Scuola Dottorale di Ingegneria
Sezione di Ingegneria dell'Elettronica Biomedica,
dell'Elettromagnetismo e delle Telecomunicazioni

XXV CICLO DEL CORSO DI DOTTORATO

Haptic Technologies for Dexterity and Smoothness in Hand Movements

Tecnologie Aptiche per la Destrezza e la Regolarità dei Movimenti della Mano

Ph.D. Student: Baldassarre D'Elia

Tutor: Prof. Tommaso D'Alessio

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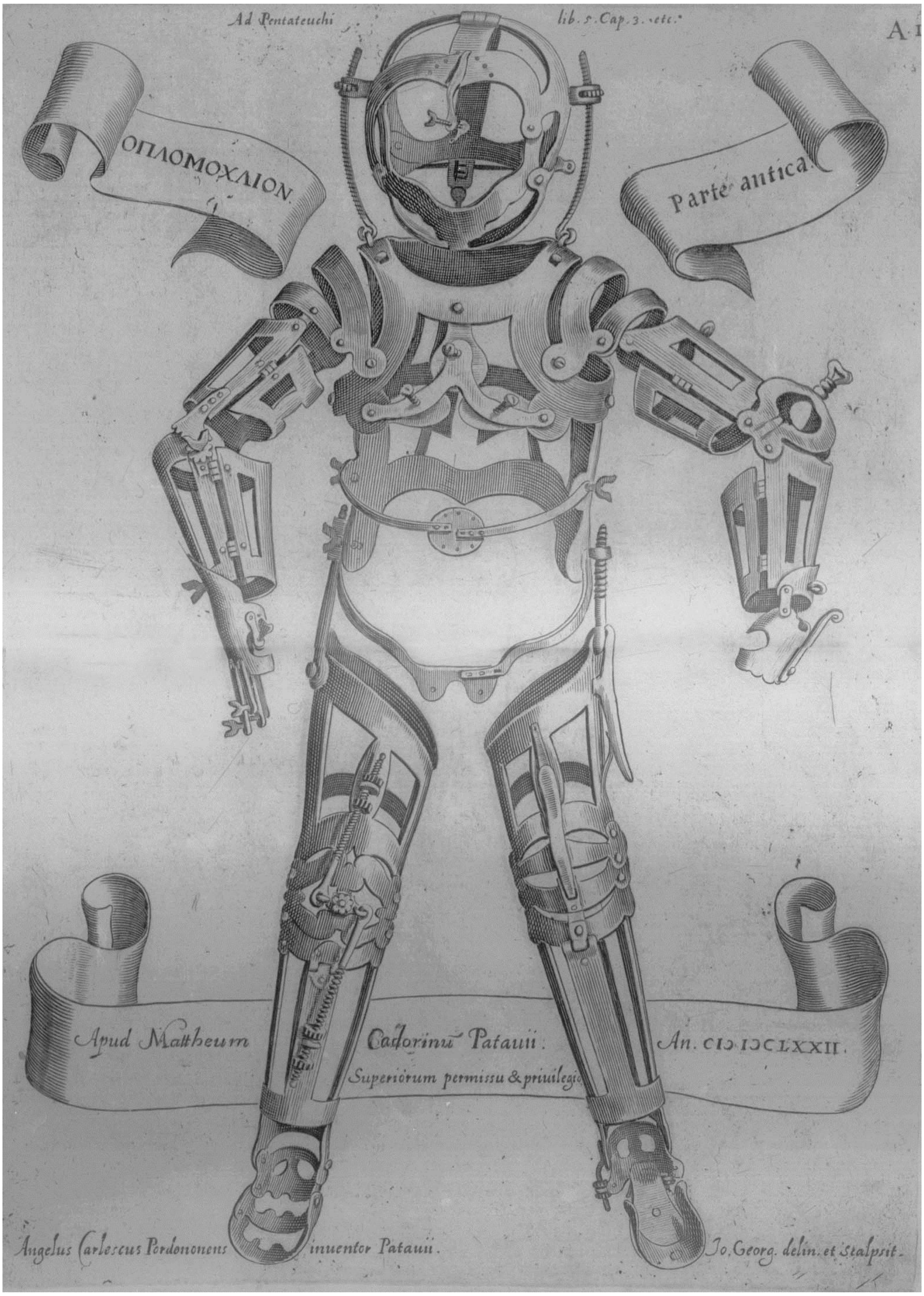
CONTENTS

To those who missed me during doctorate studies, this thesis too.



Thanks to the kindness of Mr. Paolo Granata and ITOP in Palestrina (Rome-Italy) for permission of including this print of a modern exoskeleton, the so called "Lo Smontato" – "The Disassembled"

INTRODUCTION

INTRODUCTION

Near the end of last century, a new class of electromechanical and robot-assisted systems has been introduced in clinic therapies aimed to arm training and neuro-rehabilitation of people suffering from upper limb motor control diseases, especially stroke patients, but the role of these systems for improving arm function after stroke is unclear. More recently, due to increasing in complexity and flexibility of systems and therapies, this innovative topic for research has been often called «Robot Mediated Therapy» (the acronym RMT will be used in the following). These systems are machines specialized to assist rehabilitation in practice; they are often based on a manipulator adapted to rehabilitations needings. Reviews of studies were done, aimed to assess the effectiveness of systems to improve activities of daily living, arm strength, functionality and motor control of stroke patients and the acceptability and safety of the therapy. It’s noticeable observing that more than two-thirds of patients have difficulties with reduced arm function. These reviews evaluated the results of this kind of therapy and concluded that systems for arm training did not improve activities of daily living of stroke patients. Nevertheless, systems for arm training may improve impaired motor function and strength of the paretic arm. It is, therefore, not clear if such devices are to be applied in routine rehabilitation, or when and how often they must be used. So it could be useful to introduce a new therapeutic system (in the following the term «system» will be used in brief) based on an commercial haptic interface and validate the results testing if an improvement of efficacy and efficiency could be obtained and at a better cost-effectiveness level. Depending on the mechanical characteristics of the haptic interface, the new system could complement or replace the systems in use nowadays. It’s very important to clarify that for the aim of this study the hand is considered as the upper limb extremity and only arm movements to drive the hand are taken into account, so there aren’t considerations about movement of fingers, such as in grasping.

Several kinds of diseases affecting brain, such as stroke, meningitis, injuries and Parkinson's, among others, can cause difficulties in arm motor control, strongly affecting everyday life of patients.

A high percentage, about 80%, of people affected by stroke events can survive the injury [A.S.A. http], but a lot of them are affected by consequences on language, motor control of limbs and other neuro-related functions. It has been estimated that about 1.100 000 people are struck in Europe, 750 000 in U.S.A. and 2 000 000 in China [Morasso 2010]. This figure in Italy rounds 200 000 people every year [Inizitari 2013], it's to say 0,3% of the whole population approximatively.

A physician defines a rehabilitation therapy, usually based on best practices, conducted by a physiotherapist; it lasts about 2 week in the U.S.A. and 2 months in Europe [Molinaro 2010]. As for many activities done by means of humans, in this kind of therapy it's not easy to reach a high level of measurability and repeatability, but therapists can interpret patients' needs and satisfy them with the flexibility given by their experience and professional resources. It's worthwhile to notice that different strategies can be used by the physiotherapist, one of them is the so called *"constraint induced"* approach [Morris 2006, Taub 2006 quoted in Barry 2009]: the debate about improvements and drawbacks of this approach is still open.

It's interesting to notice that during acute stroke phase, the rate of lost neuron is estimated to be one million per minute. To reduce death and loss of neurons due to stroke, therapy based on hemolytic drugs is considered to be the best practice in the acute phase [Inizitari 2013].

The chance to recover lost functions due to neural damage is allowed by a very important brain capacity: the so called «*neural plasticity*». It's based on recruitment of survived neural cells and formation of new synapses. In case of neuron located in the sensorimotor cortex [Bear 2007], there is another resource to be exploited: the rubrospinal pathway to conduct motor stimuli towards limbs

Neural plasticity has been invoked to explain another phenomenon: the “*phantom limb”* sensation that could be considered as the reversal situation of motor control impairment due to stroke. In fact in this syndrome there are neurons for motor control, but limb is missing; in the latter the limb is present but neurons are missing. Studies were done to control an artificial limb by means of neural signals, but it was observed that, after a certain period the limb is missed, neurons related to its motor control were recruited for other functions, creating new synapses with neurons belonging to other functional areas [Morabito 2011]. This consideration is one of the bases of the so called *«mobile maps»* theory.

A recent study about the influence of acoustic stimuli and noise on the therapy, pointed out that this kind of sensation may interfere with the execution of motor tasks influencing therapy results [Secoli 2011]; so this could be another aspect of this matter to be considered, possibly related with the existence of interneurons integrating informations coming from different functional areas of the brain.

In the late nineties [Krebs 1998] it was proposed the use of an electromechanical machine with a control system based on a computer program to train the arm. Developing this idea, the so called MIT-MANUS was built. Connecting the hand of the subject to be trained with the handle, the system allows the training of the arm. The training often consists doing some motor tasks on a flat horizontal surface. The tasks consist of making some movements of the hand drawing predefined trajectories. Typical trajectories are circles, eight-shapes or stars: the hand moves from a central point towards the outer zone of working space and then back to the central point, usually the star is made of 8 legs with an angular distance of about 45°. Usually circles must be repeated several times, a typical number of clockwise iterations is five and five more counterclockwise, ditto for eight-shape trajectory or stars when it takes sense. Items could be repeated with the patient closing eyes to restore, train and develop the proprioception.

During the arm movements the working space is divided in three zones: the free path, the virtual viscous area and the virtual wall. The free path is the area where the correct movement should be done. Exiting the free path, the system generates a force field creating a sensation of viscous braking so that the patient perceives this sensation as information to correct the trajectory and tries to enter the bed of free path. In case the hand moves too far from the free path, it encounters a "virtual wall", an area with a strong force field, higher than the force expressed by the trained person so that he can't move on. These sensations of viscosity and blocking pertain to the tactile perception and here is the reason why these systems are considered to be "haptic".

Moreover the system has sensors able to measure the force a patient can produce. Starting the therapy often this force level is very low, almost at a zero level or the motor control is unable to run the free path. In such conditions the machine can drag the hand and the whole limb, that are in a passive state, along the free path. Going on with the therapy protocol, the subject starts developing motor control and strength: as these abilities progress, the machine reduces the level of intervention allowing the trained person to meet the right contrast to his action. The «assistance as needed» (AAN in the following) criteria is widely considered to be satisfactory for this aim.

Along the therapy evolution some variables and related parameters can be calculated, such as position, speed, acceleration, jerk, force, rest time, and indicators can be extracted. Considerations based on statistical analysis of data and other physical entities can give information about developments and progresses in training and therapy.

During the last decade, other groups of researcher developed similar systems. Here is a list of several of them:

- MIME [Burgar 2000];
- ARM Guide [Reinkensmeyer 2000];
- Bi-Manu-Track [Hesse 2003];
- GENTLE/S [Coote 2003];
- ARMin [Riener 2005]
- BRACCIO DI FERRO [Casadio 2006]
- REHAROB [Fazekas 2007];
- NeReBot the Neuro-Rehabilitation-Robot [Masiero 2007]
- ARMEO [Gijbels et al. 2011].

For haptic systems in general, it's common to be based on a computer and to be coupled with visual information, so that the main program has to run a haptic thread and a visual thread. In case the influence of acoustic stimuli on the execution of motor tasks will be confirmed [Secoli 2011], it could be useful to introduce an acoustic thread too.

As usual, visual informations are shown on a screen: e.g. the exercise to do, a scheme of the working space, results of kinetic parameters (position, velocity, acceleration, jerk, force, rest time), data about the population under training and statistics among others.

The haptic thread has to timely manage both the control of actuators and the information coming from sensors.

The number of segments, joints and actuators depends on kinematics chosen to implement the desired trajectories of handle or handles. Actuators are often located at the joint of segments to generate the needed couples.

A few years ago, a review [Mehrholz 2008] was done, aimed to assess the effectiveness of electromechanical and robot-assisted systems for arm training to improve activities of daily living, arm strength, functionality and motor control of stroke patients, together with the acceptability and safety of the therapy. According to this review more than two-thirds of patients have difficulties with reduced arm function. Electromechanical and robot-assisted arm training are specialized machines to assist rehabilitation in clinical practice, basic features of which have been exposed in the previous chapter.

This review reviewed 11 trials, which included a total amount of 328 participants, to evaluate the results of this kind of therapy and concluded that systems for arm training did not improve activities of daily living of post-stroke people.

Strategy of this research was to search in the Cochrane Stroke Group Trials Register (October 2007), the Cochrane Central Register of Controlled Trials (*The Cochrane Library*, Issue 3, 2007), MEDLINE (1950 to October 2007), EMBASE (1980 to October 2007), CINAHL (1982 to October 2007), AMED (1985 to October 2007), SPORTDiscus (1949 to October 2007), PEDro (searched October 2007), COMPENDEX (1972 to October 2007) and INSPEC (1969 to October 2007). Other relevant conference proceedings were also hand searched and searched trials and research registers too; they checked reference lists, and contacted trialists, experts and researchers in this field, and manufacturers of commercial devices.

The selection criteria they chose preferred randomized controlled trials comparing electromechanical and robot-assisted arm training for the recovery of arm function with other rehabilitation interventions, like the ones conducted by physiotherapists, or no treatment for patients after stroke.

For data collection and analysis, two authors independently selected trials for inclusion, assessed trial quality and extracted data. They contacted trialists for additional information when needed.

The results were elaborated using standardized mean differences (SMDs) for continuous variables and relative risk differences (RD) for dichotomous variables.

Finally 11 trials, involving 328 participants, were selected and included in that review. Results showed that systems did not improve activities of daily living but arm motor function and strength improved. Electromechanical and robot-assisted arm training did not increase the risk of patients to drop out, and adverse events were rare.

On the basis of these results and according to authors' considerations and conclusions, patients who receive electromechanical and robot-assisted arm training after stroke seem not more likely to improve their activities of daily living. Nevertheless, system arm training may improve impaired motor function and strength of the paretic arm, but it is not clear if such devices should be applied in routine rehabilitation, or when and how often they should be used.

However, the results must be interpreted with caution because there were variations between the trials in the duration, amount of training and type of treatment and in the patient characteristics.

In a more recent study [Lo 2010] conclusions are drawn stating that in patients with long-term upper-limb deficits after stroke, robot-assisted therapy did not significantly improve motor function after 12 weeks, as compared with standard therapy or intensive therapy. In secondary analyses, robot-assisted therapy improved outcomes over 36 weeks as compared with standard therapy but not with intensive therapy.

To improve efficacy and efficiency in therapy at a better cost-effectiveness level, it could be useful to study and introduce a therapeutic system (the term «system» will be used in brief) based on a parallel haptic interface. Depending on the mechanical characteristics of the haptic interface, this system could complement or replace the systems in use nowadays. In this research the parallel haptic interface adopted is the «Falcon» by Novint®, developed and introduced on the market mainly for gaming purposes.

Many of the systems allow only two-dimensional («2D» in the following) movement of the handle on a plane horizontal surface: a desktop is a typical space for simulation where the hand moves to write, to draw or to use a computer mouse. However, in everyday life activities, patients normally do movements in three-dimensional («3D» in the following) space: the new system should thus be able to allow three-dimensional motor tasks.

The differences of neural correlates between horizontal and vertical movements of arm [Chao et al. 2010] show that motor control features may significantly vary when vertical forces due to objects and arm weight comes into play.

Very often in daily life activities, 3D movements with common objects had to be done against the vertical force of objects weight: the simulation of this condition should be an added feature of a new system.

Moreover information about object manipulation comes from touch too: simulating the object surface, outer texture, shape and gravitational behavior too, should be another haptic feature for a new system.

Another interesting aspect could be the introduction of an acoustic thread during object manipulation training.

On the basis of the reviewed research and studies on the principal systems designed, built up and introduced in therapies, it’s possible to conclude that this new class of machines is a useful tool for neuro-rehabilitation. In some aspects they show better features in comparison with human therapy, but they could more likely complement and integrate the activities of physiotherapists than replace them. Nevertheless some critical aspects in the clinical use are still to be clarified, so further investigations are needed to improve efficacy and efficiency of these systems. A new design of machine or the use of innovative haptic interfaces could be useful to reach this important aim.

Aim of the Project

The general aim of the research project is to build up an innovative system for upper limb rehabilitation of stroke individuals based on a haptic interface. To do so, once the system is built up, it must be tested in feasibility study to ascertain if design features are usable, stable and repeatable. After passing the feasibility study tests, it was used to collect data on healthy subject. The last thread to reach the aim of the project is the clinical validation on stroke individuals to test the influence of system features on efficacy and efficiency in rehabilitation therapy.

To reach the general aim these three objectives can be established:

1) to set up the system:
2) to test the system on healthy subjects;
3) to validate the system by clinical study.

The system set up will be exposed more in details in the following and the same will be done for the test protocol (see chapter 3, paragraph on experimental set up and protocol).

The clinical validation is not done yet and still remains for further investigations to complete the project.

In the first chapter some aspects of the stroke will be presented.

In the second chapter the haptic sense and the haptic technologies will be introduced.

The third chapter is for the system and the fourth shows an analysis of collected data.

In the last chapter some conclusions are drawn about the state of the project and results obtained.

CHAPTER I

The Stroke

«may my right hand forget its skill.

May my tongue cling to the roof of my mouth»

Psalm 137, 5 & 6 (NIV), The Bible, 1500 b.c. - 300 a.c.

CHAPTER I

1.1 The Stroke

Several brain disorders can cause difficulties in motor control, affecting everyday life quality of patients. Among them, stroke is the leading cause of disability, as its prevalence is around 3 percent of the population. It has been estimated that about 1 100 000 people are struck in Europe, 750 000 in U.S.A. and 2 000 000 in China [Vergaro et al. 2009]. The survival rate exceeds 80% [Roger et al. 2012]. Most stroke survivors can experience consequences on language, motor control of limbs and other functions associated with neural activity.

Episodes of stroke and familial stroke have been reported from the 2nd millennium BC onward in ancient Mesopotamia and Persia. Hippocrates (460 to 370 BC) was first to describe the phenomenon of sudden paralysis that is often associated with ischemia. Apoplexy, from the Greek word meaning «struck down with violence» first appeared in Hippocratic writings to describe this phenomenon. The word stroke was used as a synonym for apoplectic seizure as early as 1599, and is a fairly literal translation of the Greek term.

In 1658, in his “Apoplexia”, Johann Jacob Wepfer (1620–1695) identified the cause of hemorrhagic stroke when he suggested that people who had died of apoplexy had bleeding in their brains. Wepfer also identified the main arteries supplying the brain, the vertebral and carotid arteries, and identified the cause of ischemic stroke, also known as cerebral infarction, when he suggested that apoplexy might be caused by a blockage to those vessels.

Rudolf Virchow first described the mechanism of thromboembolism as a major factor.

When dealing with an individual who survived a stroke, after the acute treatment a physiatrist defines a rehabilitation therapy, which is usually based on best practices. Rehabilitation is conducted by a physical therapist; the duration of these procedures can last up to few months [Taub et al. 2006]. As for many human-mediated activities, in this kind of therapy it is not always easy to reach a high level of measurability and repeatability, but therapists can interpret patients' needs and satisfy them with the flexibility given by their experience and professional skills. Different strategies can be used by the physical therapist, and there is an open debate about which paradigm is most effective: among others, the most popular is the so-called «constraint induced movement therapy» [Barry 2009], whose improvements and drawbacks [Morris et al. 2006] are object of discussion in the scientific community [Nudo RJ, Wise BM, Sifuentes et al. 1996].

The chances to recover lost functions due to neural damage are allowed by a very important brain capacity: the so-called «neural plasticity» [Bear et al. 2001] that is based on recruitment of survived neural cells and formation of new synapses. In the case of neurons located in the sensorimotor cortex [Bear et al. 2007] there is another resource to be exploited: the rubrospinal pathway to conduct motor stimuli towards limbs.

Neural plasticity has been invoked to explain other phenomena: for instance, the «phantom limb» sensation that could be considered as the reversal situation of motor control impairment due to stroke. In fact, in this syndrome, the neurons deployed for motor control are present, but limb is missing; in the latter the limb is present but neurons are missing. Neural plasticity also plays a major role when individuals are asked to perform motor tasks in novel environmental conditions, such as altered force fields [Cai et al. 2006], or visual distortions [Secoli et al. 2011]. Following this principle, studies were done to control an artificial limb by means of neural signals or by hypothesizing functional electrical stimulation driven by appropriate neural commands based on the sound. However, it was observed that, after a certain period the limb is missed, neurons related to its motor control are recruited for other functions, creating new synapses with neurons belonging to other functional areas. This occurrence is at the basis of the so-called «mobile maps» theory. Different models able to interpret the neural correlates associated with motor behavior have been proposed in the literature, thus confirming the importance of this field in the research community. These models have also been used in other different research fields.

Stroke is often caused by accumulation of blood anywhere within the skull vault, the medical term for this cause is «intracranial hemorrhage». A distinction is made between blood inside the brain, intra-axial hemorrhage, and blood inside the skull but outside the brain, extra-axial hemorrhage. Intra-axial hemorrhage is due to blood in the ventricular system, intraparenchymal hemorrhage or intraventricular hemorrhage. The main types of extra-axial hemorrhage are bleeding between the dura mater and the skull, epidural hematoma, in the subdural space, subdural hematoma, and between the arachnoid mater and pia mater, subarachnoid hemorrhage. Most of the hemorrhagic stroke syndromes have specific symptoms, e.g., headache or previous head injury.

Stroke symptoms typically start suddenly, over seconds to minutes, and in most cases do not progress further. The symptoms depend on the area of the brain affected. The more extensive the area of brain affected, the more functions that are likely to be lost. Some forms of stroke can cause additional symptoms. For example, in intracranial hemorrhage, the affected area may compress other structures. Most forms of stroke are not associated with headache, apart from subarachnoid hemorrhage and cerebral venous thrombosis and occasionally intracerebral hemorrhage (ICH).

The early recognition is a very important aspect to save the affected individual and to reduce at the lowest possible consequences of stroke. Various systems have been proposed to increase recognition of stroke. Different findings are able to predict the presence or absence of stroke to different degrees. Sudden-onset face weakness, arm drift, i.e. if a person, when asked to raise both arms, involuntarily lets one arm drift downward, and abnormal speech are the findings most likely to lead to the correct identification of a case of stroke increasing the likelihood by 5.5 when at least one of these is present. Similarly, when all three of these are absent, the likelihood of stroke is significantly decreased: likelihood ratio is 0.39 [Goldstein LB & Simel DL 2005]. While these findings are not perfect for diagnosing stroke, the fact that they can be evaluated relatively rapidly and easily make them very valuable in the acute setting.

A proposed systems for early recognition include four semeiotic sign: face, arm, speech and time, often termed with their acronym FAST [Harbison J. et al. 1999]., as advocated by the Department of Health and the Stroke Association in United Kingdom, the American Stroke Association, the National Stroke Association (US), the Los Angeles Prehospital Stroke Screen (LAPSS) and the Cincinnati Prehospital Stroke Scale (CPSS). Use of these scales is recommended by professional guidelines [National Institute for Health and Clinical Excellence 2008].

For people referred to the emergency room, early recognition of stroke is deemed important as this can expedite diagnostic tests and treatments. A scoring system called «recognition of stroke in the emergency room», ROSIER, is recommended for this purpose; it is based on features from anamnesis, the medical history, and physical examination.

The stroke can be classified on the basis of different aspects, the hemorrhagic location is of prevalent interest. If the area of the brain affected contains one of the three prominent central nervous system pathways, the spinothalamic tract, corticospinal tract and dorsal column medial lemniscus, symptoms may include:

- hemiplegia and muscle weakness of the face
- numbness

- reduction in sensory or vibratory sensation
- initial flaccidity (hypotonicity), replaced by spasticity (hypertonicity), hyperreflexia, and obligatory synergies [O'Sullivan S.B. 2007].

In most cases, the symptoms are unilateral: they 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. However, since these pathways also travel in the spinal cord and any lesion there can also produce these symptoms, the presence of any one of these symptoms does not necessarily indicate a stroke.

In addition to the above CNS pathways, the brainstem gives rise to most of the twelve cranial nerves. A stroke affecting the brain stem and brain therefore can produce symptoms relating to deficits in these cranial nerves:

- altered smell, taste, hearing or vision, total or partial
- drooping of eyelid, ptosis, and weakness of ocular muscles
- decreased reflexes: gag, swallow, pupil reactivity to light
- decreased sensation and muscle weakness of the face
- balance problems and nystagmus
- altered breathing and heart rate
- weakness in sternocleidomastoid muscle with inability to turn head to one side
- weakness in tongue, inability to protrude it and/or move it from side to side.

If the cerebral cortex is involved, the CNS pathways can again be affected, but also can produce the following symptoms:

- aphasia (difficulty with verbal expression, auditory comprehension, reading and/or writing Broca's or Wernicke's area typically involved)
- dysarthria (motor speech disorder resulting from neurological injury)
- apraxia (altered voluntary movements)
- visual field defect
- memory deficits due to involvement of temporal lobe
- hemineglect due to involvement of parietal lobe
- disorganized thinking, confusion, hypersexual gestures with involvement of frontal lobe
- lack of insight of his or her disability usually stroke-related.

If the cerebellum is involved, the patient may have one or more of the following symptoms:

- altered walking gait
- altered movement coordination
- vertigo and or disequilibrium

Associated symptoms of stroke may be: loss of consciousness, headache and vomiting that usually occurs more often in hemorrhagic stroke than in thrombosis because of the increased intracranial pressure from the leaking blood compressing the brain.

If symptoms are maximal at onset, the cause is more likely to be a subarachnoid hemorrhage or an embolic stroke.

If classified focusing on causes, the stroke can be thrombotic, embolic, cardiac or systemic hypoperfusion.

Thrombotic stroke

In thrombotic stroke a blood clot, in medical term called «thrombus» usually forms around atherosclerotic plaques. Since blockage of the artery is gradual, onset of symptomatic thrombotic strokes is slower. A thrombus itself, even if non-occluding, can lead to an embolic stroke when the thrombus breaks off, at which point it is called an «embolus». Two types of thrombosis can cause stroke and they can be large or small vessel disease.

Large vessel disease involves the common and internal carotids, vertebral, and the Circle of Willis. Diseases that may form thrombi in the large vessels include, in order of descending incidence: atherosclerosis, tightening of the artery or «vasoconstriction», aortic, carotid or vertebral artery dissection, various inflammatory diseases of the blood vessel wall such as Takayasu arteritis, giant cell arteritis, vacuities, non-inflammatory vasculopathy, Moyamoya disease and fibromuscular dysplasia.

Small vessel disease involves the smaller arteries inside the brain: branches of the circle of Willis, middle cerebral artery, stem, and arteries arising from the distal vertebral and basilar artery. Diseases that may form thrombi in the small vessels include in order of descending incidence: build-up of fatty hyaline matter in the blood vessel as a result of high blood pressure and aging called «lipohyalinosis» and fibrinoid degeneration, the stroke involving these vessels is known as lacunar infarct, and small atherosclerotic plaques called «microatheroma».

Sickle-cell anemia, which can cause blood cells to clump up and block blood vessels, can also lead to stroke. A stroke is the second leading killer of people under 20 who suffer from sickle-cell anemia [National Institute of Neurological Disorders and Stroke - NINDS - 1999].

Embolic stroke

An embolic stroke refers to the blockage of an artery by an arterial embolus, a travelling particle or debris in the arterial bloodstream originating from elsewhere. An embolus is most frequently a thrombus, but it can also be a number of other substances including fat, e.g. from bone marrow in a broken bone, air, cancer cells or clumps of bacteria, usually from infectious endocarditis.

Because an embolus arises from elsewhere, local therapy solves the problem only temporarily. Thus, the source of the embolus must be identified. Because the embolic blockage is sudden in onset, symptoms usually are maximal at start. Also, symptoms may be transient as the embolus is partially resorbed and moves to a different location or dissipates altogether.

Emboli most commonly arise from the heart, especially in atrial fibrillation, but may originate from elsewhere in the arterial tree. In paradoxical embolism, a deep vein thrombosis embolises through an atrial or ventricular septal defect in the heart into the brain.

Focusing on cardiac causes, they can be distinguished between high or low-risk type [Ay H. 2005].

High risk causes are: atrial fibrillation and paroxysmal atrial fibrillation, rheumatic disease of the mitral or aortic valve disease, artificial heart valves, known cardiac thrombus of the atrium or ventricle, sick sinus syndrome, sustained atrial flutter, recent myocardial infarction, chronic myocardial infarction together with ejection fraction higher than 28%, symptomatic congestive heart failure with ejection fraction higher than 30%, dilated cardiomyopathy, Libman-Sacks endocarditis, marantic endocarditis, infective endocarditis, papillary fibroelastoma, left atrial myxoma and coronary artery bypass graft (CABG) surgery.

Low risk/potential: calcification of the ring, annulus, of the mitral valve, patent foramen ovale (PFO), atrial septal aneurysm, atrial septal aneurysm with patent foramen ovale, left ventricular aneurysm without thrombus, isolated left atrial «smoke» on echocardiography without mitral stenosis or atrial fibrillation), complex atheroma in the ascending aorta or proximal arch.

Systemic hypoperfusion

Systemic hypoperfusion is the reduction of blood flow to all parts of the body. It is most commonly due to heart failure from cardiac arrest or arrhythmias, or from reduced cardiac output as a result of myocardial infarction, pulmonary embolism, pericardial effusion, or bleeding. Low blood oxygen content, hypoxemia, may precipitate the hypoperfusion. Because the reduction in blood flow is global, all parts of the brain may be affected, especially «watershed» areas, it's to say a border zone regions supplied by the major cerebral arteries. A watershed stroke refers to the condition when blood supply to these areas is compromised. Blood flow to these areas does not necessarily stop, but instead it may lessen to the point where brain damage can occur.

Venous thrombosis

Cerebral venous sinus thrombosis leads to stroke due to locally increased venous pressure, which exceeds the pressure generated by the arteries. Infarcts are more likely to undergo hemorrhagic transformation, leaking of blood into the damaged area, than other types of ischemic stroke.

Intracerebral hemorrhage

It generally occurs in small arteries or arterioles and is commonly due to hypertension, intracranial vascular malformations (including cavernous angiomas or arteriovenous malformations), cerebral amyloid angiopathy or infarcts into which secondary haemorrhage has occurred. Other potential causes are trauma, bleeding disorders, amyloid angiopathy, drug use, especially amphetamines or cocaine. The hematoma enlarges until pressure from surrounding tissue limits its growth, or until it decompresses by emptying into the ventricular system, CSF or the pial surface. A third of intracerebral bleed is into the brain's ventricles. ICH has a mortality rate of 44 percent after 30 days, higher than ischemic stroke or subarachnoid hemorrhage, which may be classified as a type of stroke too.

Silent stroke

A silent stroke is a stroke that does not have any outward symptoms, and the patients are typically unaware they have suffered a stroke. Despite not causing identifiable symptoms, a silent stroke still causes damage to the brain, and places the patient at increased risk for both transient ischemic attack and major stroke in the future. Conversely, those who have suffered a major stroke are also at risk of having silent strokes. In a broad study in 1998, more than 11 million people were estimated to have experienced a stroke in the United States. Approximately 770,000 of these strokes were symptomatic and 11 million were first-ever silent MRI infarcts or hemorrhages. Silent strokes typically cause lesions which are detected via the use of neuroimaging such as MRI. Silent strokes are estimated to occur at five times the rate of symptomatic strokes. The risk of silent stroke increases with age, but may also affect younger adults and children, especially those with acute anemia.

1.2 Rehabilitation Therapy

The primary goals of stroke management are to reduce brain injury and promote maximum patient recovery. Rapid detection and appropriate emergency medical care are essential for optimizing health outcomes. When available, patients are admitted to an acute stroke unit for treatment. These units specialize in providing medical and surgical care aimed at stabilizing the patient's medical status. Standardized assessments are also performed to aid in the development of an appropriate care plan. Current research suggests that stroke units may be effective in reducing in-hospital fatality rates and the length of hospital stays.

Once a patient is medically stable, the focus of their recovery shifts to rehabilitation. Some patients are transferred to in-patient rehabilitation programs, while others may be referred to out-patient services or home-based care. In-patient programs are usually facilitated by an interdisciplinary team that may include a physician, nurse, physical therapist, occupational therapist, speech and language pathologist,psychologist, and recreation therapist. The patient and their family/caregivers also play an integral role on this team. The primary goals of this sub-acute phase of recovery include preventing secondary health complications, minimizing impairments, and achieving functional goals that promote independence in activities of daily living.

In the later phases of stroke recovery, patients are encouraged to participate in secondary prevention programs for stroke. Follow-up is usually facilitated by the patient's primary care provider.

The initial severity of impairments and individual characteristics, such as motivation, social support, and learning ability, are key predictors of stroke recovery outcomes. Responses to treatment and overall recovery of function are highly dependent on the individual. Current evidence indicates that most significant recovery gains will occur within the first 12 weeks following a stroke.

Knowledge of stroke and the process of recovery after stroke has developed enormously in the late 20th century and early 21st century. It was not until the year 1620 that Johan Wepfer, by studying the brain of a pig, came up with the theory that stroke was caused by an interruption of the flow of blood to the brain. This was an important breakthrough, but once the cause of strokes was known, the question became how to treat patients with stroke.

For most of the last century, people were actually discouraged from being active after a stroke. Around the 1950s, this attitude changed, and health professionals began prescription of therapeutic exercises for stroke patient with good results. Still, a good outcome was considered to be achieving a level of independence in which patients are able to transfer from the bed to the wheelchair without assistance. This was still a fairly bleak outlook, but the situation was improving.

In the early 1950s, Twitchell began studying the pattern of recovery in stroke patients. He reported on 121 patients he had observed. He found that by four weeks, if there is some recovery of hand function, there is a 70% chance of making a full or good recovery. He reported that most recovery happens in the first three months, and only minor recovery occurs after six months. More recent research has demonstrated that significant improvement can be made years after the stroke.

Around the same time, Brunnstrom also described the process of recovery, and divided the process into seven stages. As knowledge of the science of brain recovery improves, methods of intervening have evolved. There will be a continued fundamental shift in the processes used to facilitate stroke recovery.

One of the widely adopted therapies is the so called «constraint-induced» therapy.

The idea for constraint-induced therapy is actually at least 100 years old. Significant research was carried out by Robert Oden. He was able to simulate a stroke in a monkey's brain, causing hemiplegia. He then bound up the monkey's good arm, and forced the monkey to use his bad arm, and observed what happened. After two weeks of this therapy, the monkeys were able to use their once hemiplegic arms again. This is due to neuroplasticity. He did the same experiment without binding the arms, and waited six months past their injury. The monkeys without the intervention were not able to use the affected arm even six months later. In 1918, this study was published, but it received little attention.

Eventually, researchers began to apply his technique to stroke patients, and it came to be called constraint-induced movement therapy. Notably, the initial studies focused on chronic stroke patients who were more than 12 months past their stroke. This challenged the belief held at that time that no recovery will occur after one year. The therapy entails wearing a soft mitt on the good hand for 90% of the waking hours, forcing use of the affected hand. The patients undergo intense one-on-one therapy for six to eight hours per day for two weeks.

Evidence that supports the use of constraint-induced movement therapy has been growing since its introduction as an alternative treatment method for upper limb motor deficits found in stroke populations. Recently, constraint induced movement therapy has been shown to be an effective rehabilitation technique at varying stages of stroke recovery to improve upper limb motor function and use during daily activities of living. The greatest gains are seen among persons with stroke who exhibit some wrist and finger extension in the affected limb. Transcranial magnetic stimulation and brain imaging studies have demonstrated that the brain undergoes plastic changes in function and structure in patients that perform constraint-induced movement therapy. These changes accompany the gains in motor function of the paretic upper limb. However, there is no established causal link between observed changes in brain function or structure and the motor gains due to constraint induced movement therapy.

Another therapeutic approach makes use of mental practice and or mental imagery. Mental practice of movements has been shown in many studies to be effective in promoting recovery of both arm and leg function after a stroke. It is often used by physical or occupational therapists in the rehab or home health setting, but can also be used as part of a patient's independent home exercise program. Mental Movement Therapy is a tool available for assisting patients with guided mental imagery.

Electro stimulation is another tool under study. Such approach represents a paradigm shift towards rehabilitation of the stroke-injured brain away from pharmacologic flooding of neuronal receptors, instead towards targeted physiologic stimulation. Electrical stimulation mimics the action of healthy muscle to improve function and aid in retraining weak muscles and normal movement. Functional Electrical Stimulation (FES) is commonly used in «foot-drop» , one of the typical consequences affecting stroke patients gait, but it can be used to help retrain movement in the arms or legs too.

In patients undergoing rehabilitation with a stroke population or other central nervous system disorders such as cerebral palsy, Bobath, also known as Neurodevelopmental Treatment (NDT), is often the treatment of choice in North America. The Bobath concept is best viewed as a framework for interpretation and problem solving of the individual patient’s presentation, along with their potential for improvement. Components of motor control that are specifically emphasized are the integration of postural control and task performance, the control of selective movement for the production of coordinated sequences of movement and the contribution of sensory inputs to motor control and motor learning. Task practice is a component of a broad approach to treatment that includes in-depth assessment of the movement strategies utilized by the patient to perform tasks and identification of specific deficits of neurological and neuromuscular functions. Many studies have been conducted comparing NDT with other treatment techniques such as proprioceptive neuromuscular facilitation (PNF stretching), as well as conventional treatment approaches utilizing traditional exercises and functional activities. Despite being so widely used, based on the literature, NDT has failed to demonstrate any superiority over other treatment techniques available. In fact, the techniques compared with NDT in these studies often produce similar results in terms of treatment effectiveness. Research has demonstrated significant findings for all these treatment approaches when compared with control subjects and indicate that overall, rehabilitation is effective. It is important to note, however, that the NDT philosophy of «do what works best» has led to a lot of heterogeneity in the literature in terms of what constitutes as a NDT technique, thus making it difficult to directly compare to other techniques.

Mirror therapy (MT) is an innovative way to help in treating stroke patients and has been employed with some success to recover their motor capabilities. Clinical studies that have combined mirror therapy with conventional rehabilitation have achieved the most positive outcomes. However there is no clear consensus as to its effectiveness. In a recent survey of the published research it was concluded that: «In stroke patients, we found a moderate quality of evidence that MT as an additional therapy improves recovery of arm function after stroke. The quality of evidence regarding the effects of MT on the recovery of lower limb functions is still low, with only one study reporting effects. In patients with CRPS and PLP, the quality of evidence is also low.» [Rothgangel et al. 2011] .

Among other non-pharmacologic therapies, training of muscles affected by the Upper Motor Neuron Syndrome (UMNS) is one of the most relevant. Muscles affected by the Upper Motor Neuron Syndrome have many potential features of altered performance including weakness, decreased motor control, clonus, it’s to say a series of involuntary rapid muscle contractions, exaggerated deep tendon reflexes, spasticity and decreased endurance. The term «spasticity» is often erroneously used interchangeably with Upper Motor Neuron Syndrome and it is not unusual to see patients labeled as spastic who demonstrate an array of UMN findings.

It has been estimated that approximately 65% of individuals develop spasticity following stroke, and studies have revealed that approximately 40% of stroke victims may still have spasticity at 12 months post-stroke. The changes in muscle tone probably result from alterations in the balance of inputs from reticulospinal and other descending pathways to the motor and interneuronal circuits of the spinal cord, and the absence of an intact corticospinal system. In other words, there is damage to the part of the brain or spinal cord that controls voluntary movement.

Various means are available for the treatment of the effects of the Upper Motor Neuron Syndrome. These include: exercises to improve strength, control and endurance, nonpharmacologic therapies, oral drug therapy, intrathecal drug therapy, injections, and surgery. Some researchers do not agree that treating spasticity is worthwhile. However, the perseverative preoccupation of professional neurologists and therapists with the purpose of overpowering the spasticity ogre seems to be an endemic, intractably-taught delusion that afflicts both scholars and clinicians [Landau et al. 2004]. Another group of researchers concluded that «spasticity seems to contribute to motor impairments and activity limitations and may be a severe problem for some patients after stroke». Furthermore they noted: «Our findings support the opinion (…) that the focus on spasticity in stroke rehabilitation is out of step with its clinical importance» [Sommerfeld et al. 2004]. In a survey done by the National Stroke Association, however, while 58 percent of survivors in the survey experience spasticity, only 51 percent of those have received treatment for this condition.

In nonpharmacologic therapies, treatment is based on assessment by the relevant health professionals. For muscles with mild-to-moderate impairment, exercises are the main stay of management and is likely to need to be prescribed by a physiotherapist.

Muscles with severe impairment are likely to be more limited in their ability to exercise, and may require help to do this. They may require additional interventions, to manage the greater neurological impairment and also the greater secondary complications. These interventions may include serial casting, flexibility exercise such as sustained positioning programs and patients may require equipment, such as using a standing frame to sustain a standing position. Applying specially made Lycra garments may also be beneficial.

Physiotherapy is beneficial in this area as it helps post-stroke individuals to progress through the stages of motor recovery. These stages were originally described by Twitchell and Brunnstrom, and are known as the «Brunnstrom Approach» . Initially, post-stroke individuals suffer from flaccid paralysis. As recovery begins and progresses, basic movement synergies will develop into more complex and difficult movement combinations . Concurrently, spasticity may develop and become quite severe before it begins to decline . Although an overall pattern of motor recovery exists, there is much variability between each individual's recovery. As previously described, the role of spasticity in stroke rehabilitation is controversial. However, physiotherapy can help to improve motor performance, in part, through the management of spasticity.

Without its reduction, spasticity will result in the maintenance of abnormal resting limb postures which can lead to contracture formation. In the arm, this may interfere with hand hygiene and dressing, whereas in the leg, abnormal resting postures may result in difficulty transferring. In order to help manage spasticity, physiotherapy interventions should focus on modifying or reducing muscle tone. Strategies include mobilizations of the affected limbs early in rehabilitation, along with elongation of the spastic muscle and sustained stretching. In addition, the passive manual technique of rhythmic rotation can help to increase initial range. Activating the antagonist muscle in a slow and controlled movement is a beneficial training strategy that can be used by post-stroke individuals. Splinting, to maintain muscle stretch and provide tone inhibition, and cold, usually in the form of ice packs, to decrease neural firing, are other strategies that can be used to temporarily decrease spasticity. The focus of physiotherapy for post-stroke individuals is to improve motor performance, in part, through the manipulation of muscle tone.

Drugs and surgery are two more tools for stroke medical care. Depending on administration, drug therapies are classified as oral, intrathecal or injections. Oral medications used for the treatment of spasticity include: diazepam ,better known by its trade mark «Valium», dantrolene sodium, baclofen, tizanidine, clonidine, gabapentin, and cannabinoid-like compounds. The exact mechanism of these medications is not fully understood, but they are thought to act on neurotransmitters or neuromodulators within the CNS or muscle itself or to decrease the stretch reflexes. The problem with these medications is their potential side effects and the fact that, other than lessening painful or disruptive spasms and dystonic postures, drugs in general have not been shown to decrease impairments or lessen disabilities.

Intrathecal administration of drugs involves the implantation of a pump that delivers medication directly to the CNS. The benefit of this way is that the drug remains in the spinal cord, without traveling in the bloodstream and therefore often fewer side effects are observed then via oral or injections paths. The most commonly used medication for this is baclofen but morphine sulfate and fentanyl have been used as well, mainly for severe pain as a result of the spasticity.

Injections are focal treatments administered directly into the spastic muscle. Drugs used include: botulinum toxin (BTX), phenol, alcohol, and lidocaine. Phenol and alcohol cause local muscle damage by denaturing protein and thus relaxing the muscle. Botulinum toxin is a neurotoxin and it relaxes the muscle by preventing the release of a neurotransmitter (acetylcholine). Many studies have shown the benefits of BTX and it has also been demonstrated that repeated injections of BTX show unchanged effectiveness.

The last chance is often the surgical treatment for spasticity. It includes lengthening or releasing of muscle and tendons, procedures involving bones and also selective dorsal rhizotomy. Rhizotomy, usually reserved for severe spasticity, involves cutting selective sensory nerve roots, as they probably play a role in generating spasticity.

It's worthwhile to conclude this short survey of therapies noticing that recently at Ecole Polytechnique Federel de Lausanne, Prof. Grégoire Courtine, from International Paraplegic Foundation (IRP) Chair Center for Neuroprosthetics and Brain Mind Institute School of Life Sciences [Courtine 2012] is conducting new researches showing promising results for patients affected by paraplegia. The protocol is based on a proper combination of the three pillars of neurologic therapies: drugs, electrical stimulation and physiotherapy, the last one by done by therapists only or mediated by robotic systems. A proper combination of these strategic tools could lead to a strong improvement in efficacy and efficiency for stroke therapy too.

To end this chapter, I'm glad to mention the very honorable activity of A.L.I.Ce., Italian onlus association to fight against stroke (Associazione per la Lotta all'Ictus Cerebrale).

CHAPTER II

The Haptics

«Han goa nan zangoa»

Ancient adage

CHAPTER II

2.1 Haptic Sense

Haptic is a term related with touch sense, perception and feeling, with tactile activities in general. The word comes from ancient Greek language: haptikos (ἅπτικός), the verb is haptesthai (ἅπτεσθαι) meaning to grasp, to touch (ἅπτω meant «I touch» or «I fasten onto»). In the communication sciences the term haptics indicates any form of nonverbal communication involving touch and is a very important matter to study animal and human social relationship. For people suffering blindness, deafness and muteness, haptics is the only way to communicate.

Haptic perception is the process of recognizing objects through touch. It involves a combination of somatosensory perception of patterns on the skin surface (e.g.: edges, curvature, and texture) and proprioception of hand position and conformation.

People can rapidly and accurately identify three-dimensional objects by touch. They do so through the use of exploratory procedures, such as moving the fingers over the outer surface of the object or holding the entire object in the hand.

The haptic system can be defined as «the sensibility of the individual to the world adjacent to his body by use of his body» [Gibson 1966]. The link between haptic perception and body movement is very strong: haptic perception is active exploration. The haptic system can be better studied as considered a fundamental part of somatosensory system.

The somatosensory system is a diverse sensory system comprising the receptors and processing centers to produce the sensory modalities such as touch, temperature, proprioception (body position), and nociception (pain). The sensory receptors cover the skin and epithelia, skeletal muscles, bones and joints, internal organs, and the cardiovascular system.

While touch is considered one of the five traditional senses, the impression of touch is formed from several modalities. In medicine, the colloquial term «touch» is usually replaced with «somatic senses» to better reflect the variety of mechanisms involved.

Somatic senses are sometimes referred to as somesthetic senses, with the understanding that somesthesis includes touch, proprioception and, depending on usage, also haptic perception.

The system reacts to diverse stimuli using different receptors: thermoreceptors, nociceptors, mechanoreceptors and chemoreceptors.

A mechanoreceptor is a sensory receptor that responds to mechanical pressure or distortion. Normally there are four main types in glabrous skin: Pacinian corpuscles (PC in the following), Meissner's corpuscles, Merkel's discs, and Ruffini endings. There are also mechanoreceptors in hairy skin, and the hair cells in the cochlea are the most sensitive mechanoreceptors, transducing air pressure waves into nerve signals sent to the brain. In the periodontal ligament, there are some mechanoreceptors, which allow the jaw to relax when biting down on hard objects; the mesencephalic nucleus is responsible for this reflex.

Mechanoreceptors are primary neurons that respond to mechanical stimuli by firing action potentials. Peripheral transduction is believed to occur in the end-organs.

In somatosensory transduction, the afferent neurons transmit messages through synapses in the dorsal column nuclei, where second-order neurons send the signal to the thalamus and synapse with third-order neurons in the ventrobasal complex. The third-order neurons then send the signal to the somatosensory cortex.

More recent work has expanded the role of the cutaneous mechanoreceptors for feedback in fine motor control [Johansson & Flanagan 2009]. Single action potentials from rapidly adapting (RA) mechanoreceptor and PC afferents are directly linked to activation of related hand muscles [McNulty & Macefield 2001] whereas slowly adapting activation does not trigger muscle activity. Work on humans stemmed from Vallbo and Johansson's percutaneous recordings from human volunteers in the late 1970s [Johansson & Vallbo 1983]. Work in rhesus monkeys has found virtually identical mechanoreceptors.

Cutaneous mechanoreceptors are located in the skin, like other cutaneous receptors. They are all innervated by Aβ fibers, except the mechanorecepting free nerve endings, which are innervated by Aδ fibers.

Cutaneous mechanoreceptors provide the senses of touch, pressure, vibration, proprioception and others.

Cutaneous receptors can be classified according to several criteria: they can be categorized by morphology, by what kind of sensation they perceive and by the rate of adaptation. Furthermore, each type has a different receptive field.

Referring to morphology there are:

- Ruffini's end organs, detect tension deep in the skin;
- Meissner's corpuscles, detect changes in texture (vibrations around 50 Hz) and adapt rapidly;
- Pacinian corpuscles, detect rapid vibrations (about 200–300 Hz);
- Merkel's discs, detect sustained touch and pressure;

- Mechanoreceiving free nerve endings, detect touch, pressure and stretching;
- Hair follicle receptors, located in hair follicles and sense position changes of hairs.

Referring to sensation there are:

- Slowly Adapting type 1 (SA1) mechanoreceptor, with the Merkel cell end-organ, underlies the perception of form and roughness on the skin [Johnson and Hsiao, 1992] They have small receptive fields and produce sustained responses to static stimulation.
- Slowly Adapting type 2 (SA2) mechanoreceptors respond to skin stretch, but have not been closely linked to either proprioceptive or mechanoreceptive roles in perception [Toerbjork & Ochoa 1980]. They also produce sustained responses to static stimulation, but have large receptive fields.
- The Rapidly Adapting (RA) mechanoreceptor underlies the perception of flutter [Talbot et al. 1968] and slip on the skin [Johansson & Westling 1987]. They have small receptive fields and produce transient responses to the onset and offset of stimulation.
- Pacinian receptors underlie the perception of high frequency vibration [Talbot et al. 1968]. They also produce transient responses, but have large receptive fields.

Cutaneous mechanoreceptors can also be separated into categories based on their rates of adaptation. When a mechanoreceptor receives a stimulus, it begins to fire impulses or action potentials at an elevated frequency (the stronger the stimulus, the higher the frequency). The cell, however, will soon "adapt" to a constant or static stimulus, and the pulses will subside to a normal rate. Receptors that adapt quickly (i.e. quickly return to a normal pulse rate) are referred to as "phasic". Those receptors that are slow to return to their normal firing rate are called "tonic". Phasic mechanoreceptors are useful in sensing such things as texture or vibrations, whereas tonic receptors are useful for temperature and proprioception among others.

Referring to rate of adaptation there are slowly, intermediate and rapid adapting

Slowly adapting mechanoreceptors: include Merkel and Ruffini corpuscle end-organs, and some free nerve endings.

- Slowly adapting type I mechanoreceptors have multiple Merkel corpuscle end-organs.
- Slowly adapting type II mechanoreceptors have single Ruffini corpuscle end-organs.

Intermediate adapting: some free nerve endings are intermediate adapting.

Rapidly adapting mechanoreceptors include Meissner corpuscle end-organs, Pacinian corpuscle end-organs, hair follicle receptors and some free nerve endings.

- Rapidly adapting type I mechanoreceptors have multiple Meissner corpuscle end-organs.
- Rapidly adapting type II mechanoreceptors (usually called Pacinian) have single Pacinian corpuscle end-organs.

Cutaneous mechanoreceptors with small, accurate receptive fields are found in areas needing accurate taction (e.g. the fingertips). In the fingertips and lips, innervation density of slowly adapting type I and rapidly adapting type I mechanoreceptors are greatly increased. These two types of mechanoreceptors have small discrete receptive fields and are thought to underlie most low threshold use of the fingers in assessing texture, surface slip, and flutter. Mechanoreceptors found in areas of the body with less tactile acuity tend to have larger receptive fields.

Other mechanoreceptors than cutaneous ones include the hair cells, which are sensory receptors in the vestibular system of the inner ear, where they contribute to the auditory system and equilibrioception.

There are also juxtacapillary (J) receptors, which respond to events such as pulmonary edema, pulmonary emboli, pneumonia and barotrauma.

Pacinian corpuscles are pressure receptors located not only in the skin but in various internal organs too. Each one of them is connected to a sensory neuron. Because of its relatively large size, a single Pacinian corpuscle can be isolated and its properties studied. Mechanical pressure of varying strength and frequency can be applied to the corpuscle by stylus, and the resulting electrical activity detected by electrodes attached to the preparation.

Deforming the corpuscle creates a generator potential in the sensory neuron arising within it. This is a graded response: the greater the deformation, the greater the generator potential. If the generator potential reaches threshold, a volley of action potentials (nerve impulses) are triggered at the first node of Ranvier of the sensory neuron.

Once threshold is reached, the magnitude of the stimulus is encoded in the frequency of impulses generated in the neuron. So the more massive or rapid the deformation of a single corpuscle, the higher the frequency of nerve impulses generated in its neuron.

The optimal sensitivity of a Pacinian corpuscle is 250 Hz, the frequency range generated upon finger tips by textures made of features smaller than 200 micrometers [Scheibert et al. 2009].

Mechanoreceptors are located inside the body too and are known as «muscle spindles» and are related with the stretch reflex, for instance the «knee jerk» among others. The knee jerk is the popularly known stretch reflex, an involuntary kick of the lower leg, induced by a physician tapping the knee with a rubber-headed hammer. The hammer strikes a tendon that inserts an extensor muscle in the front of the thigh into the lower leg. Tapping the tendon stretches the thigh muscle, which activates stretch receptors, it's to say the muscle spindles. Each muscle spindle consists of sensory nerve endings wrapped around special muscle fibers called «spindle fibers» or «intrafusal fibers». Stretching a spindle fiber initiates a volley of impulses in the sensory neuron, a I-a type neuron, attached to it. The impulses travel along the sensory axon to the spinal cord where they form several kinds of synapses. Some of the branches of the I-a axons synapse directly with alpha motor neurons and these carry impulses back to the same muscle causing it to contract: the leg straightens.

Some of the branches of the I-a axons synapse with inhibitory interneurons in the spinal cord. These, in turn, synapse with motor neurons leading back to the antagonistic muscle, a flexor in the back of the thigh. By inhibiting the flexor, these interneurons aid contraction of the extensor.

Still other branches of the I-a axons synapse with interneurons leading to brain centers, e.g., the cerebellum, that coordinate body movements.

Transmission of information from the receptors passes via sensory nerves through tracts in the spinal cord and into the brain. Processing primarily occurs in the primary somatosensory area in the parietal lobe of the cerebral cortex.

Figure 2.1 - The cortical homunculus was devised by Wilder Penfield.

The somatosensory system, at its simplest, the system works when activity in a sensory neuron is triggered by a specific stimulus such as heat; this signal eventually passes to an area in the brain uniquely attributed to that area on the body; this allows the processed stimulus to be felt at the correct location. The point-to-point mapping of the body surfaces in the brain is called «homunculus» and is essential in the creation of a body image.

This brain-surface or cortical map is not immutable, however. Dramatic shifts can occur in response to stroke or injury. Similarly somatosensory and haptic system are involved in explanation of phenomena such as «phantom limb» and «supernumerary phantom limb». The «phantom limb» sensation could be considered as the reversal situation of motor control impairment due to stroke. In fact, in this syndrome, the neurons deployed for motor control are present, but limb is missing; in the latter the limb is present but neurons are missing.

The concept of haptic perception is related to the concept of extended physiological proprioception according to which, when using a tool such as a stick, perceptual experience is transparently transferred to the end of the tool.

Loss of the sense of touch is a catastrophic deficit that can impair walking and other skilled actions such as holding objects or using tools.

Haptic perception relies on the forces experienced during touch. This research allows the creation of virtual, illusory haptic shapes with different perceived qualities which has clear application in haptic technology.

2.2 Haptic Technology

Haptic technology, also termed as haptics in brief, is a tactile feedback technology which takes advantage of the sense of touch by applying forces, vibrations, or motions to the user. This mechanical stimulation can be used to assist in the creation of virtual objects in a computer simulation, to control such virtual objects, and to enhance the remote control of machines and devices (telerobotics and telemedicine). It has been described as "doing for the sense of touch what computer graphics does for vision". Haptic devices may incorporate tactile sensors, such as small force plate [Panarese & Benoni 2011] that measure forces and pairs exerted by the user on the interface.

Haptic technology has made it possible to investigate how the human sense of touch works by allowing the creation of haptic virtual objects. These objects are used to systematically probe human haptic capabilities, which would otherwise be difficult to achieve. These research tools contribute to the understanding of how touch and its underlying brain functions work.

One of the earliest applications of haptic technology was in large aircrafts that use servomechanism systems to operate control of surfaces. Such systems tend to be "one-way", meaning external forces applied aerodynamically to the control surfaces are not perceived at the controls. Here, the missing normal forces are simulated with springs and weights. In earlier, lighter aircraft without servo systems, as the aircraft approached a stall, the aerodynamic buffeting, a phenomena related with vibrations, was felt in the pilot's controls. This was a useful warning of a very dangerous flight condition. This control shake is not felt when servo control systems are used.

To replace this missing sensory cue, the angle of attack is measured and when it approaches the critical stall point, a stick shaker is engaged which simulates the response of a simpler control system. Alternatively, the servo force may be measured and the signal directed to a servo system on the control, known as force feedback.

Force feedback has been implemented experimentally in some excavators too and is useful when excavating mixed material such as large rocks embedded in silt or clay. It allows the operator to "feel" and work around unseen obstacles, enabling significant increases in productivity. The first US patent for a tactile telephone was granted to Thomas D. Shannon in 1973 (Not to be confused with Professor Claude Elwood Shannon, coauthor, with Harry Nyquist, Edmund Taylor Whittaker and Vladimir Kotelnikov, of the "sampling theorem", one of his fundamental theorem and research works) [Shannon 1973].

Haptics are enabled by actuators that apply forces to the skin for touch feedback, and controllers. The actuator provides mechanical motion in response to an electrical stimulus. Most early designs of haptic feedback use electromagnetic technologies such as vibratory motors, like a vibrating alert in a cell phone or a voice coil in a speaker, where a central mass is moved by an applied magnetic field. These electromagnetic motors typically operate at resonance and provide strong feedback, but produce a limited range of sensations. Next generation actuator technologies are beginning to emerging offering a wider range of effects due to more rapid response times. Next generation haptic actuator technologies include electroactive polymers, piezoelectric, electrostatic and subsonic audio wave surface actuation.

The actuators require control and early haptic response systems typically vibrated the whole device. Second generation haptic control algorithms and chips have been developed that enable location specific responses to be created.

A new technique that does not require actuators is called reverse-electrovibration. A weak current is sent from a device to the user through the object they are touching. The oscillating electric field around the skin on their fingertips creates a variable sensation of friction depending on the shape, frequency, and amplitude of the signal.

Teleoperators are remote controlled robotic tools: contact forces are reproduced to the operator; this kind of technology is called haptic teleoperation. Among the first electrically actuated teleoperators, a prototype was built by Raymond Goertz in the 1950s at the Argonne National Laboratory to remotely handle radioactive substances. Since then, the use of force feedback has become more widespread in other kinds of teleoperators such as remote controlled underwater exploration devices.

When such devices are simulated using a computer (as they are in operator training devices) it is useful to provide the force feedback that would be felt in actual operations. Since the objects being manipulated do not exist in a physical sense, the forces are generated using haptic (force generating) operator controls. Data representing touch sensations may be saved or played back using such haptic technologies. Haptic simulators are used in medical simulators, especially for surgeons training and in flight simulators for pilot training.

Videogames also beneficiates by haptic feedback, it’s commonly used in arcade games, especially racing video games. In 1976, Sega's motorbike game Moto-Cross, also known as Fonz, was one of the first game to use haptic feedback which caused the handlebars to vibrate during a collision with another vehicle. Tatsumi's TX-1 introduced force feedback to car driving games in 1983.

Simple haptic devices are common in the form of game controllers: joysticks and steering wheels among others. Early implementations were provided through optional components, such as the Nintendo 64 controller's Rumble Pak. Many newer generation console controllers and joysticks feature built in feedback devices, including Sony's Dual Shock technology. Some automobile steering wheel controllers, for example, are programmed to provide a "feel" of the road. As the user makes a turn or accelerates, the steering wheel responds by resisting turns or slipping out of control.

In 2007, Novint released the Falcon, the first consumer 3D touch device with high resolution three-dimensional force feedback; this allowed the haptic simulation of objects, textures, recoil, momentum, and the physical presence of objects in games.

In 2008, Apple's MacBook and MacBook Pro started incorporating a "Tactile Touchpad" design with button functionality and haptic feedback incorporated into the tracking surface. Products such as the Synaptics ClickPad followed thereafter.

Tactile haptic feedback is becoming common in cellular devices. Handset manufacturers like Nokia, LG and Motorola are including different types of haptic technologies in their devices; in most cases, this takes the form of vibration response to touch. Alpine Electronics uses a haptic feedback technology named «Pulse Touch» on many of their touch-screen car navigation and stereo units. The Nexus One features haptic feedback, according to their specifications.

Haptics are gaining widespread acceptance as a key part of virtual reality systems, adding the sense of touch to previously visual-only solutions. Most of these solutions use stylus-based haptic rendering, where the user interfaces to the virtual world via a tool or stylus, giving a form of interaction that is computationally realistic on today's hardware. Systems are being developed to use haptic interfaces for 3D modeling and design that are intended to give artists a virtual experience of real interactive modeling. Researchers from the University of Tokyo have developed 3D holograms that can be "touched" through haptic feedback using "acoustic radiation" to create a pressure sensation on a user's hands. The researchers, led by Hiroyuki Shinoda, had the technology on display at SIGGRAPH 2009 in New Orleans.

Research has been done to simulate different kinds of taction by means of high-speed vibrations or other stimuli. One device of this type uses a pad array of pins, where the pins vibrate to simulate a surface being touched. While this does not have a realistic feel, it does provide useful feedback, allowing discrimination between various shapes, textures, and resiliencies. Several haptics APIs have been developed for research applications, such as Chai3D, OpenHaptics, and the Open Source H3D API.

In the field of Medicine, haptic interfaces for medical simulation may prove especially useful for training in minimally invasive procedures such as laparoscopy and interventional radiology, as well as for performing remote surgery. A particular advantage of this type of work is that surgeons can perform more operations of a similar type with less fatigue. It can be stated that a surgeon who performs more procedures of a given kind will have statistically better outcomes for his patients.

Not to forget, haptic interfaces are also used in rehabilitation robotics and RMT as already shown in previous chapter.

In ophthalmology, haptic is used for supporting springs, two of which hold an artificial lens within the lens capsule after the surgical removal of cataracts.

A Virtual Haptic Back (VHB) was successfully integrated in the curriculum of Osteopathic Medicine College. Research indicates that VHB is a significant teaching aid in palpatory diagnosis (detection of medical problems via touch). The VHB simulates the contour and stiffness of human backs, which are palpated with two haptic interfaces by SensAble Technologies, the PHANToM 3.0.

Haptics have also been applied in the field of prosthetics and orthotics. Research has been underway to provide essential feedback from a prosthetic limb to its wearer. Recent work by Edward Colgate, Pravin Chaubey, and Allison Okamura et al. focused on investigating fundamental issues and determining effectiveness for rehabilitation.

In robotics, it’s possible to find artificial body part, such as the Shadow Hand, using the sense of touch, pressure, and position to reproduce the strength, delicacy, and complexity of the human grip. It was developed by Richard Greenhill and his team of engineers in London as part of The Shadow Project, now known as the Shadow Robot Company, an ongoing research and development program whose goal is to complete the first convincing artificial humanoid. An early prototype can be seen in NASA's collection of humanoid robots, or robonauts. The Shadow Hand has haptic sensors embedded in every joint and finger pad, which relay information to a central computer for processing and analysis. Carnegie Mellon University in Pennsylvania and Bielefeld University in Germany found The Shadow Hand to be an invaluable tool in advancing the understanding of haptic awareness, and in 2006 they were involved in related research.

The first PHANTOM, which allows one to interact with objects in virtual reality through touch, was developed by Thomas Massie while a student of Ken Salisbury at MIT.

New promising fields for haptics are arts and design: touching is not limited to feeling, but allows interactivity in real-time with virtual objects. Thus, haptics are used in virtual arts, such as sound synthesis or graphic design and animation. The haptic device allows the artist to have direct contact with a virtual instrument that produces real-time sound or images. For instance, the simulation of a violin string produces real-time vibrations of this string under the pressure and expressiveness of the bow (haptic device) held by the artist. This can be done with physical modeling synthesis.

Designers and modelers may use input devices with high number of DOF that give touch feedback relating to the virtual surface they are sculpting or creating, allowing faster and more natural workflow than traditional methods. This is strongly related with the fast growing of 3D printer business. Artists working with haptic technology such as vibrotactile effectors are Christa Sommerer, Laurent Mignonneau, and Stahl Stenslie, among others

Applications of haptic technology cover a wide spectrum of human interaction with technology. New researches are focusing on the mastery of tactile interaction with holograms and distant objects, which, if successful, may result in applications and advancements in gaming, movies, manufacturing, medical and other industries, especially for hazardous tasks as in nuclear and chemical plants. The medical industry stands to gain from virtual and telepresence surgeries, which provide new options for medical care. The clothing retail industry could gain from haptic technology by allowing users to "feel" the texture of clothes for sale on the internet. Future advancements in haptic technology may create new industries that were previously not feasible or realistic.

Researchers at the University of Tokyo are working on adding haptic feedback to holographic projection. The feedback allows the user to interact with a hologram and receive tactile responses as if the holographic object were real. The research uses ultrasound waves to create acoustic radiation pressure, which provides tactile feedback as users interact with the holographic object. The haptic technology does not affect the hologram, or the interaction with it, only the tactile response that the user perceives. The researchers posted a video displaying what they call the Airborne Ultrasound Tactile Display. As of 2008 the technology was not ready for mass production or mainstream application in industry, but was quickly progressing, and industrial companies showed a positive response to the technology. This example of possible future application is the first in which the user does not have to be outfitted with a special glove or use a special control, they can "just walk up and use".

One currently developing medical innovation is a central workstation used by surgeons to perform operations remotely. Local nursing staff set up the machine and prepare the patient, and rather than travel to an operating room, the surgeon can act in telepresence mode. This allows expert surgeons to operate from across the country, increasing availability of expert medical care. Haptic technology provides tactile and resistance feedback to surgeons as they operate the robotic device. As the surgeon makes an incision, they feel ligaments as if working directly on the patient.

As of 2003, researchers at Stanford University were developing technology to simulate surgery for training purposes. Simulated operations allow surgeons and surgical students to practice and train more. Haptic technology aids in the simulation by creating a realistic environment of touch. Much like telepresence surgery, surgeons feel simulated ligaments, or the pressure of a virtual incision as if it were real. The researchers, led by J. Kenneth Salisbury Jr., professor of computer science and surgery, hope to be able to create realistic internal organs for the simulated surgeries, but Salisbury stated that the task will be difficult. The idea behind the research is that «just as commercial pilots train in flight simulators before they're unleashed on real passengers, surgeons will be able to practice their first incisions without actually cutting anyone».

According to a Boston University paper published in The Lancet, «Noise-based devices, such as randomly vibrating insoles, could also ameliorate age-related impairments in balance control.» If effective and affordable haptic insoles were available, perhaps many injuries from falls in old age or due to illness-related balance-impairment could be avoided.

Finally it’s a pleasure to close this short survey on haptic technologies dropping few lines about the “Da Vinci”, a stunning Italian research achievement. It’s a medical system for neurosurgery of central nervous system (CNS in the following) combining fMRI with laser lancet to navigate the brain and to burn the cancer cells inside the cranium. The pulpit to command and drive the lancet is provided with haptic features to better drive the surgeon’s hand inside the brain and avoid possible damages due to possible mistakes during the surgeon action.

2.3 Haptic Systems for Rehabilitation

Rehabilitation robotics is a field of research dedicated to understanding and augmenting rehabilitation through the application of robotic devices. Rehabilitation robotics includes development of robotic therapies, and the use of robots as therapy aids instead of solely as assistive devices. Rehabilitation using robotics is generally well tolerated by patients and has been found to be an effective adjunct to therapy in individuals suffering from motor impairments, especially due to stroke.

Rehabilitation robotics can be considered a specific focus of biomedical engineering, and a part of human-robot interaction. In this field, clinicians, therapists, and engineers collaborate to help rehabilitate patients.

Prominent goals in the field include: developing implementable technologies that can be easily used by patients, therapists, and clinicians; enhancing the efficacy of clinician's therapies; and increasing the ease of activities in the daily lives of patients.

The field of rehabilitation robotics started to emerge in the 1960s, and has since developed into subfields focused on assistive devices, special needs education, mobility, prosthetics and orthotics, and robot mediated therapy. The International Conference on Rehabilitation Robotics occurs every two years, with the first conference in 1989. The most recent conference were held in Kyoto, Japan in 2009 and in 2011 in Zurich, Switzerland.

Current robotic devices include exoskeletons for aiding limb or hand movement such as the Tibion Bionic Leg, the Myomo Neuro-robotic System and the Berkeley Bionics eLegs; enhanced treadmills such as Hocoma's Lokomat; and robotic arms to retrain motor movement of the upper limb such as the MIT-MANUS. Some devices are meant to aid strength development of specific motor movements, while others seek to aid these movements directly. Often robotic technologies attempt to leverage the principles of neuroplasticity by improving quality of movement and increasing the intensity and repetition of the task. Over the last two decades, research into robot mediated therapy for the rehabilitation of stroke patients has grown significantly as the potential for cheaper and more effective therapy has been identified. Though stroke has been the focus of many studies due to its prevalence in North America, rehabilitation robotics can also be applied to individuals with cerebral palsy, or those recovering from orthopedic surgery.

Rehabilitation robotics may also include virtual reality technology.

More recently, starting near the end of the last millennium, several research groups deeply investigated a new generation of systems for RMT; here is a list of some them, but they are not the only ones:

- MIT-MANUS [Krebs et al. 1998]
- MIME [Burgar et al. 2000];
- ARM Guide [Reinkensmeyer et al. 2000];
- Bi-Manu-Track [Hesse et al. 2003];
- GENTLE/S [Coote et al. 2003];
- ARMin [Riener et al. 2005]
- BRACCIO DI FERRO [Casadio et al. 2006]
- REHAROB [Fazekas et al. 2007];
- NeReBot the Neuro-Rehabilitation-Robot [Masiero et al. 2007]

- ARMEO [Gijbels et al. 2011].

MIT-MANUS is the market leader in this class of systems; the studies, based on the MANUS manipulator started in the late nineties at the Massachusetts Institute of Technology in Boston, U.S. . The MIT-MANUS in particular has been studied as a mean of providing individualized, continuous therapy to patients who have suffered a stroke by using a performance-based progressive algorithm. It is based on two arms and two rotating motors at the circular joint of arms: one end is for the hand connected to the handle by means of straps, at the other end a motor is fixed to the base of the system. MIT-MANUS allows hand movements on a 2D flat surface. The system includes also a PC to run the software for control of motors, joints and kinematics, for therapy development and data collection. A screen is included to show the targets to the patients during exercises and to output informations from the PC. Typical targets for ballistic exercises are colored circles located along a circumference having the starting point at its center; the small circles light on according to a programmed sequence or randomly and patient must move the handle to reach them. Another group of targets is made by geometrical paths, typically circle and eight shaped, to be run by patients moving the handle. In the 2D virtual space the system allows to perceive forces as haptic feedback on the surface during movements: some areas near the target line are free from force field, at boundaries of this area start an elastic barrier to help the hand to stay near the target, outer of this zone there is a virtual barrier of forces to stop movements going too far from the target line. According to the «assistance as needed» criteria , another very useful feature, common to many of these systems, are forces and pairs to move passively the handle during the first phase of therapy process when patient arm lacks of force enough and motor control by body and mind is still ineffective to reach the targets. As far as the recovery process goes on and patient individuals improves the results of motor control, the component of forces expressed by the system may decrease until they are needed no more. The responsive software allows the robot to alter the amount of assistance it provides, based on the patient's speed and timing of movement. This allows for a more personalized treatment session without the need for constant therapist interaction. An additional benefit to this type of adaptive robotic therapy is a marked decrease in spasticity and muscle tone in the affected arm. Different spatial orientations of the robot allow for horizontal or vertical motion, or a combination in a variety of planes. The vertical, anti-gravity setting is particularly useful for improving shoulder and elbow function.

About ten years ago, a group of Italian researchers started a study to make an innovative system that could improve what offered by other systems and overcome some of their limitations. This new robotic workstation for neurological rehabilitation was named Braccio di Ferro. It was designed by having in mind the range of forces and the frequency bandwidth that characterize the interaction between a patient and a physical therapist, as well as a number of requirements that are considered to be essential for allowing a natural haptic interaction: back-drivability, very low friction and inertia, mechanical robustness, the possibility to operate in different planes, and an open software environment, which allows the operator to add new functionalities and design personalized rehabilitation protocols. Braccio di Ferro is an open system and, in the spirit of open source design, is intended to foster the dissemination of robot therapy. Moreover, its combination of features is not present in other commercially available systems.

ARMEO is the name of a group of systems for RMT by Hocoma company and refers to a set of machines for stroke RMT: Armeo Power, Armeo Spring and Armeo Boom. There are two more machines of this kind among the other Hocoma products: Armeo Spring Pediatric, aimed to rehabilitation therapy of children, and Manovo Spring.

It can be observed that all this kind of systems makes use of a screen to show targets, motor tasks and other informations, that is placed in a vertical position, in front of the patient or the technical operator, as usual for interactions with PCs. It could be an improvement to have a screen especially dedicated, to show targets and motor tasks, placed horizontally and as big as the 2D working space where it is possible to run the end effector: in this way the targets can be reached looking directly at the operative surface without having to do a mental transposition between the vertical virtual space and the horizontal working space.

CHAPTER III

Materials and Methods

«A man is a better tooled animal»

CHAPTER III

3.1 The Haptic Interface Falcon

In 2007 the Novint Company launched on U.S. market a parallel haptic interface, called "Falcon", at very affordable price, targeted to passionate gamers to give them a new input/output device capable to introduce gaming people into an exciting enhanced virtual world where they could experience the touch perception by means of haptic feedback. The falcon isn't stricto sensu an innovative product from a technical point of view. A similar device is the "Omega.3" made by a Swiss company, Force Dimension, aimed to satisfy needings of professional and medical application, but the cost of this device is much higher then the Falcon, about one order of magnitude. Of course Omega.3 technical specifications are better than the Falcon ones, moreover the Falcon doesn't comply medical International Standards while Omega does.

Figure 3.1 – A photograph of the Falcon haptic interface with handle in rest position [Martin & Hillier 2009].

The more relevant technical specifications of the Falcon are the following:

- 3D Touch Workspace ≈ 10 x 10 x 10 cm
- Force Capabilities max ≈ 10 N
- Position Resolution > 400 dpi
- Quick Disconnect Handle < 1 second change time

– Communication Interface USB 2.0

– Size ≈ 23 x 23 x 23 cm

– Weight ≈ 30 N

– Power 30 watts, 100V-240V,50Hz-60Hz

The handle has three degree of freedom: it can be moved freely along three axis inside its workspace and this is the reason why this kind of interfaces is considered to have a parallel kinematics. It's of interest for the research project that the handle can be disconnected and changed with another one, the only alternative is a pistol grip shaped handle by now. More handles with different ergonomic shapes were experimentally tested by the Novint, but they are not for selling at present time. Moreover the disconnection system allows to preserve the functionality of buttons located on the handle, this feature could be useful to get or send information to the Falcon or the PC directly via the electrical contacts.

Some of these specifications were stressed and tested by researchers for application as a robot manipulator [Martin & Hillier 2009]. It was found that error in the steady state encoder value ranges from 1 to 36 encoder counts, equivalent to an error of 1,2° at the base-leg joint; error for commanding force values ranges from 0.2% to 8.6% of full-scale range over four experimental trials. The variation is most likely attributable to static friction.

Simple calculations showed that during the experiments, the actuating legs underwent acceleration of the order of 10^3 degrees/s^2, with the encoder traces showing no step changes that would indicate evidence of significant system slop. As expected, the highly non-linear nature of the kinematics is revealed, with end-effector locations that are nearer to the centre of the workspace displaying higher sensor resolution, with the lowest end-effector error achievable when all three legs are at the midpoint of their stroke. The average over the entire workspace is 30 encoder counts per 1mm positioning error. The work has characterised the Novint's Falcon haptic device with sufficient fidelity to create usable kinematic and dynamic models.

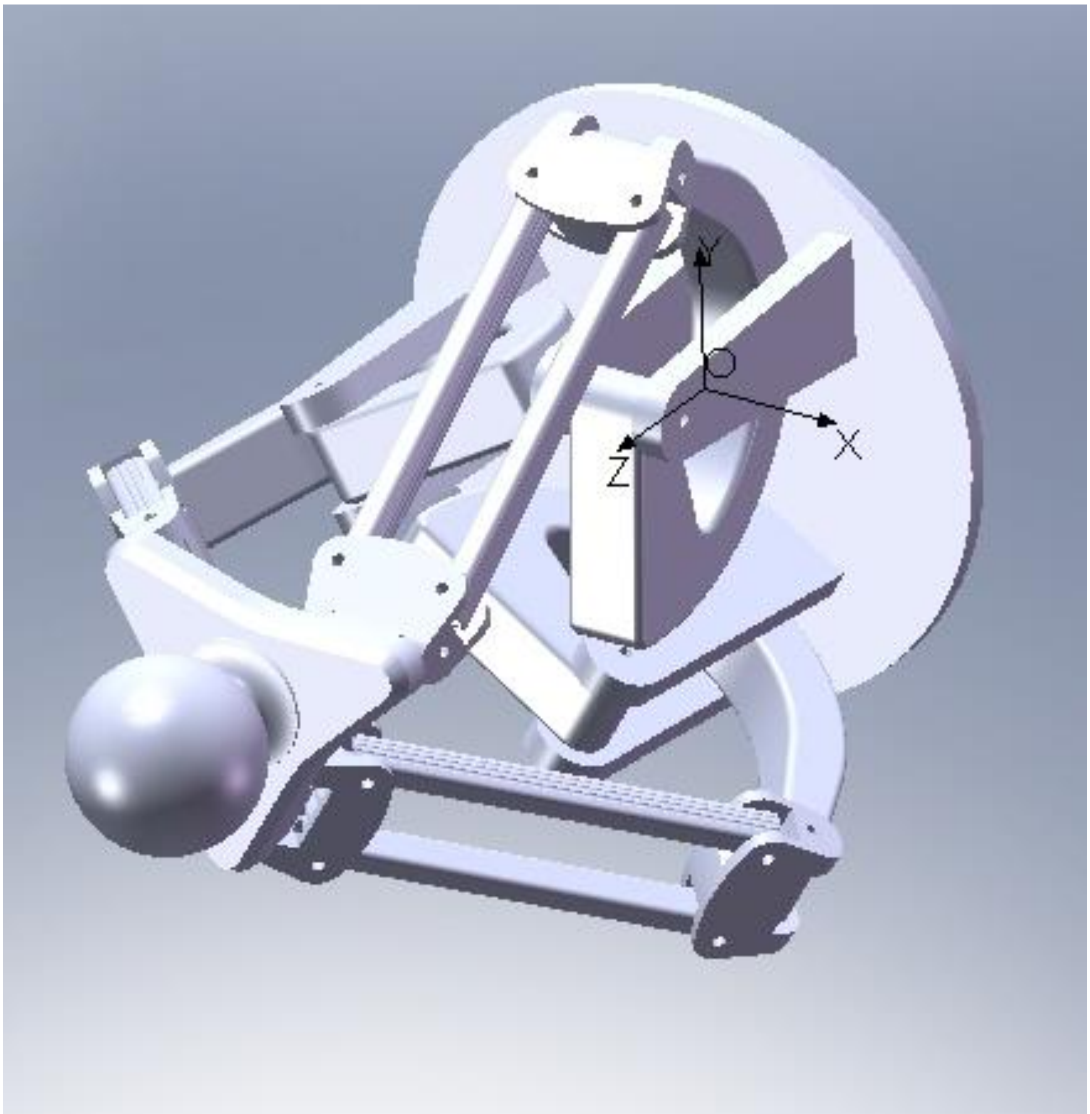


Figure 3.2 – CAD model generated for the Novint Falcon haptic device [Martin & Hillier 2009].

Technical specifications show that the Falcon can be connected to American and European electric networks but a very important remark must be done about this point. The original power supply of the Falcon we got directly from the Novint company, is made according to the United States of America (U.S.A.) electrotechnical standards, so the electrical network features to feed the power supply are 60 Hz for the frequency of alternate current (AC) and 110 Voltas for the voltage. The rated power is 30 VA with 0,9 A as nominal value of direct current (DC) output and 36 V for the output voltage. To avoid hazards and damages for the Falcon, a new power supply was provided which features comply standards for European electrical network.

To avoid the slipping of the Falcon a small silicon carpet was set on the surface of the desktop; this was not enough when the Falcon operates with haptic feedback exerting the forces on the handle grasped by the individuals. In this case two clamps were added at its footing to stabilize the Falcon.

3.2 The Haptic System Based on Falcon

The system is made of two principal hardware elements: a PC and the Falcon, connected to the PC by a universal serial bus (USB) compliant with 2.0 specifications.

About the PC, it has a Pentium V microprocessor running at 3 GHz with 2 GB of random access memory and a 500 GB hard disc. A first attempt to install the Falcon drivers under Windows 7 operative system failed and the same happened after trying to install the drivers under Windows Vista operative system; finally the Falcon drivers started to work fine under Windows XP operative system.

After some runs of the software purchased in bundle with the Falcon to test its haptic features for gaming purpose, the software development kit (SDK in the following) was installed.

The Falcon Tutorial that can be downloaded from the Novint website or Wikipedia worked fine, showing a full fan of Falcon features: getting info about handle button, coupling of keybord keys and defined end-effector functions, time shaping of forces and data logging of handle position in workspace could be easily tested. The tutorial scripts were written in a C-like language called “Squirrel”, the extension of runnable program in Squirrel is «.nut», of course. It was possible to develop a script allowing the recording of handle position in a logging file and thanks to this script the feasibility data collection could start at Biolab[3] with the first group of volunteers. Awfully the Squirrel lacks of some simple command to open or close file for appending of data get by the encoders of the three Falcon legs (sometimes called arms too) and difficulties to introduce haptic and visual feedback in the scripts; furthermore the website of squirrel language seems to be abandoned and dismantled and it was impossible to get support from squirrel authors. An attempt was made to install the SDK and the libraries by Novint that should work under Visual C++ but results were poor and shallow, moreover it was impossible to get support from Novint website that seemed to be abandoned, possibly due to economic troubles that leaded to the acquisition of Novint by another company. As consequence it was decided to try the use of H3D software and results were satisfactory. So finally haptic feature of the Falcon and visual feedback could be implemented and collection of the so called «haptic data» could start.

3.3 Experimental Set-Up and Protocol

The experimental set up is based on the system: the Falcon is placed on the desktop, its handle is in front of the individual. The volunteer is seated comfortably with the center of the shoulder joint near the symmetry plane of the Falcon. The upper limb is free of any constraint, so the arm of the chair cannot be used as elbow rest.

In a first introductory phase of the test, the individual receives some general informations about the aim of the project and some general data about her or his characteristics, such as age, height, weight and sex among others, are registered for statistical analysis on the volunteer population.

Than a short training period start, during which the test operator shows and tells to the subject how to do the exercise, the type of exercises to do and what are their characteristics. The volunteer is invited to do some exercises for training before recording starts.

The individual is asked to say when she or he is ready to start, than the operator starts running the software for data acquisition and finally the subject can start doing the exercise. After five iteration of the motor task are made, the acquisition is stopped and the procedure restart to record data of another exercise. After doing all the exercises according to the experimental protocol, the recording session is considered as to be closed and a new recording session with another subject can start.

3.4 Methods

Once raw data are recorded in a logging file, they are used to extract kinematic variables and parameter. In fact, the raw data are a sampling of the Falcon handle position in the workspace. The log file is opened in MATLAB and sampled positions are the elements of a three column matrix. After a preprocessing, the position data are filtered by a second order Butterworth filter: the cut frequency is chosen 20 times lower than the sampling frequency. Than the position data are differentiated to get mean velocity in sampled intervals. Newly the same Butterworth filter is applied to smooth velocity values and then calculate accelerations. The same method is applied to accelerations to calculate the jerk. Once the kinematic variables matrixes are calculated, some parameters can be extracted such as statistical values, typically mean and standard deviation values.

Among many others, a meaningful parameter proposed to evaluate smoothness of movement is the so called «Mean Squared Jerk Ratio» (MSJr in the following) [Hogan N. & Sternad D. 2007 e 2009].

It is defined according to the following relation:

$$MSJ_{ratio} = \frac{MSJ}{MSJ_{min}} = \frac{\int_o^d J(t)^2 dt}{(360A^2/d^5)}$$

where:

J(t) is the amplitude of instantaneous value of the jerk;

MSJ_{min} is calculated according to relation for rhythmic movements;

A the amplitude of movement;

d the duration of movement.

For each exercise the value of MSJr shown in the next chapter for statistical analysis is the mean value calculated over the five iterations.

CHAPTER IV

Statistical Analysis

of Collected Data

and Extracted Parameters

‘‘Everyone knows what a curve is, until he has studied enough mathematics to become confused through the countless number of possible exceptions.’’

Felix Klein

CHAPTER IV

4.1 Feasibility Data

Data collected by means of the system on healthy subjects can be classified in three main groups:

1) Data to test the feasibility and good functioning of the system, in the following they'll be called «feasibility data»;
2) Data to test the functioning of the system using haptic features, in the following they'll be called «haptic data»;
3) Data from a group of elderly people to compare their results with results from already collected data so that the effect of ageing on smoothness can be investigated, in the following they'll be called «elderly data»;

Referring to upper limb motor control, all people enrolled are considered to be healthy subjects, it's to say nobody declared to suffer from specific motor control diseases, such as stroke, Parkinson or other syndromes related with arm or hand movements.

Feasibility data were collected mainly during the summer of 2011 on a group formed by 8 young individuals (2 female and 6 male individuals, aged about 27±3 years). Volunteers were self-selected people, most of them belonging to the crew of Bioengineering Laboratory at Roma Tre University.

According to the protocol to collect feasibility data, they were asked to perform exercises under the following conditions:

- Left or right hand;
- Two type of trajectories, circle or cross;
- Two direction of circulation, clockwise or counterclockwise;
- Three different planes parallel to the principal anatomic planes, coronal, sagittal and transverse;
- Opening or closing eyes.

Every possible combination of these conditions leads to a number of 48 exercises performed by each individual during a recording session. It’s worthwhile noticing that, according to the experimental protocol, each file contains data of an exercise repeated five times.

Raw data, coming from files where positions of the handle of the system are recorded, were processed to extract values of kinematic variables: velocity, acceleration and jerk.

The clew formed by position points sampled during an exercise is represented in figure 4.1.

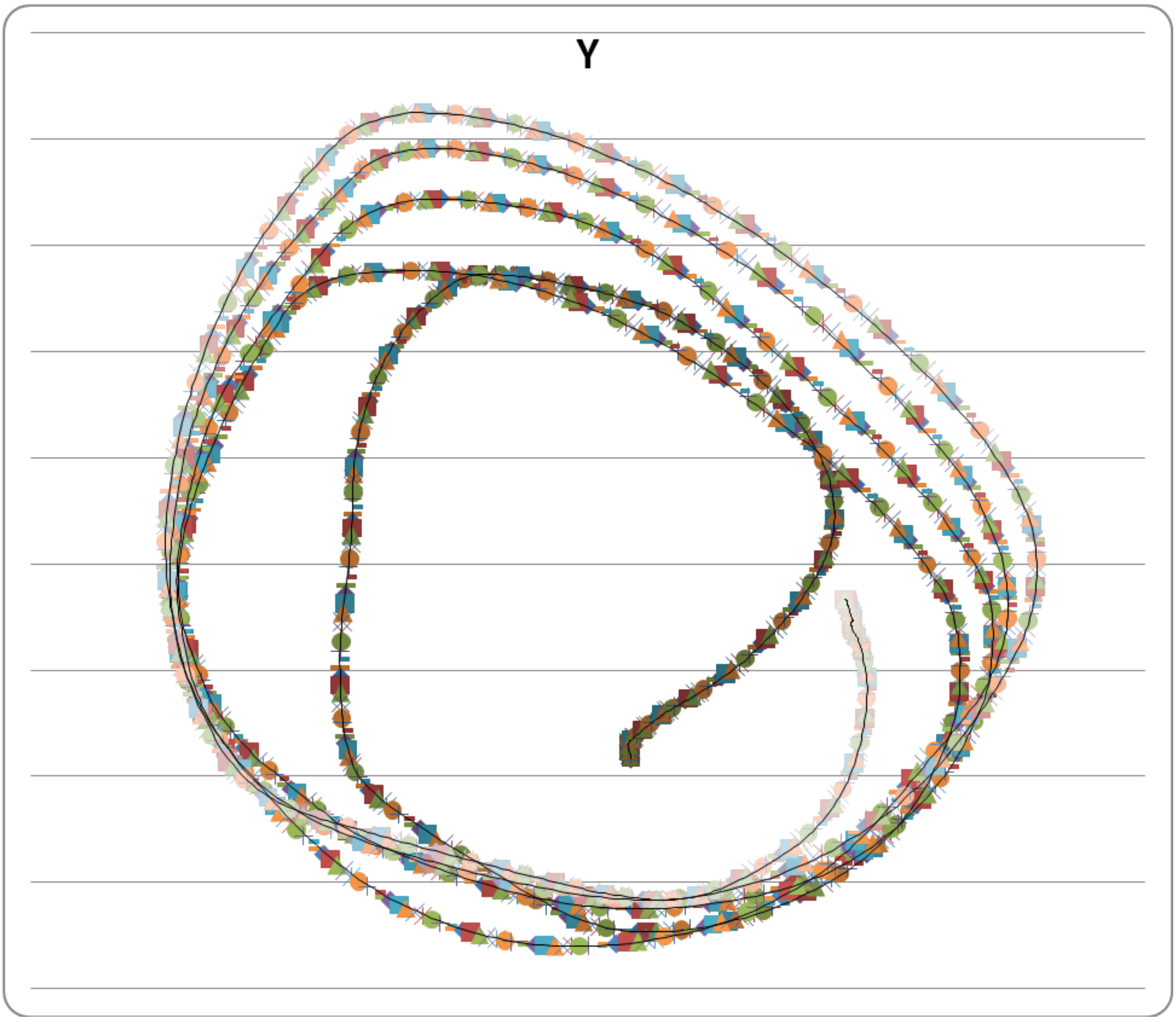


Figure 4.1 Plot of a quasi two dimensional circular trajectory exercise on a frontal plane projected on X-Y plane of Falcon workspace, five iterations. Lengths are in meters.

A plot of a circular trajectory evolution along the time is shown in figure 4.2. It can be observed that variation on Z axe of Falcon workspace is lower than on X and Y axes due to the quasi two dimensional frontal plane characteristic of the trajectory.

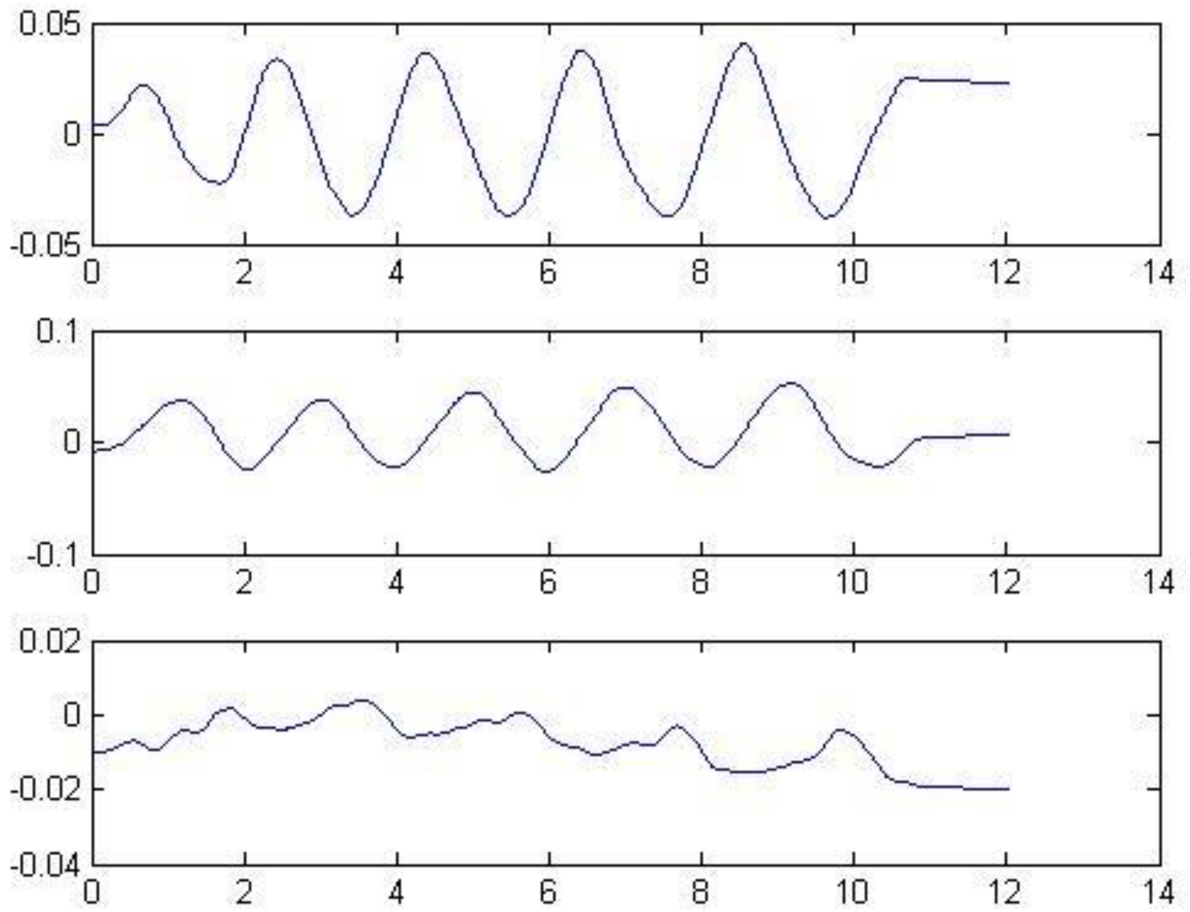


Figure 4.2 Plot of a circular trajectory evolution, five iterations. Upper panel shows component along X axe of working space, central panel shows component along Y axe, lower panel shows component along Z axe. Lengths are in meters. Time scale is in seconds.

An example of extracted velocity is shown in fig. 4.3 and refers to an exercise of quasi two dimensional circular trajectory performed on three different planes.

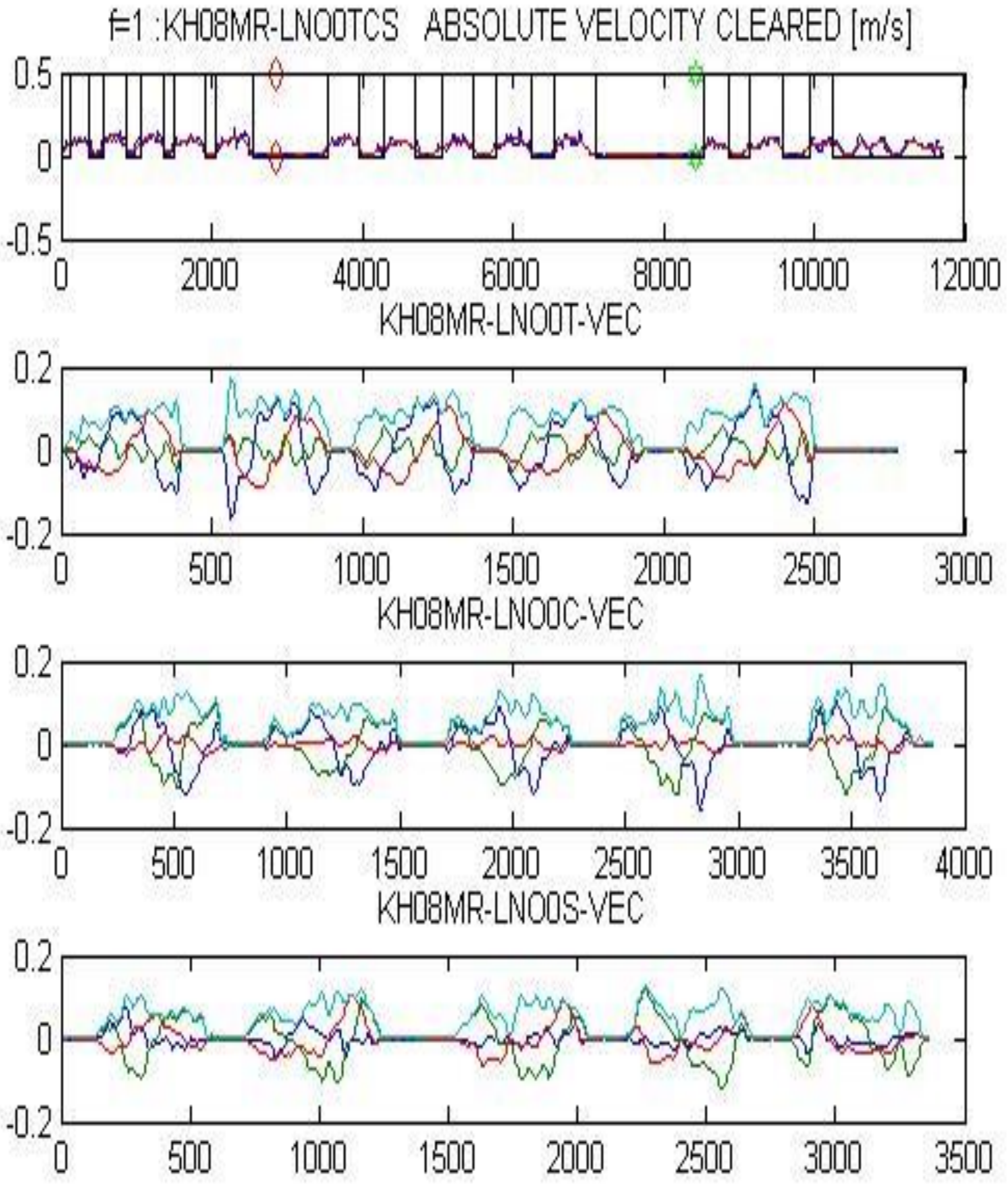


Figure 4.3 Absolute velocity extracted from an exercise of quasi two dimensional circular trajectory performed on three different planes. Upper panel shows absolute velocity

(blue line) of three exercises included in just one record. Second panel refers to a trajectory parallel to the transverse plane (horizontal). Third panel refers to a trajectory parallel to the coronal plane (in front of the subject). Lower panel refers to a trajectory parallel to the sagittal plane. Light blue line shows values of absolute velocity evolution along the time. Blue lines are for X-component of velocity, green lines for Y-component, red lines for Z-component. Speed is in meters/second, horizontal axes of each diagram show number of sample, sampling frequency is 166 samples/second.

4.2 Haptic Data

After the haptic features were added to the system, during the spring of 2012 a group of 8 people (2 female and 6 male individuals, aged about 26±3 years, 5 of them already enrolled in the feasibility data group) were asked to perform the exercises under the following conditions:

- Left or right hand;
- Two direction of circulation;
- With or without haptic feedback;
- With or without visual feedback;

Every possible combination of these conditions leads to a number of 16 exercises to be performed in each session. Taking into account considerations coming from the analysis of feasibility data, to shorten the duration of recording session for each individual only one type of trajectory, the circle one, was considered. Moreover, due to difficulties in representing a three dimensional scene with fix or variable point of view and taking into account considerations coming from the analysis of feasibility data, only one plane parallel to the coronal anatomic plane was considered. As consequence the volunteers were asked to draw quasi two dimensional circles on a plane in front of them inside the Falcon workspace. The haptic feedback consists of a radial force field that is null along the target trajectory and increases up to 3 N at a distance of 2.6 cm. Open or closed eyes exercises were performed without haptic stimuli, in a way similar to feasibility data. Looking at a green circle target on a black PC screen was assumed to be the visual feedback in presence of haptic feedback.

An overview of MSJ_{ratio} extracted by each exercise of healthy individuals for haptic data is shown in fig. 4.4. It can be seen the field of variation ranging between the lower value close to 10^5 and the higher value less than 10^9.

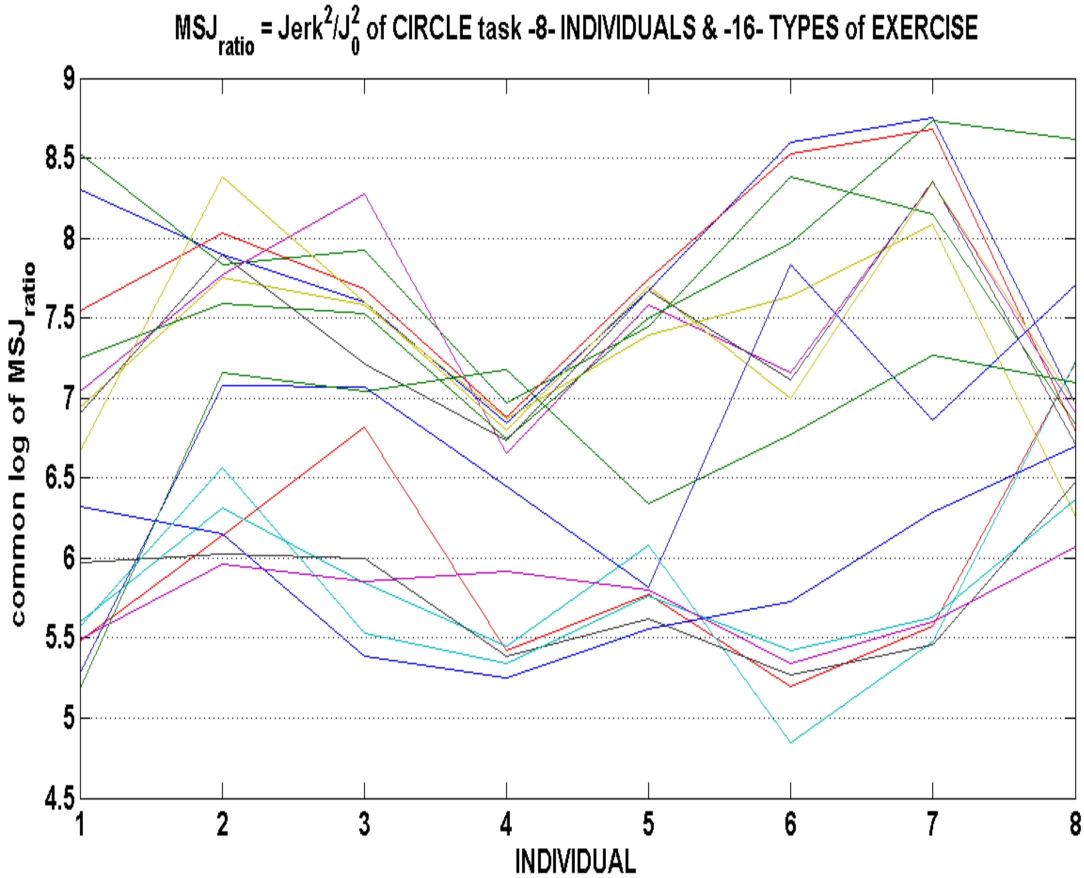


Figure 4.4 Overview of MSJ_{ratio} extracted by each exercise of healthy individuals for haptic data. Each colored line refers to a type of exercise characterized by specific conditions.

4.3 Elderly Data

In October 2012, data were collected from the last group of volunteers. It is formed by 8 members (7 female and 1 male individuals, aged about 67±4 years) of Social and Cultural Center entitled to Luigi Volpicelli, placed close to our Department of Applied Electronic. They performed the same exercises proposed to the haptic group so that a comparison between results coming from the analysis of their data can be done and some conjectures about the effect of age on smoothness can be drawn.

An overview of MSJ_{ratio} extracted by each exercise of elderly individuals is shown in fig. 4.5. It can be seen the field of variation ranging between the lower value greater than 10^4 and the higher value over 10^9.

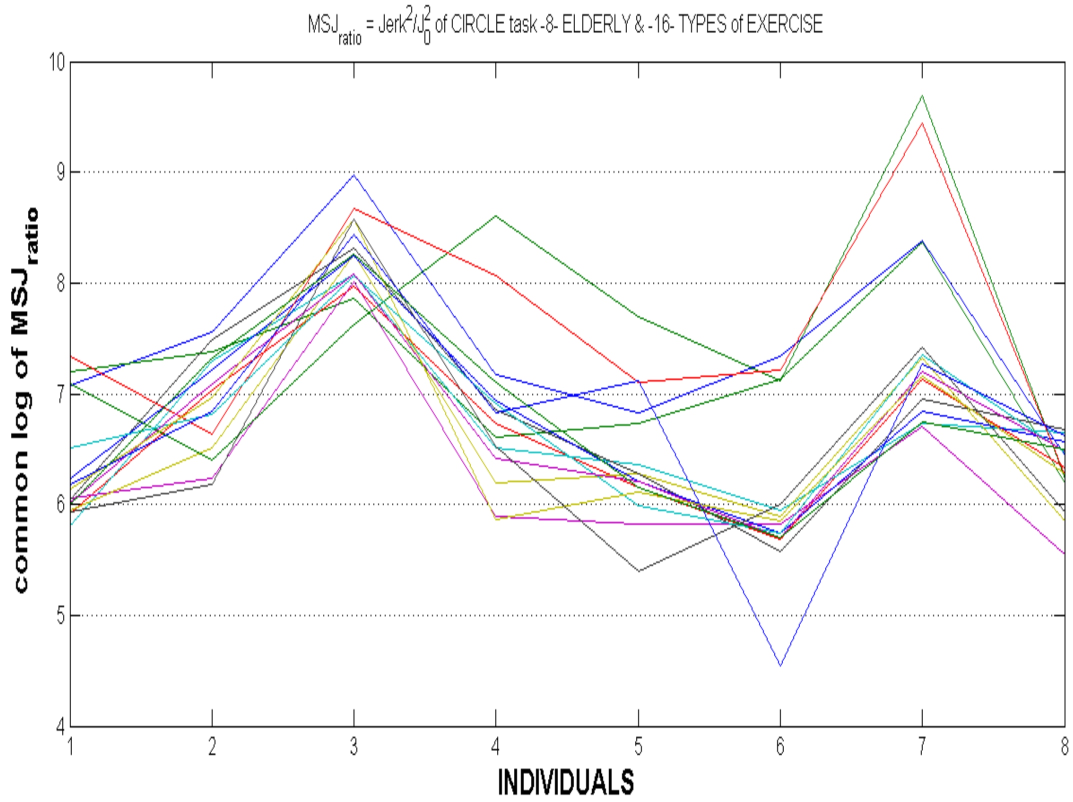


Figure 4.5 Overview of MSJ_{ratio} extracted by each exercise of elderly individuals. Colored lines refer to a type of exercise characterized by specific conditions.

4.4 Statistical Analysis

Once the kinematic variables were extracted and some important parameters, MSJ_{ratio} among others, were calculated for each exercise a statistical analysis was done. It's worthwhile remember that MSJ_{ratio} is considered to be one of the parameter more significantly related with smoothness of movements [Hogan 2007], this is the reason why a statistical analysis was done focusing on MSJ_{ratio} . Statistical analysis allowed to calculate for every types of exercise the mean values and standard deviation for healthy volunteer enrolled in the data groups. Furthermore, to ascertain what conditions are more influencing for movement smoothness, an analysis of variance was done.

Referring to feasibility data, an overview of mean values and standard deviation of MSJ_{ratio} is given in figure 4.6. It's possible to observe that mean values of MSJ_{ratio} for crosses are greater than values extracted from circle trajectories, the distance is a bit more than 1 order of magnitude (1 step in the log scale of y axe). This observation is confirmed by analysis of variance, results are shown in figure 4.7 and the lower value of p ppparameter is associated to the shape of trajectory, circle or cross.

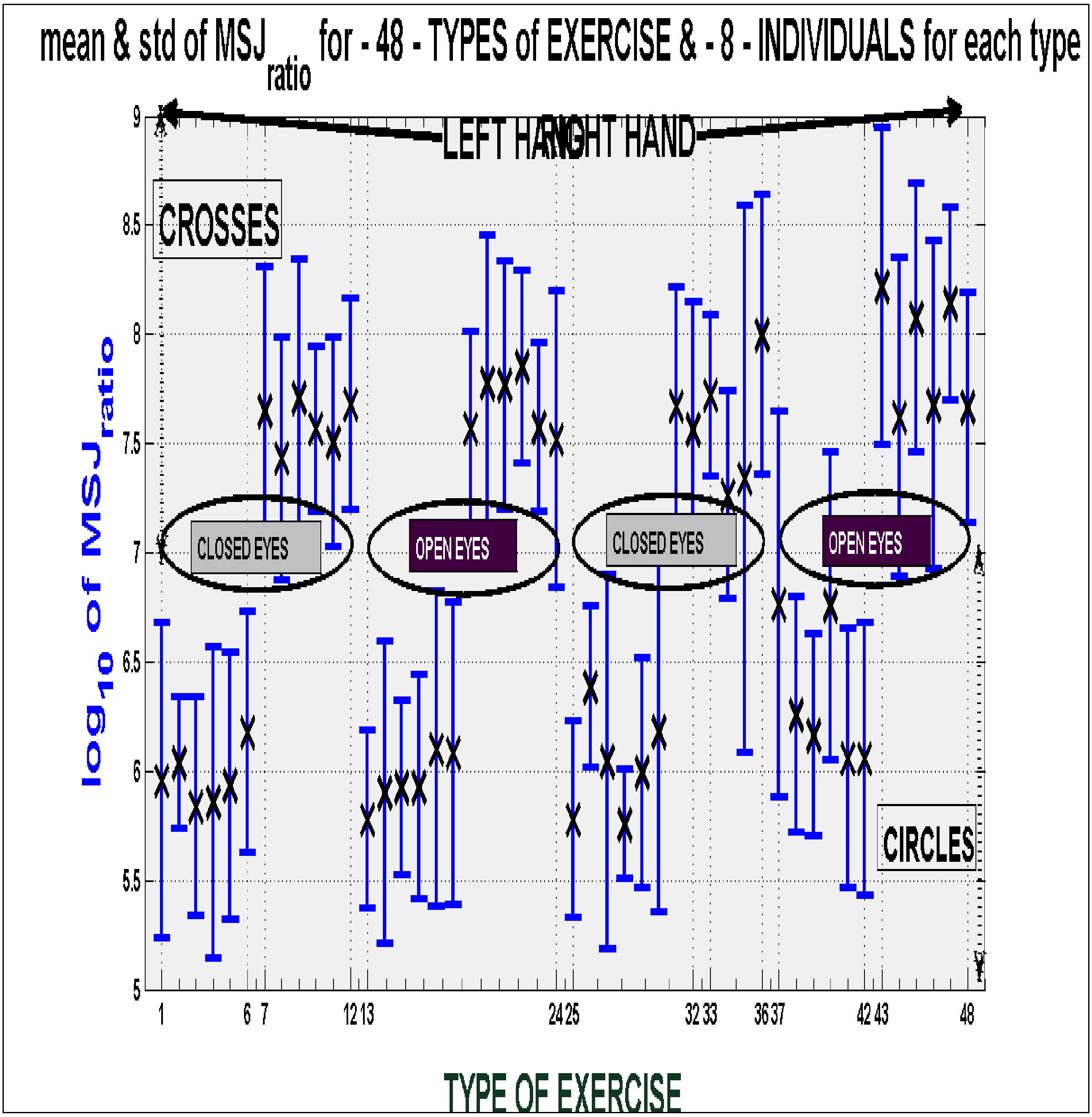


Figure 4.6 Mean values and standard deviation of MSJ_{ratio} for each type of exercise performed by feasibility group.

On the left (types from 1 to 24) exercises done by left hand, on the right (types from 25 to 48) the other ones done by right hand.

In each group of six values close to each other, the first group of three refers to clockwise direction and the other triplet is for counterclockwise.

Values in the lower zone of diagram (from 1 to 6, 13 to 18, 25 to 30, 35 to 42) refer circle trajectory types of exercises, in upper part values refer to cross trajectory. Types of exercise from 1 to 12 and from 25 to 36 were done closing eyes, the other ones (13 to 24 and from 36 to 48) with open eyes.

Types of exercise on a frontal plane (parallel to coronal one) are related with number 1,4,7,10,13,16,19,22,25,28,31,34,37,40,43 and 46.

Types of exercise on a plane parallel to sagittal one are related with number 2,5,8,11,14,17,20,23,26,29,32,35,38,41,44 and 45.

Types of exercise on horizontal plane (parallel to transverse one) are related with number 3 and his multiples until number 48.

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
X1	51.847	7	7.407	4.57	0.0157
X2	2.708	1	2.708	2.48	0.1593
X3	2.909	1	2.909	4.07	0.0835
X4	251.771	1	251.771	862.1	0
X5	0.149	1	0.149	1.76	0.226
X6	0.245	2	0.123	0.48	0.6277
X1*X2	7.645	7	1.092	5.33	0
X1*X3	5.005	7	0.715	3.49	0.0013
X1*X4	2.044	7	0.292	1.43	0.1938
X1*X5	0.593	7	0.085	0.41	0.8935
X1*X6	3.567	14	0.255	1.24	0.2415
X2*X3	1.863	1	1.863	9.1	0.0028
X2*X4	0.295	1	0.295	1.44	0.2306
X2*X5	0.558	1	0.558	2.73	0.0998
X2*X6	0.115	2	0.057	0.28	0.7555
X3*X4	0.045	1	0.045	0.22	0.6383
X3*X5	0.002	1	0.002	0.01	0.9166
X3*X6	2.47	2	1.235	6.03	0.0027
X4*X5	0.182	1	0.182	0.89	0.3458
X4*X6	0.484	2	0.242	1.18	0.308
X5*X6	0.176	2	0.088	0.43	0.6508

Constrained (Type III) sums of squares.

Figure 4.7 Analysis of variance of MSJ_{ratio} for 48 types of exercises performed by 8 individuals of feasibility group.

X1 subject class, refers to the individual and it's assumed to be the random class.
X2 hand class, refers to the hand, left or right, used to do exercises.
X3 eye class, refers to condition of eyes, opened or closed, during exercises.
X4 shape class, refers to the shape of trajectory, cross or circle, to be drawn.
X5 direction class, refers to direction of movement, clockwise or counterclockwise.
X6 plane class, refers to the plane where volunteers are asked to do the movement.

The same statistical analysis were done on the same data taking into account the laterality of subjects: data of right hand belong to the «dominant» class for dexterous people, it's to say people using very often the right hand for one handed motor tasks (writing, using tools, moving a computer mouse); on the other hand, for lefty people data associated to «dominant» class come from exercises done with left hand. Another aspect of laterality involves direction of circulation, as consequence were introduced two new classes: «inward» and «outward». Inward class refers to exercises done in clockwise direction for dexterous people and counterclockwise for lefty people; just the opposite for outward class: counterclockwise direction for dexterous people and clockwise for lefty people. In term of matrix containing the MSJ_{ratio} values, each column contains values for one specific type of exercise, characterized by its own conditions, and each row contains values of one individual. To move from the original body side (left or right hand) matrix to the laterality (dominant or non-dominant) matrix the following two changes must be applied to the row of lefty individuals

- first: to exchange the block of elements from 1 to 24 with the block of elements from 25 to 48 (so that data of left hand are moved in the dominant zone of the matrix),

- second: to swap each odd column number with its neighbor even column number (so that clock and counterclockwise are moved to inward, the odd numbered column, and outward, the even numbered column, elements of the matrix).

From the point of view of dominance, results coming from analysis of variance are shown in figure 4.8 and can be observed that p parameter is a bit lower for dominance (dominant or non-dominant) than for hand class (left or right), ditto for ward class (inward or outward) compared to clock direction class (clock and counterclockwise).

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
SUBJECT	51.847	7	7.407	6.02	0.0072
DOMINANT	5.474	1	5.474	7.85	0.0264
EYE	2.91	1	2.91	4.07	0.0835
SHAPE	251.771	1	251.771	862.1	0
CLOCK	0.149	1	0.149	1.76	0.226
PLANE	0.245	2	0.123	0.48	0.6277
SUBJECT*DOMINANT	4.879	7	0.697	3.43	0.0015
SUBJECT*EYE	5.005	7	0.715	3.51	0.0012
SUBJECT*SHAPE	2.044	7	0.292	1.44	0.1904
SUBJECT*CLOCK	0.593	7	0.085	0.42	0.892
SUBJECT*PLANE	3.567	14	0.255	1.25	0.2363
DOMINANT*EYE	1.965	1	1.965	9.66	0.0021
DOMINANT*SHAPE	0.559	1	0.559	2.75	0.0983
DOMINANT*CLOCK	0.076	1	0.076	0.37	0.5417
DOMINANT*PLANE	0.62	2	0.31	1.52	0.2197
EYE*SHAPE	0.045	1	0.045	0.22	0.6373
EYE*CLOCK	0.002	1	0.002	0.01	0.9164
EYE*PLANE	2.47	2	1.235	6.07	0.0026
SHAPE*CLOCK	0.183	1	0.183	0.9	0.3443
SHAPE*PLANE	0.484	2	0.242	1.19	0.3058
CLOCK*PLANE	0.176	2	0.088	0.43	0.6491
Error	63.89	314	0.203		
Total	398.955	383			

Constrained (Type III) sums of squares.

Figure 4.8 Analysis of variance of MSJ_{ratio} taking into account the dominance effect for 48 types of exercise performed by 8 individuals of feasibility group .

The same statistical analysis was done for the haptic group of data. an overview of mean values and standard deviation of MSJ_{ratio} is given in figure 4.9.

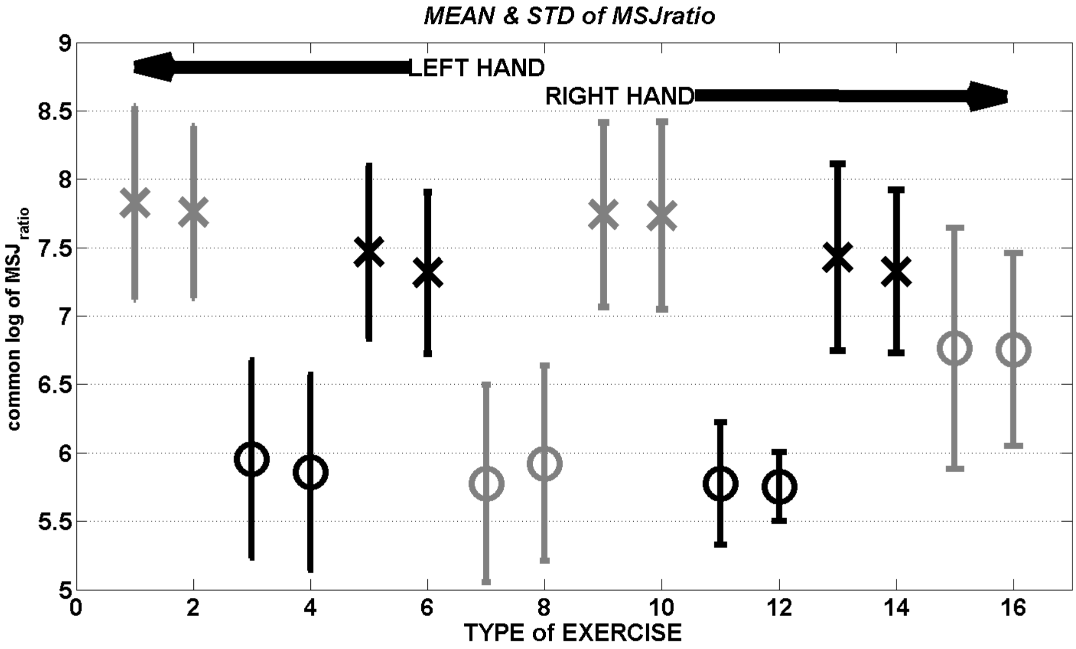


Figure 4.9 Mean values and standard deviation of MSJ_{ratio} for each type of exercise performed by haptic group.

On the left (types from 1 to 8) exercises done by left hand, on the right (types from 9 to 16) the other ones done by right hand.

Odd numbers refers to clockwise direction and even numbers are for counterclockwise.
Values in the lower zone of diagram (round markers) refer to types of exercises, done without haptic feedback.

Values in the upper zone of diagram (cross markers) refer to types of exercises, done with haptic feedback.

Types of exercise with visual feedback are plotted in grey, in black without the visual feedback.

An overview of mean values and standard deviation of MSJ_{ratio} for elderly group is in figure 4.10. The statistical analysis was done in the same way as for the haptic group of data.

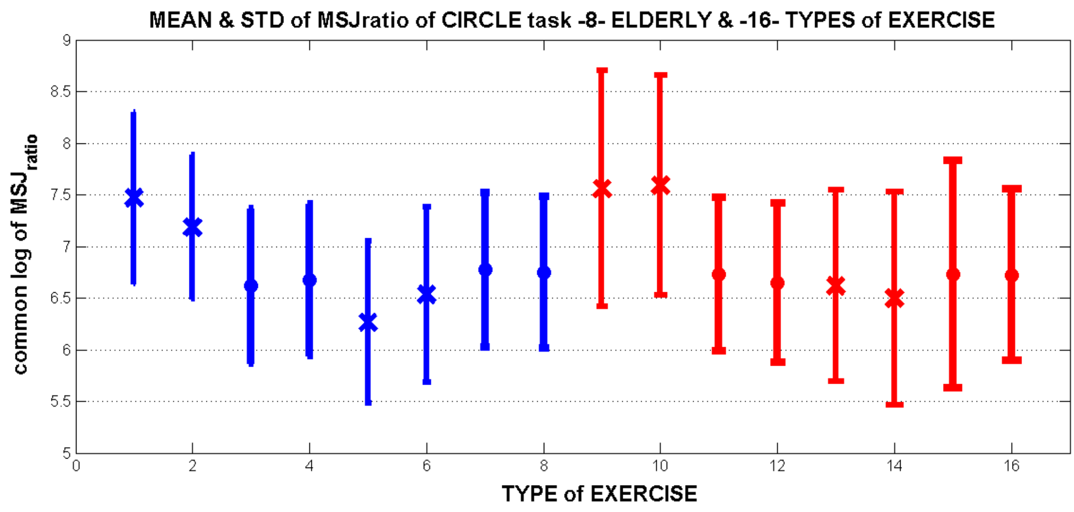


Figure 4.10 Mean values and standard deviation of MSJ_{ratio} extracted for each type of exercise from elderly group of data.

On the left (blue lines) exercises done by left hands, on the right the other ones (red lines) done by right hands .

Cross markers refers to exercises done under haptic feedback condition, round markers are for exercises without haptic feedback. Odd numbers refers to clockwise direction and even numbers are for counterclockwise.

Finally, mean values and standard deviation of MSJ_{ratio} extracted for each type of exercise from haptic group data and elderly group data were merged together and an overview can be seen in figure 4.11.

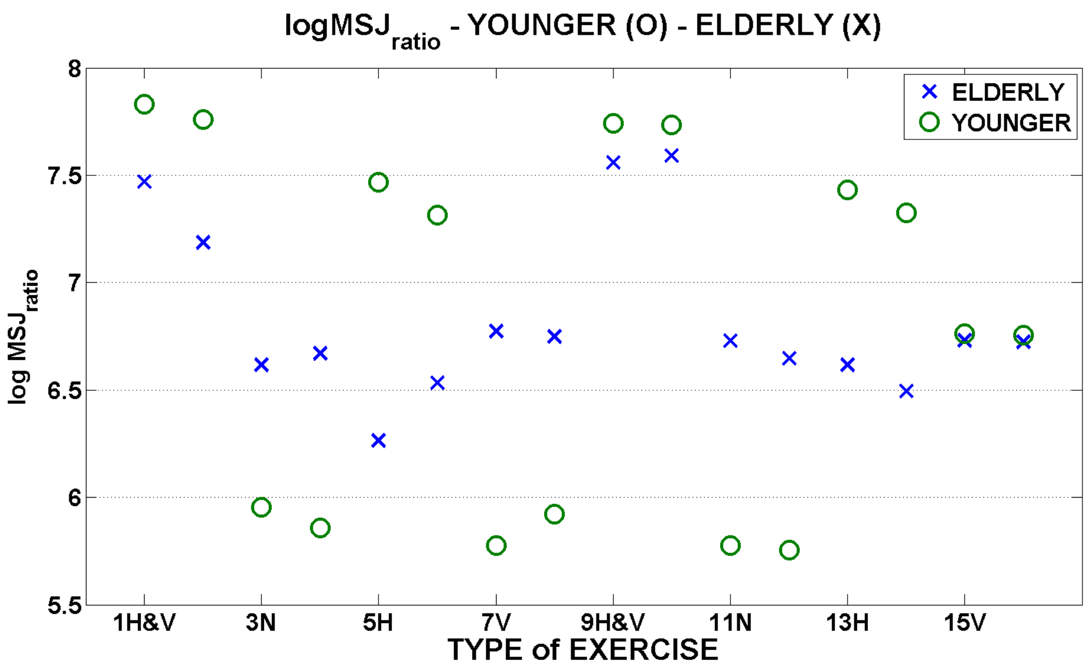


Figure 4.11 Mean values and standard deviation of MSJ_{ratio} extracted for each type of exercise from haptic and elderly group data.

Green circles refer to haptic group, blue crosses refer to elderly group.

On the left (from 1 to 8) types of exercise done by left hands, on the right the other ones (from 9 to 16) done by right hands .

Couples 1 and 2, 5 and 6, 9 and 10, 13 and 14 refer to exercises done with haptic feedback, the rest are without haptic feedback.

Couples 3 and 4, 7 and 8, 11 and 12, 15 and 16 refer to exercises done with visual feedback, the rest are without visual feedback.

Odd numbers refers to clockwise direction and even numbers are for counterclockwise.

CHAPTER V

Results and Conclusions

«The long run is a misleading guide to current affairs. In the long run we are all dead»
John Maynard Keynes

CHAPTER V

5.1 Results

Having in mind the research project, some considerations will follow about what objectives were reached by this research on hand movements by means of the haptic system.

First of all, the general aim to make a new haptic system for upper limb RMT has been reached only partially, in fact the system has been built up, but tested only on healthy people, so it lacks of tests on patients to get a clinical validation. Nevertheless the system is working fine, so the feasibility objectives can be considered as reached.

The software programs for functioning with haptic feedback and three dimensional virtual representation are stable and flexible enough to use the system for a variety of visual and motor tasks in controlled conditions.

The software programs developed for data collection and for extraction of parameters allow to use the system as a good tool for hand movement analysis.

Finally analysis of data collected on healthy people, extracted kinematic variables and other parameters, thanks to the statistical analysis, can be used to draw some very first conjectures about smoothness of basic hand movements. Moreover these data and derived statistical parameters can be considered as the first records of a much larger database on hand motor control. Such database, after a clinical validation, could be useful to early detect the presence and development of motor control diseases and quantify its severity; on the other hand it could allow to better measure and track the results of rehabilitation process. In other words, the system could be used not only for rehabilitation purposes, but as diagnostic tool too. It’s noticeable that these two medical purposes can be reached by means of just one equipment.

5.2 Conclusions

Referring to the statistical analysis shown in the previous chapter, data collected on healthy people, extracted kinematic variables and parameters, can be used to draw some conjectures about smoothness of basic hand movements. In case of more studies on larger groups of people will confirm these very first results, the system could be useful to improve efficacy and efficiency of RMT therapy protocols and knowledge about hand movements.

Let's start considering the statistical analysis of data coming from feasibility group already presented in chapter 4 at paragraphs 4.1 and 4.4.

The strong influence of trajectory shape, cross or circle, on mean values of MSJ_{ratio} can be clearly appreciated looking at figure 4.6. In fact values in the lower zone of diagram refer to exercises characterized by circle shaped trajectory, higher values in upper part of diagram refer to cross trajectory. This difference will be called «shape spread effect» in the following, or simply «shape spread» to shorten.

The detection of shape spread is a reasonable result considering that almost all the joint of human body can be well approximated as to be cylindrical or spherical. As consequence, motor tasks made of curve lines should be easier and smoother to execute than movements to draw straight lines. This observation can explain why the circles are smoother and less jerked than crosses.

Table 5.1 summarizes the analysis of variance done for jerk parameters and confirms that the trajectory shape is the most influencing condition on jerk. It can be observed that influence is stronger on MSJ_{ratio} than on MSJ because the ratio is considered to be a better indicator of smoothness [Hogan 2007]. Moreover there is no influence of conditions on MSJ_{min} because it's an indicator related with global parameters of movement, such as duration and amplitude, and not to the instantaneous values of jerk, so this jerk parameter in practice results to have a random relation with condition characterizing the type of exercise.

The visual feedback condition is another influencing factor, but weaker than shape trajectory.

TABLE 5.1 - Analysis of variance for jerk parameters MSJ, MSJ_{Min} AND MSJ_{ratio}

	EYE	TRAJ	PLN
MSJ	-	**	-
MSJ_{min}	-	-	-
MSJ_{ratio}	*	***	-

p values for several classes representing conditions of exercise types in feasibility group: visual feedback (EYE), trajectory shapes (TRAJ) and planes (PLN).

*** if ≤0.005,** if ≤0.05, *if≤0.1, - if> 0.1

When laterality, dominant or non-dominant hand, is taken into account instead of the simple body side, left or right hand, lower values of p reveal an increased influence of laterality class and ward class with respect to body side and clock direction of circulation.

Let's now consider the statistical analysis of data coming from haptic group already introduced in chapter 4.2 and 4.4. The strong influence of haptic feedback on MSJ_{ratio} can be clearly appreciated taking a look at figure 4.9. In fact values in the upper side of diagram (cross markers) refer to exercises performed with haptic feedback and lower values in down side of diagram (round markers) refer to exercises done in absence of haptic feedback. This situation is similar to what observed about the feasibility group for trajectory shape influence: so, similarly to what stated for shape spread, this difference will be called «haptic spread effect» in the following, or simply «haptic spread» to shorten.

In this case it's possible to conclude that haptic feedback, as a force field with direction transverse to motor task target, for younger healthy people is a cause of disturbance for motor control system aimed to get a correct execution of motor task. This could be a problem for the optimal selection of force in RMT according to the fundamental criteria of «assistance as needed». In fact the minimum level of assistance to improve motor task accuracy could lead to increase the jerk so that movement is less smoothed. Here a possible conflict can be found between geometry (accuracy on the target) and kinematic (smoothness). If so, in RMT protocols a tradeoff between these two aspects of motor control should be taken into account to ensure a good therapeutic process.

But the statistical analysis of data coming from elderly group, already introduced in chapter 4 at paragraphs 4.3 and 4.4, seems to falsify what stated previously about the effect of haptic feedback disturbance on haptic group. In fact, figure 4.10 shows a reduced spread between jerk of exercises done with or without feedback. This is more evident looking at figure 4.11: all mean values of MSJ_{ratio} coming from types of exercise performed with haptic feedback by the haptic group (green circles in the upper zone of figure 4.11) are greater than the corresponding values coming from the elderly group (blue crosses in figure 4.11). Similarly it happens for types of exercise performed without the haptic feedback: all mean values of MSJ_{ratio} from the haptic group (green circles in the lower zone of figure 4.11) are lower than the corresponding values coming from the elderly group, with only one exception that will be discussed later. These observations allow believing that the higher haptic spread of the haptic group, in comparison with the elderly group, could be another useful parameter to check motor control capability. The reason of this reduced spread effect with respect to the age could be related with a reduced capacity to perceive the haptic stimulation and/or a reduced ability to control movements. Similarly to what stated for shape and haptic spread, this reduction of haptic spread will be called «age reduction of haptic spread effect» in the following, or simply «age spread» to shorten.

As stated few lines above, there is only one exception to the age spread: the exercises done with just visual feedback and right hand only. Mean values of MSJ_{ratio} for these types of exercise (numbered 15 for clockwise condition and 16 for counterclockwise) are placed in figure 4.11 near the right border. Mean values of MSJ_{ratio} of elderly group (the two blue crosses on the right) are slightly lower than the corresponding values for haptic group (the two green circles on the right), in practice they can be considered as to be equal. This is in contrast with age spread. A possible explanation could come from the dominance: the motor control of dominant hand maintains enough motor skills ability and dexterity due to everyday life activities. These activities reduce the effect of age on motor control system and this could be in accordance with the «use or lose» principle widely present in neurosciences. An analysis based on dominance criteria, similarly to what was done for feasibility group, could enforce this explanation.

Studies on the effect of haptic feedback showed that it has a reduced disturbing influence on movements of patients affected by motor control disease. It can be speculated that haptic spread, found in haptic group and reduced in elderly group, could be negligible or even inverted for patients, but it need a clinical validation to confirm such prediction, of course. If prediction will be confirmed, haptic spread could become a useful parameter for diagnosis and to monitor the rehabilitation process.

As further investigations making use of the system, not only clinical validation must be done, but a volunteer group enlargement should be considered too.

It could be worthy to do a sensitivity analysis about force feedback level to ascertain if the spread effects are negligible under a threshold value.

Moreover the system could be enriched by sensors, such as a force plate [Panarese & Benoni 2011], to allow measurements of forces and pairs applied by the hand to the handle. About the handle, it could be interesting to investigate the influence of its shape on dexterity and smoothness.

Finally, a very important aspect to investigate is the relation between smoothness and geometry of movements with empirical tests (S.I.S.A., Fugel-Meyer, blocks and others currently used in good medical practice) to evaluate hand motor control capability [Osu et al. 2011]. The system could be a useful tool to clarify what physical variables better correlates with empirical test scales.

I do believe haptics technologies strengthen new hopes for achievements of future therapies: a future disclosing new horizons to our society thanks to haptics is near to come.

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Wikipedia

Some informations and excerpts are taken from the following pages:

Falcon

Fine motor skill

Haptics

Haptic Technologies

Mechanoceptors

Phantom Limb

Somatosensory System

Stroke

Stroke Recovery

Supernumerary Body Part

PODCAST

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ANNEX I

ABSTRACT DELLA TESI IN LINGUA ITALIANA

Scuola Dottorale di Ingegneria
Sezione di Ingegneria dell'Elettronica Biomedica,
dell'Elettromagnetismo e delle Telecomunicazioni

Tecnologie Aptiche
per la Destrezza e la Regolarità
dei Movimenti della Mano

Baldassarre D'Elia

XXV Ciclo della formazione Dottorale

Docente guida Professor Tommaso D'Alessio

1.1 Sommario

Lo scopo principale della attività di ricerca è stato realizzare un sistema aptico per la riabilitazione in grado di valutare la destrezza nei movimenti della mano e favorirne il recupero terapeutico. Di questo sistema potrebbero beneficiare tutti i pazienti che soffrono di difficoltà in alcuni movimenti del braccio e della mano. Attualmente già esistono o sono in fase di studio sistemi di questo tipo, ma sono relativamente costosi ed anche inefficaci o inefficienti per alcuni aspetti. La terapia basata sull'utilizzo di questi sistemi viene frequentemente indicata con la sigla RMT, acronimo dell'espressione «Robot Mediated Therapy». Peraltro, anche la terapia tradizionale condotta manualmente dai fisioterapisti presenta limiti ed inconvenienti, oltre ad un costo ancor più elevato di quella con le macchine in commercio. Nell'ambito del lavoro di ricerca, ho realizzato un prototipo funzionante di sistema aptico, sperimentato su volontari sani, raccogliendo ed elaborando i dati per l'analisi del movimento della mano Per far questo, ho realizzato alcuni dei programmi necessari al funzionamento, alla raccolta ed all'elaborazione dei dati. I risultati più significativi vengono mostrati nei capitoli finali.

Alcuni dei risultati ottenuti sono stati presentati sia all'ultima riunione annuale del Gruppo Nazionale di Bioingegneria, tenutasi presso il nostro ateneo nel giugno scorso, sia alla "International Conference on NeuroRehabilitation" tenutasi a Toledo nel novembre scorso.

1.2 Introduzione

Per elaborare il progetto di ricerca, ho effettuato un'ampia indagine sulla letteratura esistente ed ho redatto, in lingua inglese, un breve resoconto sulle principali macchine robotizzate per la riabilitazione degli arti superiori di pazienti, specialmente quelli colpiti da ictus, dal titolo "Review of Haptic Robots for Rehabilitation of upper Limb". Tra i vari articoli analizzati, quelli che esprimono considerazioni critiche sui limiti di applicazione, di efficacia e di efficienza rispetto alla migliore prassi clinica, sono stati considerati particolarmente significativi.

Per realizzare un sistema aptico per la riabilitazione motoria di pazienti affetti da discinesie, in particolare quelle derivanti da ictus cerebrale, ho realizzato un piano di lavoro nel quale si descrivono gli obiettivi generali e quelli specifici del progetto di ricerca. Il principale obiettivo è quello di realizzare un sistema che possa affiancare, ed in taluni casi sostituire, quelli maggiormente in uso, superando alcuni dei limiti di cui si è detto, migliorandone efficacia ed efficienza nonché la flessibilità d'utilizzo, il tutto con costi notevolmente inferiori.

Tra gli obiettivi generali del piano di lavoro per l'attività di ricerca, il primo è la realizzazione del sistema che espongo più in dettaglio qui di seguito.

1.3 Realizzazione del Sistema

Per la realizzazione del sistema è stata usata l'interfaccia aptica Falcon della ditta Novint, che presenta le seguenti caratteristiche:

Spazio di lavoro 10 x 10 x 10 cm

Forza massima 10 N

Dimensioni 23 x 23 x 23 cm

Peso 30 N

Potenza assorbita 30 W

Risoluzione > 400 dpi

Interfaccia USB 2.0

Impugnatura intercambiabile

Ho studiato la documentazione relativa, parallelamente allo studio dei linguaggi C/C++, per programmare l'interfaccia in modo da poter poi raccogliere i dati relativi alla posizione del pomello dell'interfaccia durante l'esecuzione di compiti motori. Una volta realizzato tale programma, sono state svolte delle prove per verificare le funzionalità necessarie al proseguimento della ricerca, in particolare le prove su volontari sani. Alcuni dei dati inizialmente raccolti sono stati elaborati per ricavare parametri cinematici.

Per quanto riguarda l'esecuzione e la registrazione di traiettorie con il pomello dell'interfaccia, dopo aver redatto il protocollo sperimentale sono stati raccolti i primi dati sui volontari sani.

Nel protocollo si chiedeva di compiere 5 ripetizioni di ogni esercizio, muovendo il pomello per eseguire l'esercizio in diverse condizioni quali:

- la mano da utilizzare (destra o sinistra),
- la traiettoria del movimento (circonduzioni o croci),
- il verso di percorrenza (orario o antiorario), il piano di riferimento ideale (parallelo al piano sagittale, coronale o trasverso),
- il feedback di tipo visivo (occhi chiusi o aperti e monitor davanti) e aptico (con o senza un campo di forze).

E' stato reclutato un primo gruppo di 11 volontari (età media di circa 27 anni) e recentemente è stato reclutato un secondo gruppo di 25 volontari più anziani (circa 64 anni in media), per osservare se e in quale modo l'età dei soggetti influenzi i parametri considerati. I dati relativi a questo secondo gruppo sono stati elaborati per 8 di essi, quelli relativi agli altri sono in fase di elaborazione.

I dati sono stati elaborati per calcolare varie grandezze cinematiche quali: durata, lunghezza della traiettoria percorsa, velocità, accelerazione e jerk. Inoltre è stata effettuata un'analisi statistica dei risultati ottenuti per ricavarne valori medi e scarto tipo. Infine, l'esecuzione dell'analisi della varianza ha consentito di porre in evidenza quali sono le condizioni che maggiormente influenzano le grandezze in gioco.

Successivamente l'estrazione delle grandezze cinematiche ha consentito di calcolare un parametro ritenuto particolarmente significativo [Hogan & Sternad 2007 e 2009] per valutare la regolarità dei movimenti, denominato Mean Squared Jerk ed indicato con la sigla MSJ. Per generalizzare e rendere meglio confrontabili i risultati delle prove sperimentali condotte in condizioni anche molto diverse tra loro, è stato introdotto anche il Mean Squared Jerk Ratio (indicato con la sigla MSJr), un parametro adimensionale che è pari al rapporto tra MSJ e il cosiddetto «minimum jerk» msj0 definito secondo la seguente relazione [Hogan 2007]:

$$MSJ_0 = 360 \cdot A^2/d^6$$

nella quale sono:

A l'ampiezza del movimento

d la sua durata.

Il campo di variazione di MSJr è comunque assai ampio, anche nei casi di studio più frequentemente analizzati (traiettorie lineari, circolari o a forma di otto), sia per soggetti sani sia per persone affette da discinesia, ed anche per sani che imitino il movimento patologico.

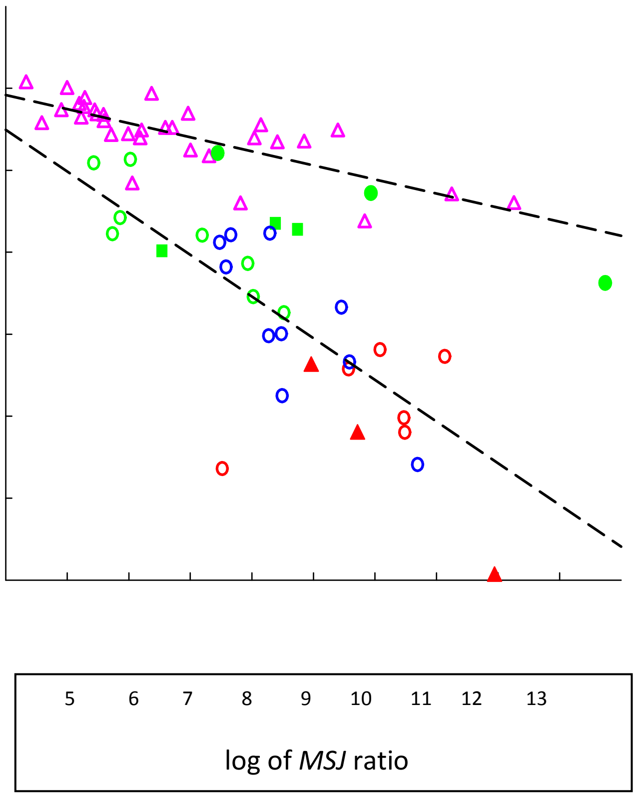

Fig. 1 - MSJ_r in ascissa e *MedianLC* (mediana del negativo del logaritmo della curvatura κ) in ordinata, per traiettorie della mano che portano un bicchiere dal tavolo alla bocca. I triangoli rosa sono per i volontari sani ed i pazienti nell'utilizzo della mano non colpita dall'infermità, cfr. fig. 5 in [Osu et al. 2011].

I valori sono tipicamente compresi in circa 10 ordini di grandezza tra 10^4 e 10^{14}, per ciò MSJr viene generalmente espresso o rappresentato nei grafici in forma di logaritmo decimale come si può osservare in fig. 1 [Osu et al. 2011].

1.4 Risultati e Conclusioni

Come accennato in precedenza, molti dei dati raccolti sono stati elaborati per ricavare parametri cinematici significativi, quali la variazione dell'accelerazione nel tempo, c.d. scatto o «jerk», di particolare rilevanza in questo tipo di studi.

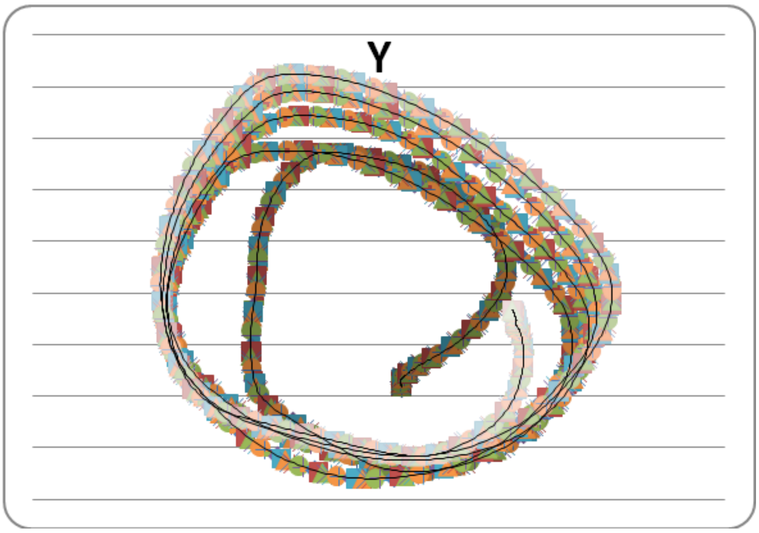

Fig. 2a - Evoluzione nello spazio di lavoro della posizione del pomello durante l'esecuzione di cinque circonduzioni su un ideale piano frontale. Coordinate x e y espresse in metri.

A titolo di esempio si presentano in fig. 2a e 2b i grafici che rappresentano l'evoluzione temporale della posizione del pomello nello spazio di lavoro (coordinata x, per le posizioni lungo l'asse sinistra-destra, coordinata y per le posizioni lungo l'asse basso-alto e coordinata z per le posizioni lungo l'asse postero-anteriore) durante l'esecuzione di cinque circonduzioni su un ideale piano frontale.

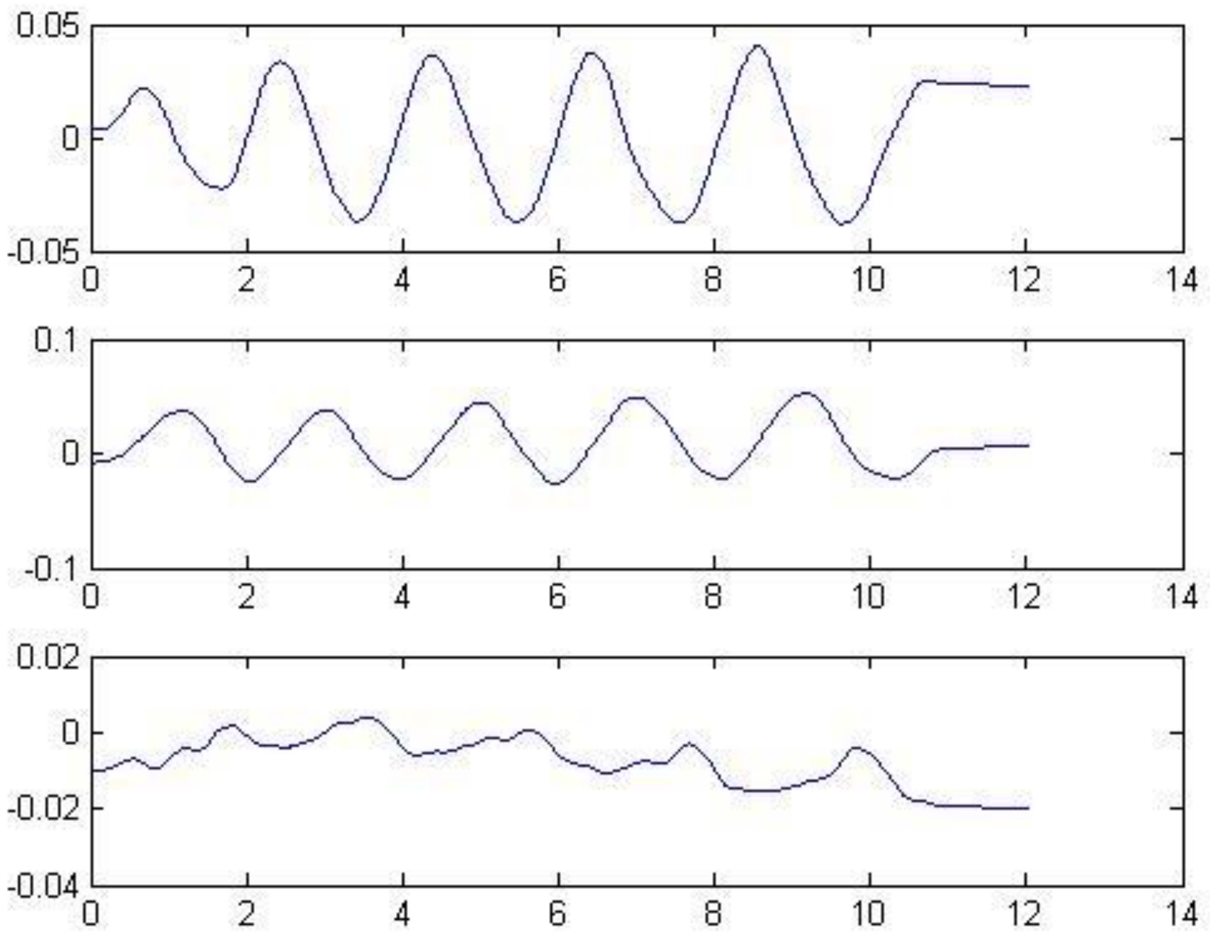

Fig. 2b - Evoluzione temporale della posizione del pomello nello spazio di lavoro durante l'esecuzione di cinque circonduzioni su un ideale piano frontale. L'asse delle ordinate esprime il tempo in secondi. Dall'alto verso il basso si mostrano in ordinata le coordinate x, y e z espresse in metri. Si può osservare il campo di variazione lungo l'asse z ridotto rispetto a quello lungo gli assi x e y in quanto il compito motorio ideale è teso a svolgere le circonduzioni su un ideale piano frontale.

L'asse delle ordinate esprime il tempo in secondi. Dall'alto verso il basso si mostrano in ordinata le coordinate x, y e z espresse in metri. Si può osservare che il campo di variazione lungo l'asse z è minore rispetto a quello lungo gli assi x e y in quanto il compito motorio è teso a svolgere le circonduzioni su un ideale piano frontale In fig. 3 si mostra il grafico che rappresenta l'evoluzione temporale della velocità in modulo durante l'esecuzione di un analogo compito motorio da parte di uno dei volontari.

Per ognuno dei diversi tipi di esercizio è stato valutato MSJr ed è stato effettuato il confronto per lo stesso compito effettuato in condizioni opposte (e.g.: destra/sinistra, orario/antiorario, visivo/cieco) o secondo il piano di esecuzione. Sono stati confrontati anche i compiti svolti nelle stesse condizioni ma che differiscono per la traiettoria (e.g.: cerchi/croci). Per quest'ultimo caso si può facilmente osservare che le croci, costituite da segmenti tendenzialmente lineari, presentano un valore di MSJr maggiore rispetto ai movimenti circolari. Ciò è in accordo con quanto ci si può attendere, considerando che quasi tutte le articolazioni del corpo [Wafa Skalli 2011] e quindi anche quelle del braccio e della mano, possono essere schematizzate come vincoli cilindrici o sferici che meglio si prestano ad effettuare movimenti caratterizzati da una geometria tendenzialmente circolare.

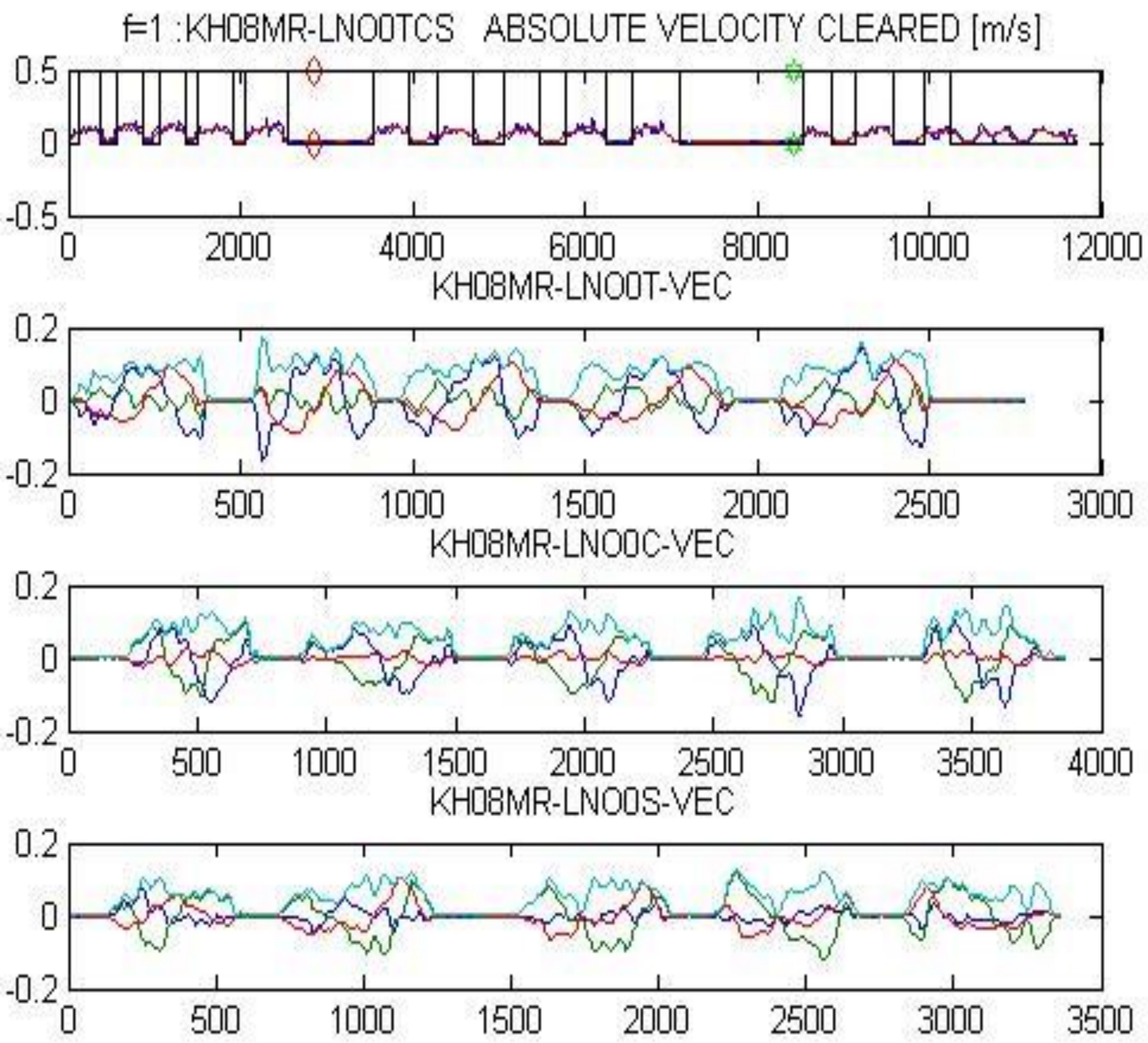

Fig. 3 - Evoluzione della velocità del pomello durante l'esecuzione di cinque circonduzioni su tre distinti piani, paralleli ai piani anatomici di riferimento (T=trasverso/orizzontale, C=coronale/frontale, S=sagittale) .

Velocità sull'asse delle ordinate in [m/s] e numero del campione lungo l'asse delle ascisse. Frequenza di campionamento $f_c \approx 166$ kS/s. Durata complessiva del compito circa 1 minuto e 10 secondi.

Inizialmente, a ciascun volontario è stato chiesto di effettuare 48 esercizi secondo le seguenti caratteristiche di esecuzione: mano (sinistra o destra), visione (occhi aperti o chiusi), traiettoria (cerchi o croci), verso (orario o antiorario), piano (coronale, sagittale o trasverso).

A titolo esemplificativo la fig. 4 mostra i confronti di cui si è detto per uno dei volontari.

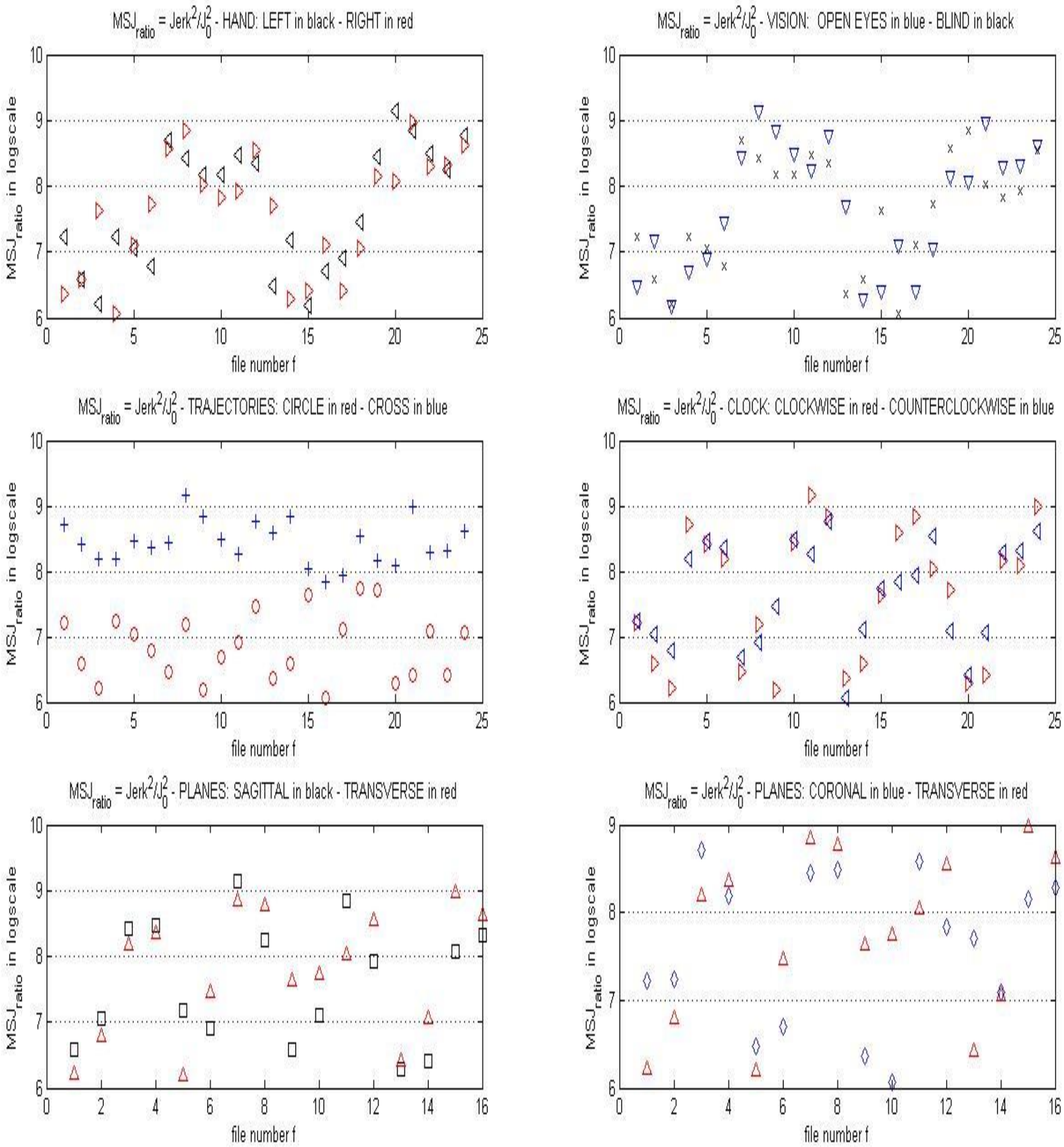

Figura 4 – [per righe, da sinistra verso destra e poi dall'alto in basso]

Valori di MSJ_r (in ordinata) per un volontario: confronto per diverse condizioni di esecuzione

– mano, sinistra o destra;
– visione, occhi aperti o chiusi;
– traiettoria, cerchi o croci;
– verso, orario o antiorario;
– piani, sagittale e trasverso;
– piani, coronale e trasverso.

Per approfondire e meglio caratterizzare il confronto tra mano destra e mano sinistra, per tutti i volontari è stato calcolato il rapporto tra MSJr effettuato con la mano destra e quello ottenuto effettuando la stessa traiettoria nelle stesse condizioni con la mano sinistra; è stata poi calcolata la media di questo rapporto per tutte le traiettorie considerate (cfr. fig. 5).

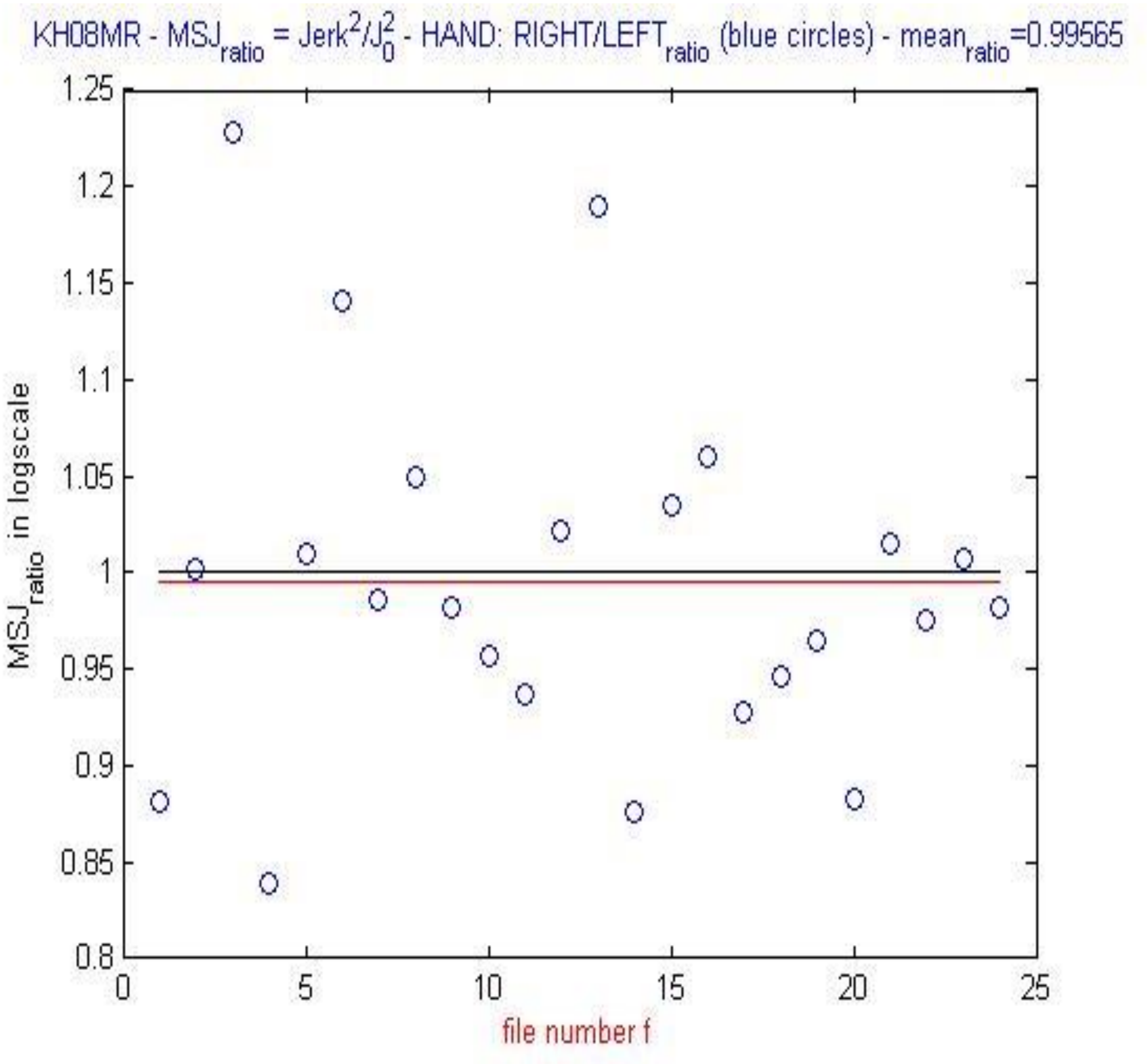

Figura 5 – Valori del rapporto (in ordinata) tra MSJ_r relativo alla mano destra ed alla mano sinistra, per un volontario di lateralità dichiarata prevalentemente destra. In rosso la linea che rappresenta il valor medio di questo rapporto relativo ai 24 compiti registrati nelle seguenti condizioni:

- visione, occhi chiusi (esercizi da 1 a 12) o aperti (esercizi da 13 a 24);
- traiettoria, cerchi (esercizi da 1 a 6 e da 13 a 18) o croci (esercizi da 7 a 12 e da 19 a 24);
- verso, orario (esercizi da 1 a 3, da 7 a 9, da 13 a 15, e da 19 a 21) o antiorario (esercizi da 4 a 6, da 10 a 12, da 16 a 18 e da 22 a 24)
- piani, coronale (esercizi 1,4,7,10,13,16,19,22) o sagittale (esercizi 2,5,8,11,14,17,20,23) o trasverso (esercizi 3,6,9,12,15,18,21,24).

Questo rapporto, per i volontari fin qui analizzati, risulta compreso in un intervallo pari a ±10% e, per tutti i volontari tranne uno, il valore di MSJr della mano dominante risulta sempre maggiore di quello della mano non dominante. Questo risultato, che sembra in contrasto con l'idea intuitiva per cui la mano non dominante dovrebbe mostrare una minore regolarità dei movimenti, potrebbe essere dovuto al fatto che i volontari hanno tutti eseguito prima i compiti motori con la mano dominante e poi con l'altra: un fenomeno di apprendimento potrebbe aver influito su questo risultato.

L'analisi statistica dei valori calcolati di MSJr e l'analisi della varianza svolta per le diverse condizioni di esecuzione degli esercizi, consentono di evidenziare alcuni risultati significativi nell'ambito della ricerca condotta. Il risultato dell'analisi statistica dei primi 48 esercizi, svolti senza feedback aptico, è schematicamente rappresentato nel grafico di fig. 6.

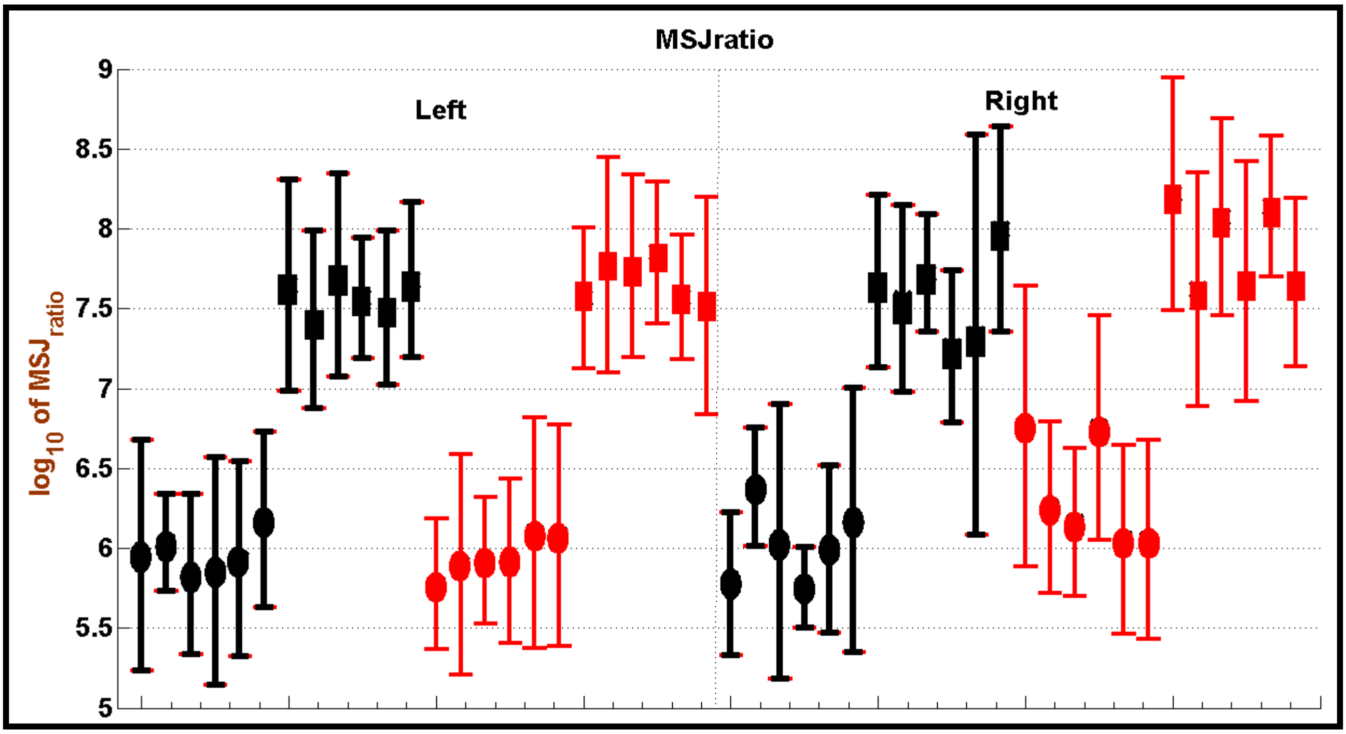

***Figura 6** - Valor medio e deviazione standard di MSJr per ciascun esercizio senza feedback aptico svolto dai volontari sani.*

L’ordinata consente di leggere il logaritmo decimale del MSJr .

I 24 esercizi sulla sinistra sono stati eseguiti con la mano sinistra, i restanti 24 con la mano destra. Il MSJr dei segmenti con un ovale al centro si riferisce agli esercizi con traiettorie circolari, gli altri si riferiscono alle traiettorie a croce e si riconoscono per il rettangolo al centro. Si può osservare che i valori relativi alle traiettorie a croce sono di circa un ordine di grandezza più grandi rispetto a quelli delle traiettorie circolari.

In rosso si mostrano gli esercizi svolti con gli occhi aperti ed in nero quelli svolti con gli occhi chiusi.

In ciascuno degli 8 gruppi di 6 esercizi, che si succedono da sinistra verso destra, i primi 3 si riferiscono a quelli svolti in senso orario e gli altri 3 in senso antiorario. In ciascuno di questi gruppi da 3 esercizi, il primo viene eseguito su un piano frontale e verticale parallelo al piano coronale, il secondo è parallelo al piano sagittale ed il terzo è su un piano orizzontale, parallelo al piano trasverso.

Questi primi dati mostrano che esiste una differenza significativa tra il jerk degli esercizi nei quali i soggetti eseguono una traiettoria circolare e quelli in cui eseguono una traiettoria a forma di croce. L’influenza del tipo di traiettoria è più evidente su MSJr, quasi un ordine di grandezza tra le traiettorie circolari e quelle a forma di croce.

Un’influenza, seppur di minore entità, del feed-back visivo (occhi aperti o chiusi) si potrebbe avere su MSJr. E’ interessante osservare che alcuni volontari hanno spontaneamente affermato di ritenere più agevole l’esecuzione degli esercizi ad occhi chiusi anziché ad occhi aperti.

Non è emersa un'influenza dell'orientamento dei piani su MSJr, sebbene esistano studi che mostrano una significativa differenza tra correlati neurali relativi all'esecuzione di traiettorie verticali rispetto a quelle orizzontali.

Non vi è relazione tra le condizioni di esecuzione degli esercizi e MSJmin. Ciò è accettabile dato che la definizione di questo parametro è funzione solo della durata e dello spazio percorso e non dei valori istantanei del jerk.

Sulla base di questi risultati iniziali, ho deciso di analizzare il movimento della mano dei soggetti sani sempre attraverso l'estrazione dei parametri relativi al jerk, ma inserendo anche un feedback aptico secondo quanto consentito dalle caratteristiche dell'interfaccia. Ai volontari è stato chiesto di eseguire altri 8 esercizi caratterizzati dalle seguenti condizioni:

traiettoria idealmente circolare su un piano frontale parallelo a quello coronale,

mano destra o mano sinistra;

senso orario o antiorario

con o senza feedback visivo.

Il feedback aptico è realizzato con un campo di forze di geometria cilindrica nello spazio di lavoro e di tipo radiale in un piano parallelo al piano xy. La forza è nulla lungo una circonferenza di diametro pari a 0,07 m e diretta verso la circonferenza sia all'interno che all'esterno del cerchio.

Il feedback visivo è costituito da una circonferenza di riferimento rappresentata con una linea verde sullo schermo da 22 pollici del pc il cui diametro apparente è di circa 0,19 metri. Ai volontari è stato chiesto di mantenere un piccolo cerchietto bianco, del diametro apparente di circa 1 cm, il più vicino possibile alla circonferenza bersaglio. Il cerchietto bianco rappresenta sullo schermo la posizione del pomello dell'interfaccia nello spazio virtuale. Il valore massimo della forza radiale ai bordi dello spazio di lavoro è di circa 3 N.

L'analisi statistica dei valori calcolati di MSJr e l'analisi della varianza svolta per le diverse condizioni di esecuzione degli esercizi, consente di evidenziare alcuni risultati significativi che sono esposti nel seguito.

Il risultato dell'analisi statistica degli 8 esercizi, eseguiti con feedback aptico, e degli altri 8, eseguiti senza feedback aptico, è schematicamente rappresentato nel grafico di fig. 7.

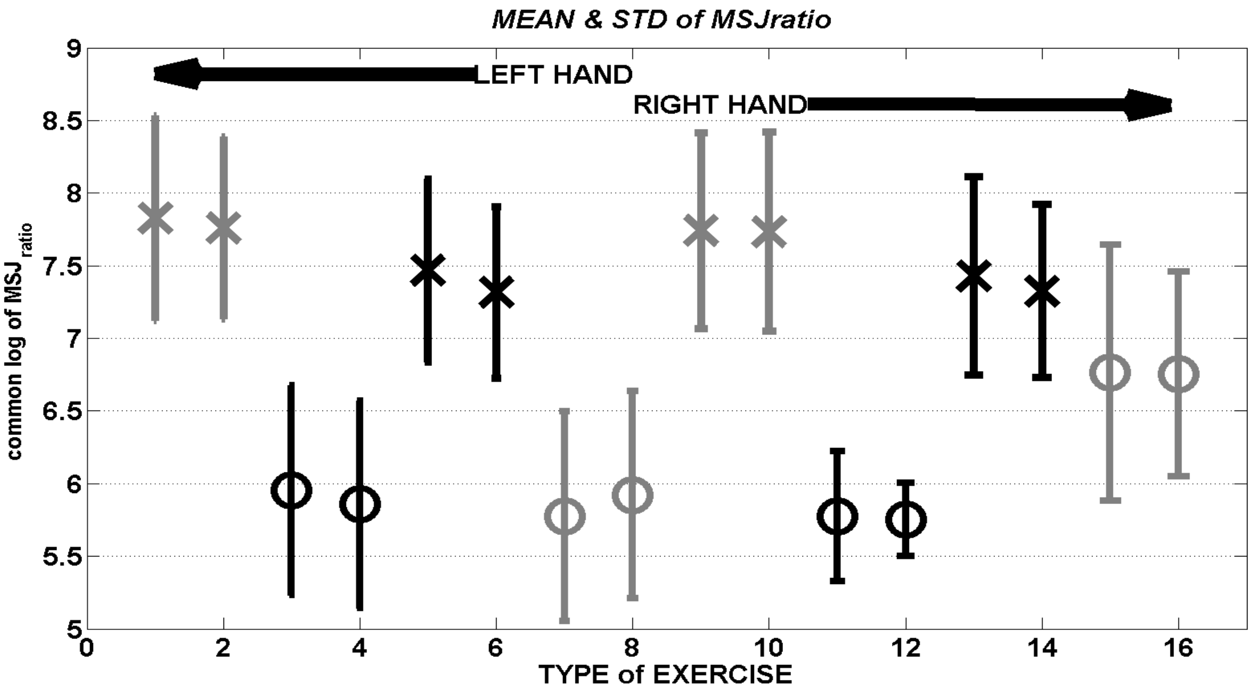

Figura 7 *– Valor medio e scarto tipo di MSJ$_{ratio}$ (logaritmo decimale). Mano destra (a destra) o mano sinistra (a sinistra); con (croci) o senza (cerchi) feedback aptico; con (in grigio) o senza (in nero) feedback visivo. I numeri dispari si riferiscono alle circonduzioni in senso orario e quelli pari al verso antiorario.*

Si può osservare che i valori di MSJratio sono più alti per tutti gli esercizi eseguiti con feedback aptico. I valori più elevati di MSJratio si hanno per gli esercizi eseguiti con feedback aptico e feedback visivo.

In conclusione posso affermare che:

è stato realizzato un sistema utilizzabile nella riabilitazione motoria di pazienti che soffrono di discinesie della mano;

sono stati raccolti dati su una popolazione (suddivisa in due gruppi di età) di volontari sani per verificare la funzionalità dell'apparecchio e per poterli poi confrontare con quelli eventualmente saranno raccolti con i pazienti;

dai dati di posizione dell'impugnatura della interfaccia aptica, sono stati estratti MSJratio ed altri parametri relativi al jerk.

Questi primi risultati mostrano dunque una forte influenza del tipo di traiettoria sulla regolarità dei movimenti, ma al tempo stesso anche il feedback aptico mostra una notevole influenza che si può interpretare come un elemento di disturbo. Poiché in molti sistemi per la RMT si utilizza il feedback aptico per migliorare l'esecuzione dei movimenti secondo il principio dell'«assistenza quando/quanto necessaria» («assist as needed»), se in futuro questi risultati iniziali saranno confermati e generalizzati, si dovrà tenere conto di questo effetto disturbante nello stabilire i livelli di forza adeguati per migliorare il processo terapeutico.

Questi risultati mostrano che anche il feedback visivo incrementa il jerk dei movimenti: ciò si potrebbe attribuire al conflitto tra regolarità ed accuratezza del movimento, ipotizzando che una maggiore accuratezza comporti un jerk più elevato. Nelle attività della vita quotidiana («Daily Life Activity» spesso indicata con l'acronimo ADL o DLA) che interessano particolarmente i pazienti che soffrono di questo genere di patologie, in molti movimenti non è tanto la regolarità del movimento che interessa, ma piuttosto un efficace raggiungimento dell'obiettivo (punto finale della traiettoria nello spazio, tipicamente la bocca nel mangiare), ma esistono anche i casi in cui la regolarità riveste un ruolo preponderante (come nella manipolazione di liquidi in un contenitore, tipicamente per il bere). Anche in questo caso l'analisi diagnostica e la prassi terapeutica, con o senza l'implicazione della RMT, dovrebbero tenere conto del necessario compromesso tra geometria e cinematica del movimento.

Infine, quando il feedback aptico si dimostra essere un elemento disturbante più che coadiuvante, il disturbo potrebbe essere maggiore quanto migliore è il controllo motorio da parte dell'organismo e quindi dovrebbe risultare maggiore:

nei sani più che nei pazienti (e ciò è confermato da altri lavori);

nei giovani rispetto agli anziani (e ciò si desume dal confronto tra i due gruppi studiati, anche se sono stati elaborati solo i primi dati del secondo gruppo),

per la mano dominante rispetto all'altra (ma ciò non può emergere dalla mia ricerca a causa del protocollo sperimentale che prevede sempre l'utilizzo della mano dominante prima della seconda)

quella dell'arto impedito rispetto a quello sano nei pazienti post-ictus o parkinsoniani (e ciò potrebbe emergere da un eventuale studio su questi tipi di pazienti).

Anche questo aspetto, se confermato e generalizzato, dovrebbe essere tenuto in conto nell'ambito della terapia condotta con sistemi aptici.

Una causa dell'inefficacia o inefficienza dei sistemi attuali per la RMT potrebbe quindi essere legata al fatto che quasi tutti consentono solo movimenti bidimensionali su un piano o sono finalizzati al recupero della forza più che dei movimenti più fini. L'utilizzo di un feedback aptico è considerato assai utile per il recupero della forza nei movimenti dell'arto, ma al tempo stesso le forze di assistenza possono influire negativamente sulla regolarità del movimento, specialmente nei movimenti fini. Quindi nella riabilitazione di movimenti più piccoli, spesso presenti nelle ADL, sarà necessario valutare quale sia il miglior compromesso tra forza di feedback, che aiuta la precisione dei movimenti, e il necessario livello di regolarità affinché il gesto sia compiuto con successo.

I principali risultati di questa ricerca sono stati la realizzazione del sistema aptico ed il suo utilizzo per raccogliere dati cinematici di esercizi svolti da persone sane. I dati raccolti sono stati analizzati e studiati per poter esprimere considerazioni sulla relazione tra un parametro quantitativo quale il jerk, legato alla regolarità del movimento, e le diverse condizioni che possono influenzarlo.