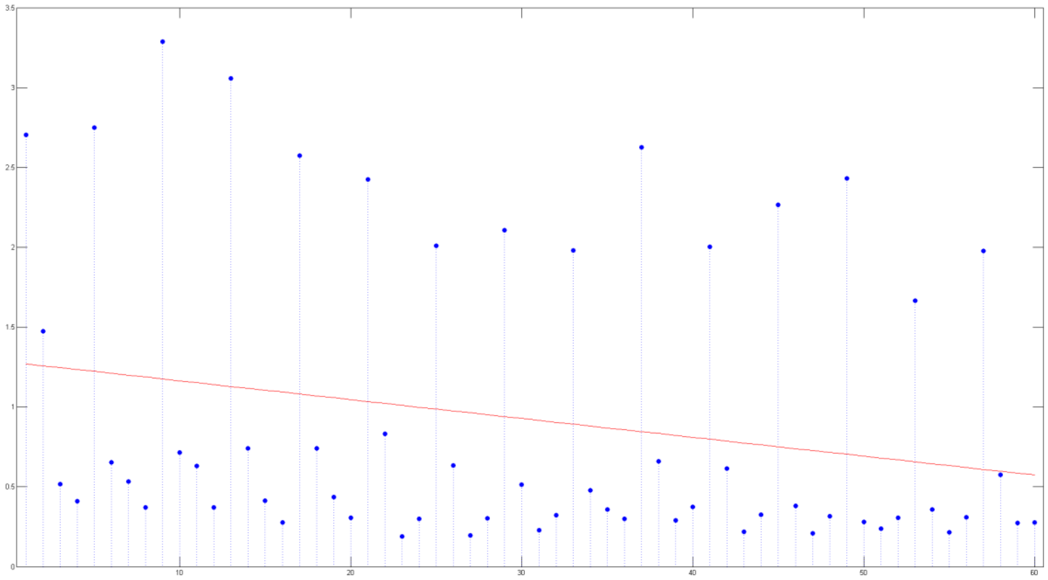


Figure V.20 – Subject n.3 , NRMSE coefficients for all the included sensors grouped for 5, 10 and 15cm of the radius

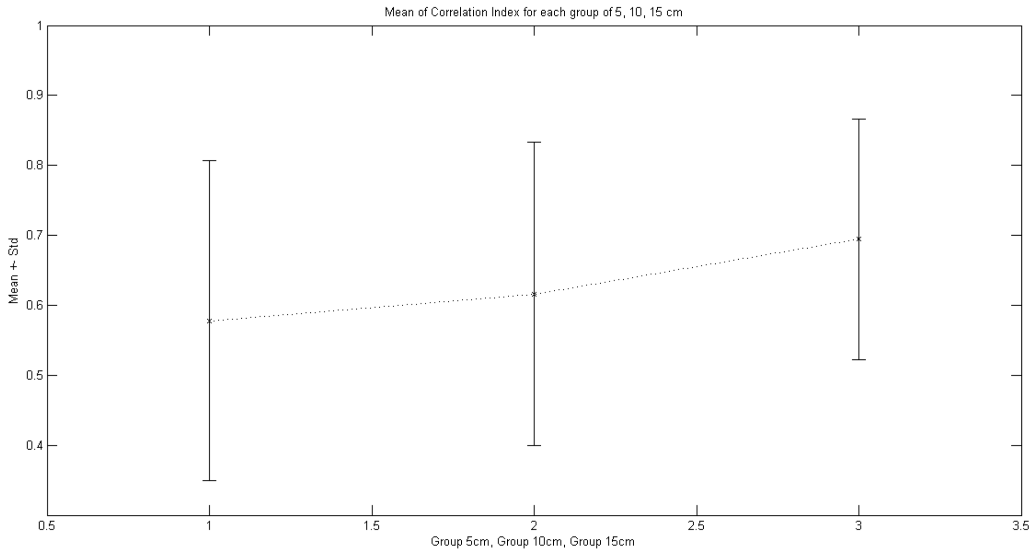


Figure V.21 – Subject n.3 , Correlation index, mean ± std of group 5, 10 and 15cm

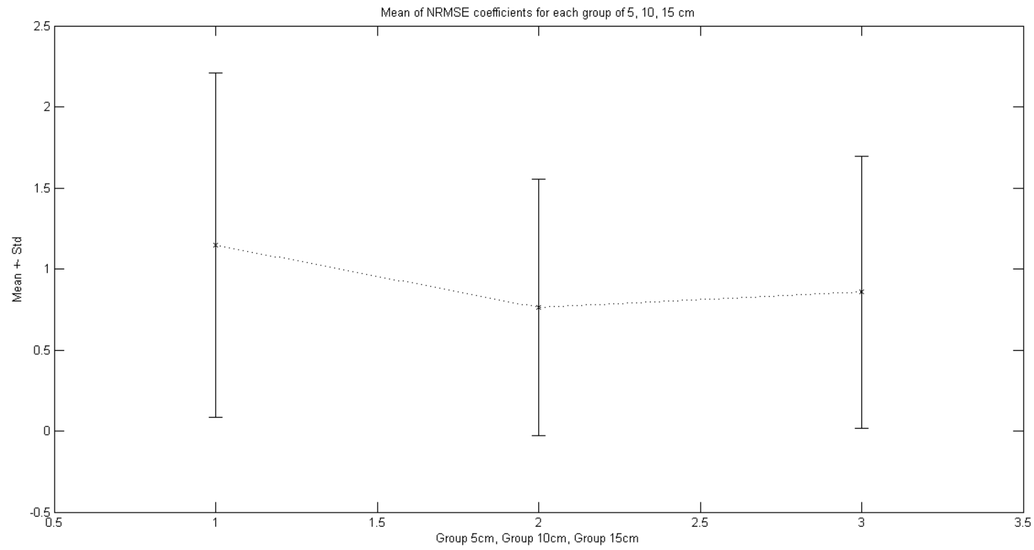


Figure V.22 – Subject n.3 , NRMSE coefficients, mean ± std of group 5, 10 and 15cm

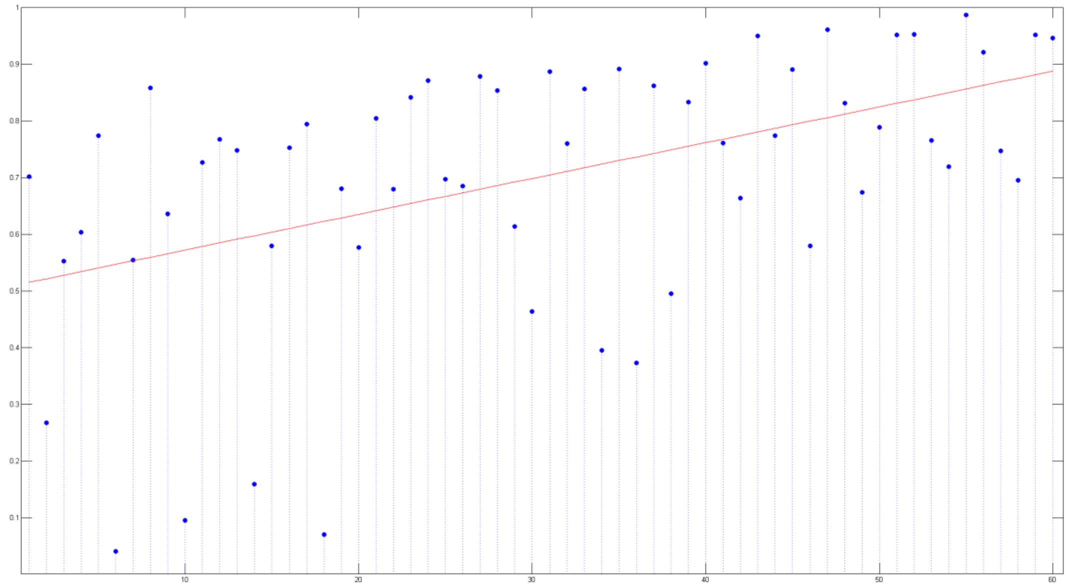


Figure V.23 – Subject n.4 , Correlation coefficients for all the included sensors grouped for 5, 10 and 15cm of the radius

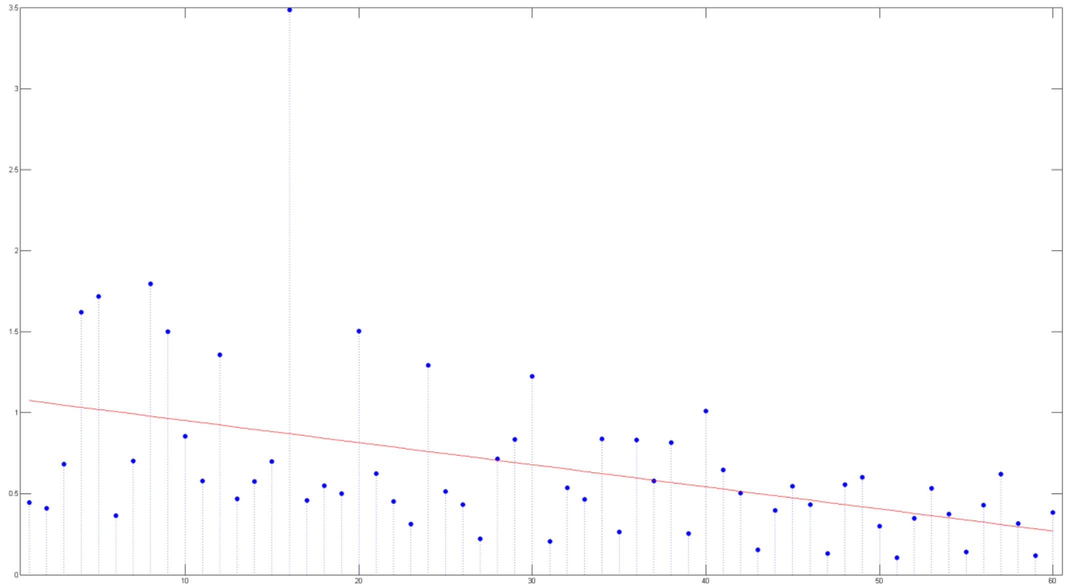
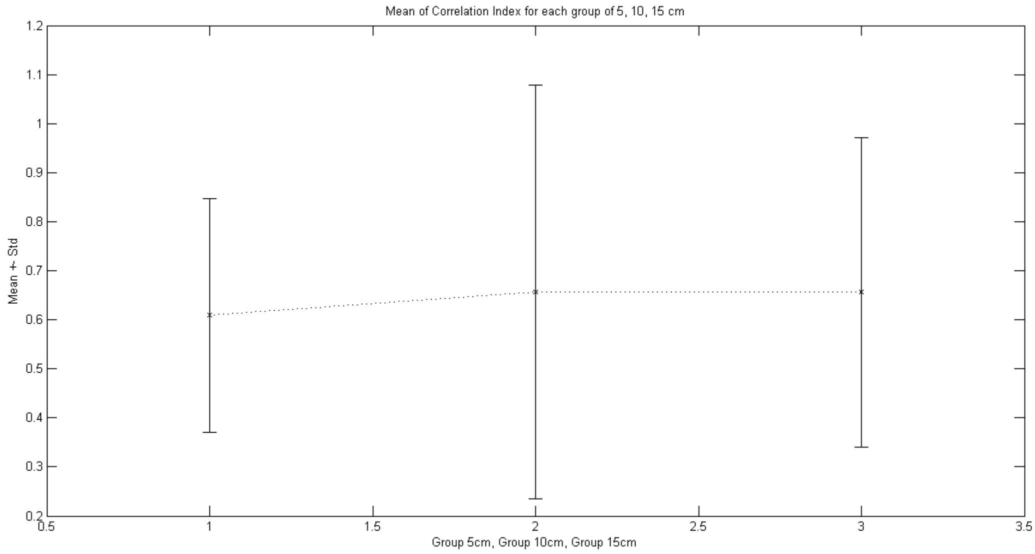


Figure V.24 – Subject n.4 , NRMSE coefficients for all the included sensors grouped for 5, 10 and 15cm of the radius



V.25 – Subject n.4 , Correlation index, mean ± std of group 5, 10 and 15cm

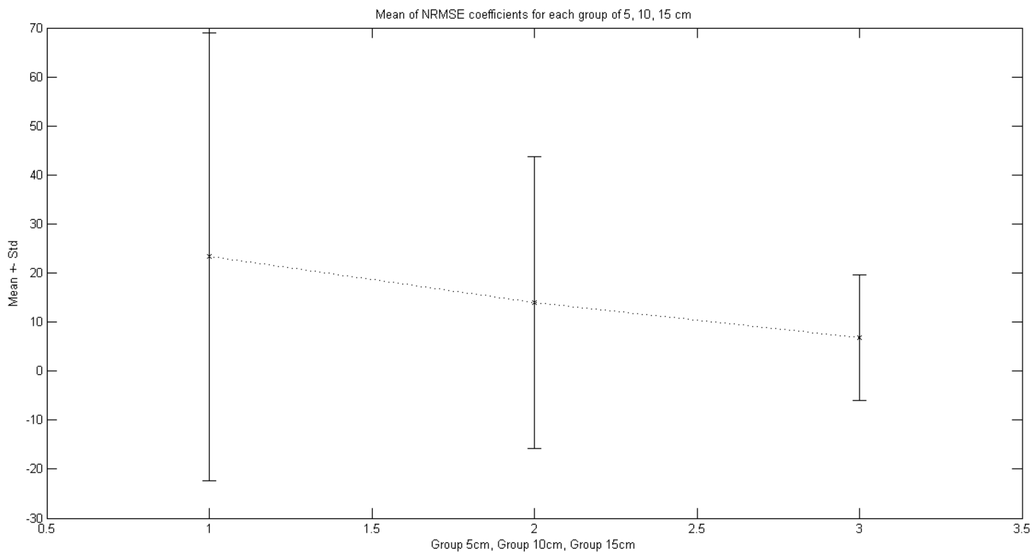


Figure V.26 – Subject n.4 , NRMSE coefficients, mean ± std of group 5, 10 and 15cm

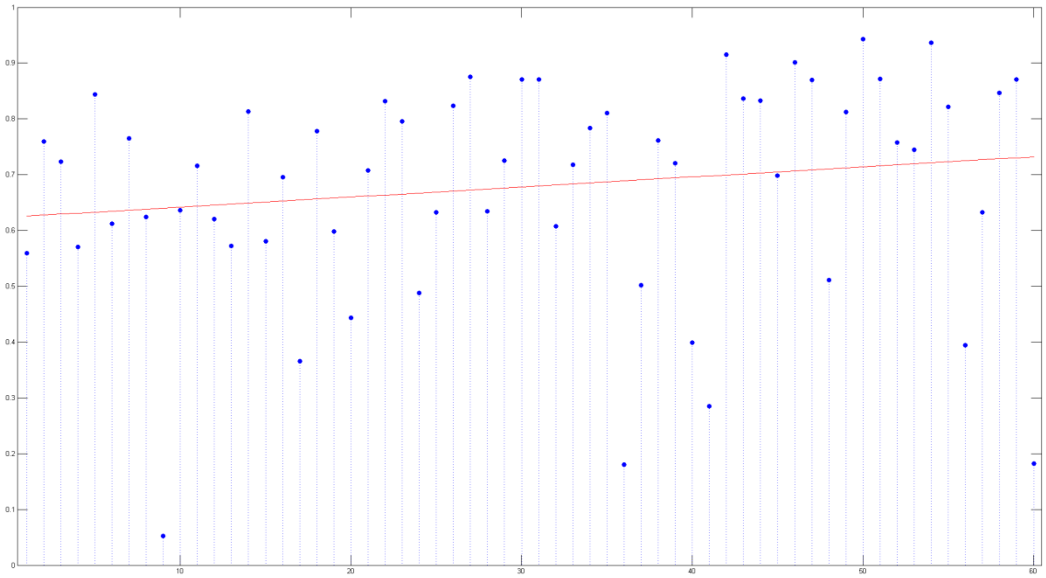


Figure V.27 – Subject n.5 , Correlation coefficients for all the included sensors grouped for 5, 10 and 15cm of the radius

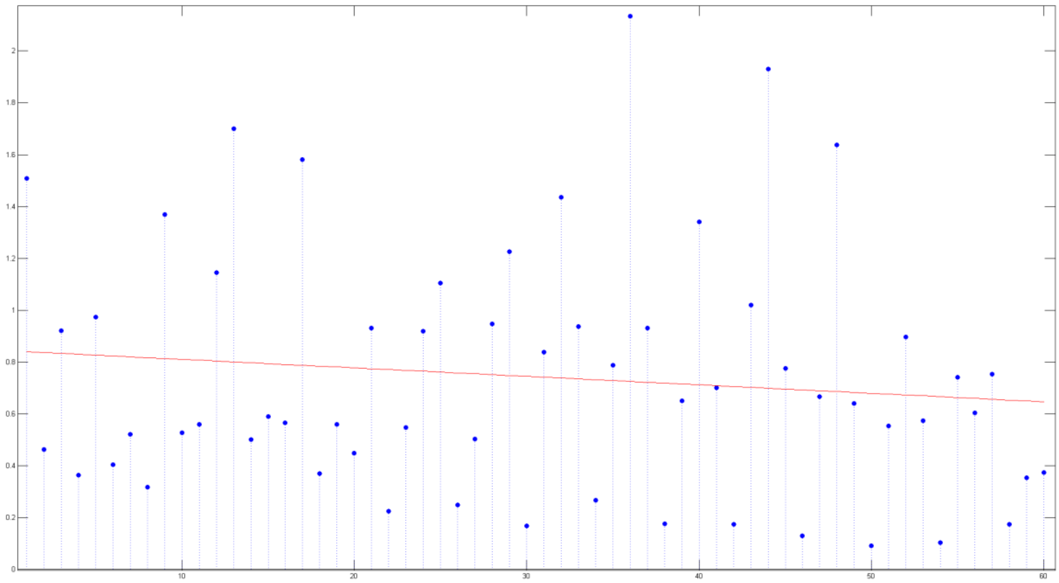
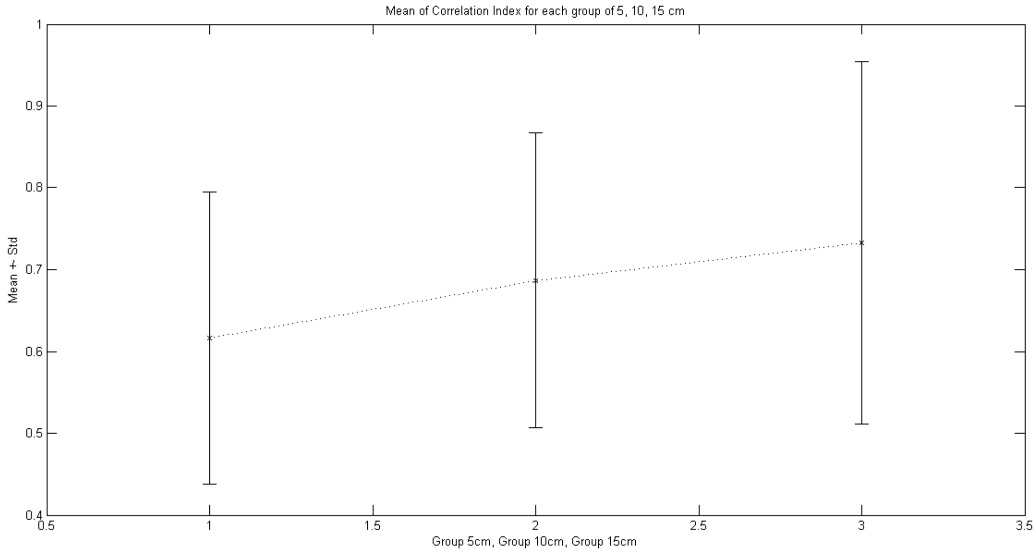
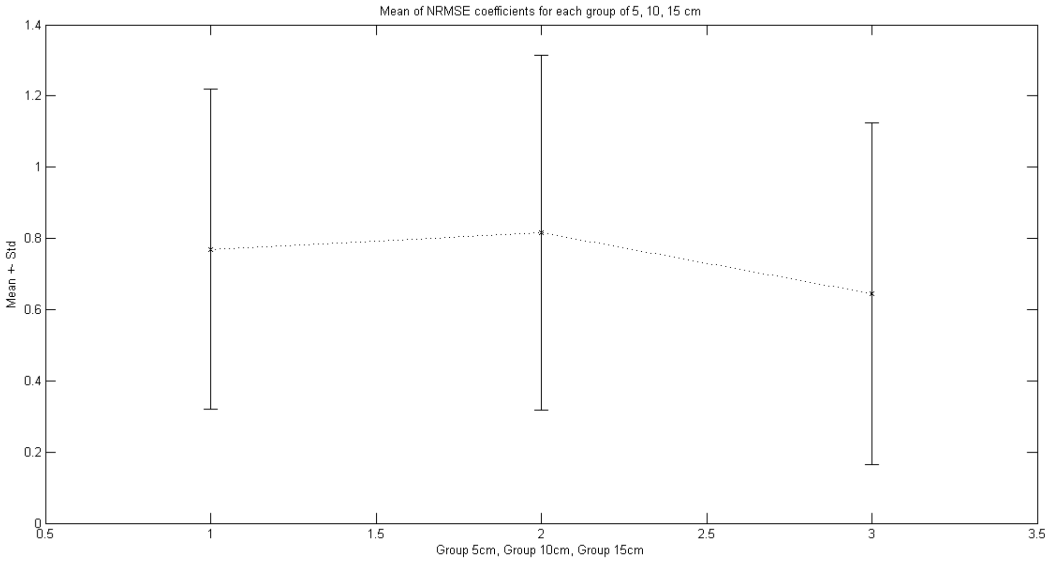


Figure V.28 – Subject n.5 , NRMSE coefficients for all the included sensors grouped for 5, 10 and 15cm of the radius



V.29 – Subject n.5 , Correlation index, mean ± std of group 5, 10 and 15cm



V.30 – Subject n.5 , Correlation index, mean ± std of group 5, 10 and 15cm

For each subject is possible to observe a positive trend regarding the correlation and a negative trend regarding the NRMSE.

The result show that the comparison between the movement done by the left arm that is simulating the side of the body injured, and the right arm that is simulating the unimpaired and reference arm for the training, confirm the efficacy of the introduction of EMG analysis during a rehabilitation training.

In order to have a general picture above all the subjects, the single result obtained were collected in one graph where for 5,10 and 15cm there are the trials of each subject. In the next graphs is possible to observe that merging the results of all the subjects, and for different movements, still there is a general positive trend for the correlation coefficients and the NRMSE is decreasing as long as the radius of the movement done by the left arm is getting bigger.

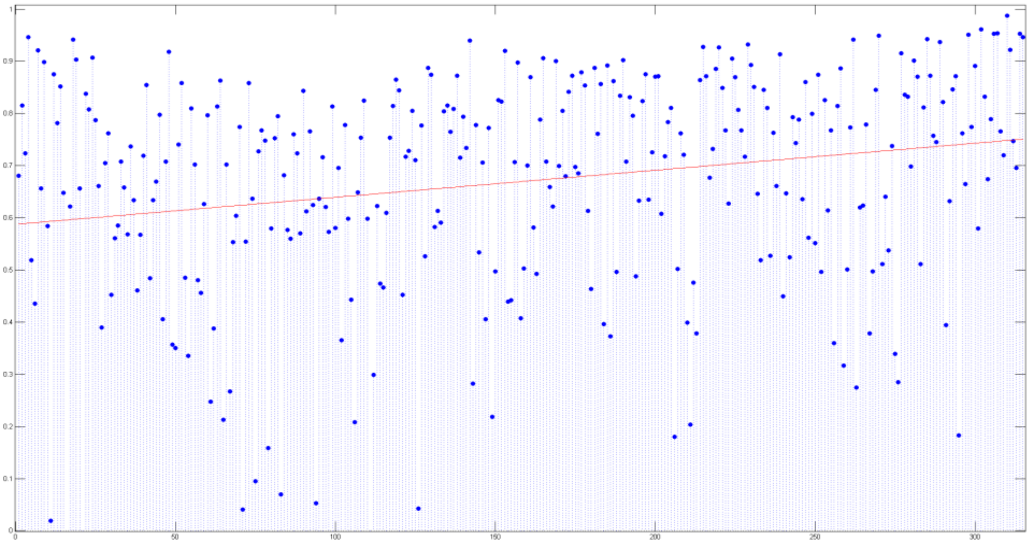


Figure V.31 – Correlation coefficient for all the subject grouped for 5, 10 and 15cm

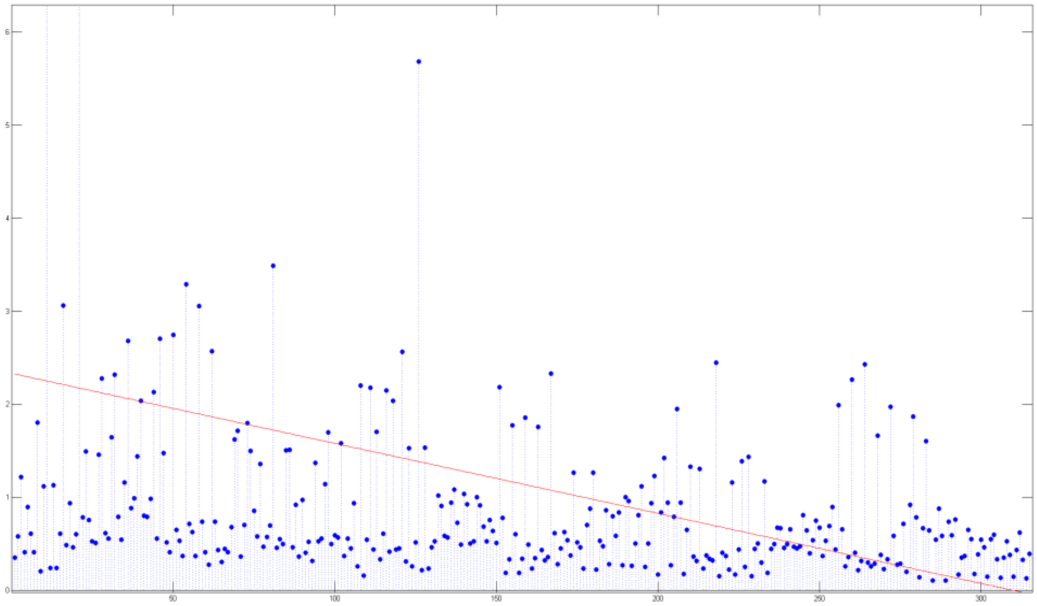


Figure V.32 – NRMSE coefficient for all the subject grouped for 5, 10 and 15cm

The next step is to evaluate the mean and the standard deviation along all the repetition and for only the included sensors, for each subject and on each group of 5, 10 and 15cm of radius.

The graphs below show again a positive trend for the Correlation and a negative trend for the NRMSE.

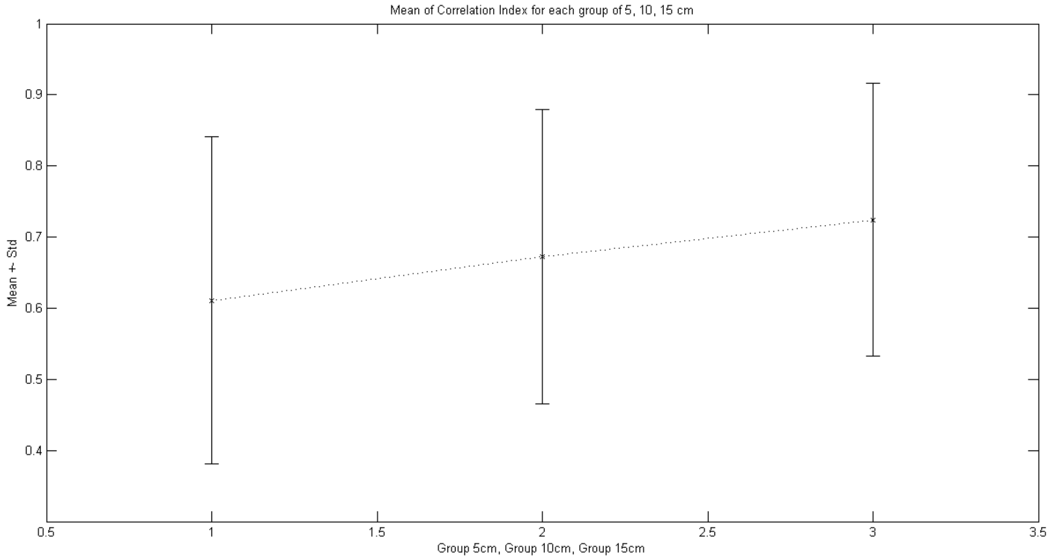


Figure V.33 – Trend of the Correlation index for all the subject, mean ± std

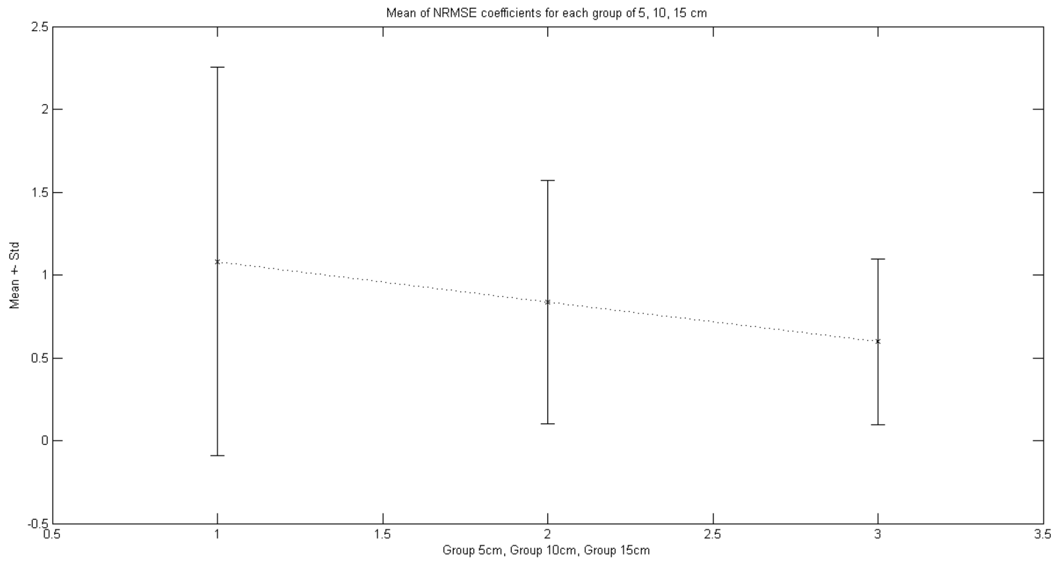


Figure V.34 – Trend of the NRMSE coefficients for all the subject, mean ± std

Now we focus only on the Correlation index.

The slope of the line showed before is positive but it’s interesting to permute randomly the elements in each group in order to understand if the slope remain positive.
After 50 random permutations in each group the slope of the line fitting is :
1e-3 * (0.4889 ± 0.0420). The slope is still positive.

The last important step is to verify if the results have a statistic relevance.

For this reason a statistical ***Student t-test*** [22] has been applied to the data. With the T-test is possible to understand if the growth of the mean is due to the “case” or because of the therapy.

All the correlation coefficients from the subjects were collected in a matrix and grouped for 5,10 and 15 cm. After the exclusion of some sensors for each subject, a matrix 105x3 is obtained, where 105 is the number of the correlation coefficients from all the subjects and 3 are the groups.

	Group 5cm	**Group 10cm**	**Group 15cm**
1	0.0188	0.6093	0.8488
2	0.6560	0.7105	0.8926
3	0.7616	0.8043	0.9139
…	…	…	…
105	0.4432	0.3994	0.9465
Mean	**0.6111**	**0.6726**	**0.7243**
Std Deviation	**0.2301**	**0.2070**	**0.1915**

The test has been repeated two times:

- The first between Group 5cm and 10cm.
  In this case **p=0.0109**.
- The second between Group 10cm and 15cm.
  In this case **p=0.0436.**

For both the results emerges a rejection of the null-hypothesis for less than 5%.

The Student t-test works on the hypothesis that pools of data come from a Gaussian distribution. To demonstrate this hypothesis a quantile-quantile plot (in Matlab *qqplot*) has been used to show the comparison between the distribution of the data and a straight line corresponding to a Gaussian distribution.

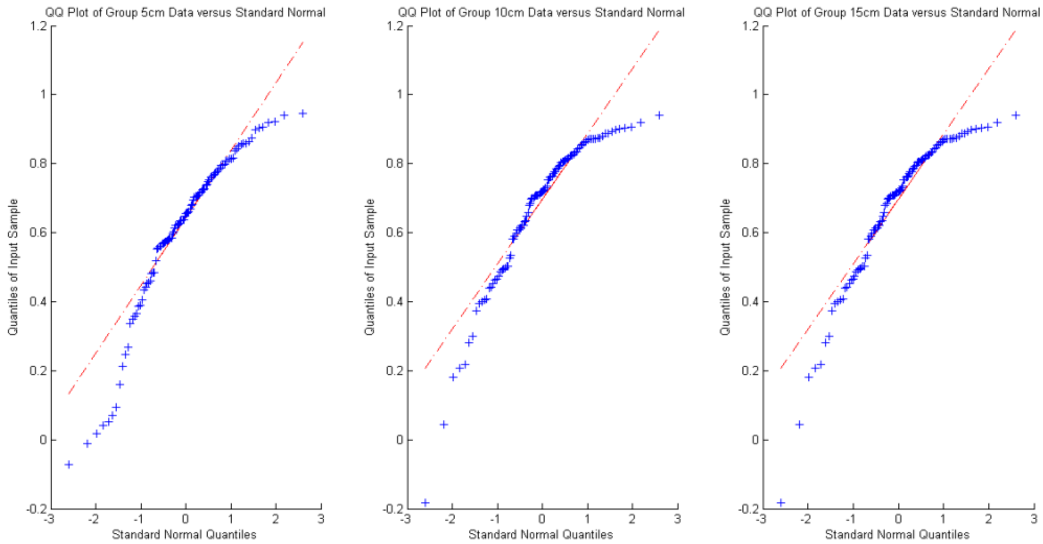


Figure V.35 – Quantile-quantile plot for each Group vs. Gaussian distribution

The distribution of the data from each group represent a "normal skewed distribution".

For this reason is more appropriate to use a ***Wilcoxon signed-rank test*** [23] that works on the hypothesis come from a skewed distribution.

The test has been repeated two times:

- The first between Group 5cm and 10cm.
  In this case **p=0.0247**.
- The second between Group 10cm and 15cm.
  In this case **p=0.0371.**

For both the results emerges a rejection of the null-hypothesis for less than 5%. We can assume that the growth of the mean from 0.6111 to 0.7243, and so the difference between these two numbers, is not due to the "case" but is statistically relevant.

References

1. World Health Organisation (1978). *Cerebrovascular Disorders (Offset Publications).*
2. http://en.wikipedia.org/wiki/Stroke#Care_and_rehabilitation.
3. A.D.A.M. Medical Encyclopedia, PubMed Health.
4. E. Selzer, S. Clarke, G. Cohen, W.Duncan, H.Gage, Text of neural repair, Cambridge U. Press.
5. Lotze M, Braun C, Birbaumer N, Anders S, Cohen LG: Motor learning elicited by voluntary drive**.** *Brain* 2003, 126(4):866-872.
6. Perez MA, Lungholt BK, Nyborg K, Nielsen JB: Motor skill training induces changes in the excitability of the leg cortical area in healthy humans. *Exp Brain Res.* 2004, 159(2):197-205.
7. M. Sivan , J. O'Connor , S. Makower , M. Levesley, B. Bhakta, Systematic review of outcome measures used in the evaluation of robot-assisted upper limb exercise in stroke, J Rehabil Med 2011; 43: 181–189.
8. Clinical trial n.NCT00372411, Robotic Assisted Upper-Limb Neurorehabilitation in Stroke Patients .

9. R. Brewer, K. McDowell,C. Worthen-Chaudhari, Poststroke Upper Extremity Rehabilitation:A Review of Robotic Systems and Clinical Results.
10. Luft AR, McCombe-Waller S, Whitall J, Forrester LW, Macko R, Sorkin JD, Schulz JB, Goldberg AP, Hanley DF. Repetitive bilateral arm training and motor cortex activa-tion in chronic stroke: a randomized controlled trial. JAMA. 2004;292(15):1853–61.
11. Lum PS, Reinkensmeyer DJ, Lehman SL. Robotic assist devices for bimanual physical therapy: preliminary experi-ments. IEEE Trans Rehabil Eng. 1993;1(3):185–91.
12. National Instrumens, Operating Instructions and Specifications NI 9205.
13. National Instrumens, User Guide and Specifications NI WLS/ENET-9163.
14. http://en.wikipedia.org/wiki/Electromyography.
15. M. B. I. Reaz,M. S. Hussain, F. Mohd-Yasin , Techniques of EMG signal analysis: detection, processing, classification and applications.
16. C. J. de Luca, Surface EMG:detection and recording , Delsys.
17. M. Zecca, S. Micera, M. C. Carrozza, P. Dario – Control of Multifunctional Prosthetic Hands by Processing the Electromyographic Signal.

18. Ascension Technology Corporation - Installation and Operation Guide .

19. Seniam Project - http://www.seniam.org/

20. Pearson Correlation Coefficient http://en.wikipedia.org/wiki/Pearson_product-moment_correlation_coefficient.

21. Root Mean Square - http://en.wikipedia.org/wiki/Root_mean_square_deviation

22. Student's_T-test - http://en.wikipedia.org/wiki/Student's_t-test

23. Wilcoxon signed-rank test - http://en.wikipedia.org/wiki/Wilcoxon_signed-rank_test

24. Taub, E; G Uswatte (1999). "Constraint-induced movement therapy: a new family of techniques with broad application to physical rehabilitation - a clinical review". *Journal of Rehabilitation Research & Development* 36 (3): 237–51.

25. Lin, K; C Wu, T Wei, C Lee, J Liu (2007). "Effects of modified constraint-induced movement therapy on reach-to-grasp movements and functional performance after chronic stroke: a randomized controlled study". *Clinical Rehabilitation* 21 (12): 1075–86.

26. Wolf, S; Carolee Winstein, J. Philip Miller, Edward Taub, Gitendra Uswatte, David Morris, Carol Giuliani, Kathye E. Light, Deborah Nichols-Larsen, (2006). "Effect of Constraint-Induced Movement Therapy on Upper Extremity Function 3 to 9 Months After Stroke". *The Journal of the American Medical Association* 296 (17): 2095–2104.

27. B. Lange, S. Flynn & A. Rizzo (2009). "Initial usability assessment of off-the-shelf video game consoles for clinical game-based motor rehabilitation". *Physical Therapy Reviews* 14 (5): 355–362.