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Application of robotic and mechatronic systems to neurorehabilitation

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1. Introduction

During the last decades, the potentiality of robotics as a tool for neuroscientific investigations has been demonstrated, thus contributing to increase knowledge on biological systems. On the other hand, a detailed analysis of the potentialities of these systems (Dario et al., 2003) based on recent neuroscientific achievements, in particular about the mechanisms of neurogenesis and cerebral plasticity underlying the motor learning and the functional recovery after cerebral injury, highlights the advisability of using the robotic technologies, as systems able to contribute to a breakthrough in the clinical procedures of neurorehabilitative treatments. Several examples of robotic machines applied to both neuroscience and neurorehabilitation can be found in the literature (Krebs et al., 1998; Colombo et al, 2000).

One of the main scientific and technological challenges is represented by the design and development of innovative robotic and mechatronic systems able to i) simplify interaction modalities during assisted motor exercises, ii) enhance adaptability of the machines to the actual patient performance and residual abilities, iii) provide a comprehensive picture of the psycho-physiological status of the patient for assessment purposes, through the integrated use of brain imaging techniques.

The basic assumption of this work relies on a human-centred approach applied to the design of robotic and mechatronic devices aimed at carrying out neuroscientific investigations on human sensorimotor behaviour, delivering innovative neurorehabilitation therapies and assessing the functional recovery of disabled patients. Special attention is paid to the issues related to human-machine interaction modalities inspired to human motor mechanisms and the design of machines for the analysis of human motor behaviour and the quantitative assessment of motor performance.

2. Background

In industrialized societies, several factors contribute to a growing need for rehabilitative services, as complement and support to surgical and pharmacological treatments. The main

of them are the increasing longevity of the population, the trend towards reducing the duration of hospitalization, the use of therapies that can treat highly progressive debilitating diseases, the increased incidence of severe and moderate disabilities resulting from the activities at risk of injury and trauma, the use of advanced techniques of resuscitation.
The need for appropriate rehabilitative therapies has an increasing importance in many motor disorders of neurological origin: in this case we speak more specifically of neurorehabilitation.
Millions of people worldwide suffer from motor disorders associated with neurological problems such as stroke, brain injuries, spinal cord injuries, multiple sclerosis, Parkinson's disease.
A brief outlook to the Italian situation can help to understand the impact: each year in Italy about 196,000 strokes occur[1] with approximately 20% of affected people who die within the first month following the acute event and 30% of survivors are severely disabled. Of these 196,000, 80% are first episodes, whereas 20% are relapses.
Stroke represents the third leading cause of death in industrialized countries, after cardiovascular diseases and cancer and the leading cause of disability with a significant impact at individual, family and social level (Feygin et al., 2003; Murray et al., 1997; Marini et al., 2004).
The incidence of stroke progressively increases with age: it reaches the maximum value in people over 85 years old (24.2%) with a male predominance (28.2%) than females (21.8%). The prevalence of stroke in the Italian elderly population (age 65-84 years) is equivalent to 6.5% and is slightly higher in men (7.4%) than in women (5.9%). Stroke affects, although to a lesser extent, young people: every year about 27,000 people in productive age (<65 years) are affected (SPREAD, 2007).
In the U.S., the estimated cost of hospitalization due to stroke in 1998 is $68.9 billion (Heart Disease and Stroke Statistics 2009 Update) .

The traditional therapy methods present some limits, which is important to focus on. In many of the above mentioned cases, the traditional motor rehabilitative approaches involve manipulation of the paretic upper limb by the therapist. Usually the treatment is planned by assessing *ex ante* the residual abilities of the subject and can last several hours a day: it can be often a long and exhausting exercise for both the patient and the therapist.
The therapeutic treatments can be extended for several months after hospitalization, during which patients must travel daily to the clinical facilities and face hard discomforts for themselves and their family.
Moreover, for many motor disorders is not yet sufficiently clear what are the therapeutic approaches and clinical protocols that are objectively more effective for a better recovery of motor function; it partly derives from the fact that the residual abilities of the patient are often assessed by using largely subjective methods of measure, and that makes difficult an adequate evaluation of rehabilitation treatment's effects on the patient.
The nature of these treatments, which have to be administered by therapists on a patient at a time, and the lack of methodologies and tools able to compare the different rehabilitative therapies and their effectiveness make the costs associated to rehabilitation services typically high; thus, the ratio between the number of qualified human resources to be used for the rehabilitative services and the number of patients is often higher than one. It is also difficult

[1] Data extrapolated from the population in 2001.

to define methods for assessing and improving the cost/effectiveness ratio related to specific rehabilitation programs.

The use of robotic machines for neurorehabilitation is inspired by the neurophysiological evidence showing that, starting from the cellular level, synaptic connections undergo continuous changes, in response to physiological events, environmental stimuli (processes of learning and memory) and damages to the Central Nervous System (CNS)[2].

The topology of the motor and sensory cortex is not fixed, but flexible and adaptable to learning and experience (Donoghue et al., 1996). This characteristic of the motor cortex has important implications for rehabilitation: a) rapid changes in cortical activity can occur, b) the intensive training of cortical area may occur at the surrounding areas' expense and c) cortical areas can adapt their functions to those changes.

Thanks to the brain imaging techniques, such as functional Magnetic Resonance Imaging (fMRI), Positron Emission Tomography (PET), Transcranial Magnetic Stimulation (TMS) associated to Motor Evoked Potentials (MEP) and electrical stimulation, changes in CNS's excitability and topology can be shown. Through the use of such techniques, it is possible to identify regions that have suffered a damage and apply a specific therapy.

The sensorimotor learning is influenced by physical (sensory feedback such as vision, hearing and proprioception), psychological (pleasure/pain, motivation, emotional impulses and desire) and cognitive (decision making, planning, reasoning, concentration and attention, language and understanding, previous experiences) factors.

It can be facilitated by the repetition of movements directed to specific targets (goal-oriented movements), the strengthening of muscles and the increase of the range of motion (ROM), the modulation of spasticity, an increased demand of focusing attention on the movement and the increase of sensory stimuli.

In recent years different research groups have studied and developed innovative robotic and mechatronic systems able to let the patient perform repetitive and goal-oriented movements. These systems can provide a safe and intensive training[3] that can be carried out in association with other types of treatment, appropriate to the different residual motor abilities, potentially able to significantly improve the rehabilitation outcomes, to perform an objective assessment and to improve the planning and use of healthcare resources.

In the rehabilitation assisted by a robot, the patient's role is undoubtedly central: the machine supports, and, if necessary, completes, the movement performed by the patient according to his/her residual motor abilities ("assisted as needed" control strategy).

[2] The terms *neuroplasticity* or *neural plasticity* are used to point out the sequence of changes in chemical (interaction between neurotransmitter and receptor), electrical (long-term depression and long-term potentiation) and molecular (activation of transcription factors and protein synthesis) responses, which lead to a reorganization of connections in the cerebral areas and, consequently, to cognitive changes and stable behaviours.

[3] During each training session using robotic systems, a high number of movements can be performed: the repetition of motor actions is a factor which can promote the recovery of motor functions.

People suffering from motor disorders can perform the rehabilitation therapy with the support of a "rehabilitation machine"[4].
The patient, through the interaction with these systems, receives different sensorimotor and cognitive inputs, such as proprioceptive and visual *stimuli*, motivational incentives[5]: by using appropriate sensors, the machine is capable of measuring dynamic variables of clinical interest during the performance of active and passive movements by the patient. Thus, a quantitative assessment of specific physiological mechanisms, of motor recovery and functional skills can be carried out. This type of assessment is much more accurate than those using traditional methods. In addition, the machine may enable the therapist to plan the treatment and let the patient execute a wide sequence of movements, which can be useful for the limb rehabilitation.
The application of machines to rehabilitation is sometimes limited by technical and functional factors; their real advantage in clinical applications has been only partially proved. However, there are solid arguments that encourage researchers to design and develop innovative systems for rehabilitation, which derive a direct benefit from the scientific and technological progress in the field of bioengineering, particularly in biomedical robotics and mechatronics.
The clinical potential of these machines, however, is clearly significant as they can, on the one hand, assist the therapist in the administration of a patient-specific physical therapy, with the accuracy and repeatability, typical of the robotic systems, and on the other hand, to acquire quantitative information on the patient's movements.
Such information may be useful for the evaluation of both the patient's motor function and the mechanisms of motor recovery. These machines can also enable the patient to perform rehabilitative sessions in a semi-autonomous modality, and, in principle, even at his/her own home, thus reducing the need for the therapist's continuous commitment[6].
The technological innovation in robotics and mechatronics has contributed to achieve encouraging results in the knowledge of motor recovery mechanisms and to a real progress in the rehabilitation field, with a potential high impact.

[4] A "rehabilitation machine" is a mechatronic or robotic system able to support the therapist during the administration of programmable and customized rehabilitation programs. It is composed by a mechanical structure where the following modules are present: 1) actuators, 2) energy supply, 3) proprioceptive and exteroceptive sensors, providing information on the machine status and the interaction between the machine and the environment, respectively, 4) a microcontroller, dedicated to the processing of data from sensors and generation of motor control commands and 5) a human-machine interface (graphical user interface), dedicated to user inputs, data recording and feedback output.
[5] The patient feels often rewarded by the use of high-tech systems for rehabilitation. Besides, motivational incentives are strongly stimulated by the use of graphical interfaces which provide a feedback on the performed movements, which are linked to the recovery of essential functionalities for his/her daily life.
[6] This therapy known as "tele-rehabilitation" is based on the integration of high-tech systems (i.e., a robotic system for rehabilitation) and telecommunication infrastructures (i.e., cable connections, optical fibres, wireless networks and satellite systems): it is aimed at enabling the execution of rehabilitation treatments at own home or rehabilitation centre, through the direct remote supervision and monitoring by physicians and therapists.

In the wide range of technological applications developed in the context of biomedical robotics, undoubtedly a class of particular importance is represented by the systems for the rehabilitation of patients who have a reduced mobility, following an injury or disease.
In the next paragraphs, robotic systems for upper and lower extremities rehabilitation and mechatronic systems for the functional assessment and the movement analysis for this type of patients will be described.

3. Robotic systems for upper limb rehabilitation

The World Health Organization estimates that each year 15 million people worldwide are affected by a stroke and 5 million of those are living with a permanent disability (WHO). The majority of post-stroke patients is able to recover an independent walking, but many of them fail to obtain a functional use of upper limbs, even after a prolonged rehabilitation treatment: these functional limitations are responsible for a significant reduction quality of life (Nichols-Larsen et al., 2005).
One year after the acute event, patients are usually considered chronic and rehabilitative therapies are often suspended, but several studies have shown that improvements in motor abilities induced by rehabilitative therapies may also occur in patients with chronic damage from 6 to 12 months after the acute event (Duncan et al., 1992; Hendricks et al., 2002).
Recent approaches that involve a repetitive training of upper limbs with activities aimed at task-oriented movements have provided evidence of improvements in hemiparetic patients more than a year after the stroke. In particular, the Constraint-Induced Movement Therapy (CIMT), based on an intense practice functionally oriented to hemiparetic upper limbs tasks obtained by a restriction of the unimpaired upper limb seems to be effective in reducing long-term disability (Miltner et al., 1999; Wolf et al., 2006). The motivation for using this type of treatment is based on the evidence that stroke and other neurological damages cause a partial destruction of cortical tissue, with the involvement of sensorimotor areas, that can determine incorrect motor programmes. However, CIMT requires a significant level of motor function and is not suitable to patients with severe weakness or spasticity due to neurological damage.
Other treatments based on high-intensity and task-oriented active upper limbs movements led to significant improvements in cortical reorganization and motor function in people with disabilities, more than a year after the stroke (Fasoli et al., 2003; Duncan et al., 2005). Unfortunately, these traditional treatments for post-stroke rehabilitation shows some drawbacks: they require a manual interaction by the therapists that must be provided on a daily basis for several weeks: the administration of an intensive treatment for each patient is proved to be difficult and costly.
Several robotic devices for rehabilitation have been recently developed to overcome these disadvantages: they are able to provide a safe and intensive therapy to patients with different degrees of motor impairment (Riener et al., 2005a).
Furthermore, the training with the support of the robot can be extremely precise, intense and prolonged. The robotic systems can also measure the progress of the patient in an objective way, increase the effectiveness of treatment and reduce the costs associated with the healthcare system.
Several reviews have shown the robot-assisted sensorimotor treatments and task-orients repetitive movements can improve muscle strength and motor coordination in patients with

neurological damage (Kwakkel et al., 2008; Mehrholz et al., 2008), although a limited number of clinical studies have examined the effect of upper limb robot-aided post-stroke rehabilitation using robust study designs (i.e., Randomized Controlled Trial)[7].

Among these, only three studies involved more than 30 subjects, and only two trials focused on pre- and post-treatment measures in experimental and control group (Lum et al., 2002; Krebs et al., 2000), of which only one was an RCT about the effects of the robot therapy provided to patients in the sub-acute phase (Krebs et al., 2000).

Among the most advanced robotic systems providing a growing amount of experimental data, the "MIT-Manus" (InMotion[2], Interactive Motion Technologies. Inc., Cambridge, MA, USA), designed at the Massachusetts Institute of Technology (MIT), holds a special role (Hogan et al., 1995) (Figure 1a).

The clinical trial started in 1994 at the Burke Rehabilitation Hospital, White Plains, NY, USA and recently many hospitals around the world use the "MIT-Manus" robotic system as tool for the upper extremities rehabilitation therapy in patients with neurological damage.

In Europe, the first example of this robotic system was purchased by the Scuola Superiore Sant'Anna in Pisa, Italy in 1995 and is currently at the Neurological Rehabilitation and Traumatic Brain Injury Unit at Auxilium Vitae Rehabilitation Centre in Volterra, Italy, where clinical trials on hemiparetic subjects are in progress.

The "MIT-Manus" is an operational-type robotic system characterized by a human-machine interface which is limited to the robot's end-effector[8] (Figure 1b). Unlike in industrial robots, where any contact with the human operator is usually excluded for safety reasons, the "MIT-Manus" was specifically designed to interact with the patient in a safe, stable and, when necessary, compliant way.

These characteristics are obtained through the use of a control scheme, called "impedance control", which modulates the movement of the robot in order to adapt itself to the upper limb's dynamics of the patient. The "MIT-Manus" can move, drive or disturb the upper movement of a subject and enables the recording of significant variables such as position, speed and the forces applied at the end-effector (Krebs et al., 1998). The distinctive characteristics of the "MIT-Manus" robotic system are: high reversibility mechanism (back-drivability), low mechanical impedance, which can readily adapt to the actions of the patient and the control system, which through the above mentioned "impedance control" modulates the reactions of the system to mechanical disturbances and ensure a compliant behaviour[9].

In fact, the machine was designed so as to have an intrinsic low impedance, low isotropic inertia (0:33 ± 1 kg, maximum anisotropy 2:1), low isotropic friction (0:28 ± 0.84 N,

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[7] A Randomized Controlled Trial (RCT) represents the most rigorous way of determining the cause-effect relation between treatment and outcome. It is a study in which recruited participants are randomly allocated to receive one of several clinical interventions. One of these interventions is the control (e.g. a standard practice), the other is the experimental treatment (e.g. robot-aided therapy).

[8] A different class of robotic systems for rehabilitation is represented by the exoskeleton-type systems, where the contact between the patient and the machine is extended to the whole impaired limb (or part of it).

[9] The robot assists the patient's movements in order to make their execution easier: only if the patient is not able to perform a movement, the robot's control system assists and guides the paretic upper limb in order to complete it.

maximum anisotropy 2:1) and is capable of producing a definite range of forces (0-45 N) and impedance (0-2 N/mm).
The rehabilitation treatment using the “MIT-Manus” consists of a series of complex motor tasks to be performed by the patient, who is asked to move the robot’s end-effector (Figure 1b) to perform movements aimed at hitting targets in a bidimensional space (reaching tasks).

(a) (b)

Fig. 1. The “MIT-Manus” robotic system: a patient during the robotic therapy (a) end-effector of the robotic system

Specific biomechanical parameters, which are computed starting from the above mentioned physical variables recorded by the “MIT-Manus” system, can be used for the characterization of the patient's motor performance, together with other parameters calculated from the electroencephalographic signals (EEG) for the assessment of motor areas activation, before and after treatment (Figure 2).
The different clinical experimental trials performed using “MIT-Manus” were described in several articles. The results of a study performed on 96 patients, including 40 subjects in the control group and 56 subjects in the experimental group, showed an improvement of the latter over the former, according to the results of functional assessment performed by using different clinical scales, including the Motor Status Score for the shoulder and elbow (MSS-SE), the Motor Power Scale (MP) and the modified Ashworth scale (MAS) (Volpe et al., 2000).
The results of our clinical trials, in publication, confirm the significant improvement of motor damage by 1) an increase in MSS-SE values for both the shoulder and the elbow joint, 2) a decrease in the MAS values for the shoulder joint, 3) no increase in the MAS values for the elbow joint and 4) an increase of the ROM for the shoulder joint: the data are statistically significant and were recorded before and after the treatment in chronic hemiparetic subjects, which was administered for 6 weeks, 3 sessions per week, 45 minutes for each therapy session.
The three months follow-up has revealed a further reduction of the motor damage due to an increase in the ROM of the shoulder joint.
In conclusion, our results showed that the improvement in motor skills after a neurological damage may continue even a year after the acute event.

Fig. 2. A subject during the the robotic therapy using the MIT-Manus and recording of EEG signals for the functional assessment

The results of the questionnaires designed to measure the acceptability of the robotic therapy and distributed to the patients at the end of the experimental trial, showed a substantial acceptance of the robotic therapy, which can not considered as substitutive of the traditional rehabilitation treatments and the role of the therapist.

A clinical trial with chronic hemiparetic subjects in sub-acute phase, currently in progress, is aimed at assessing the effects of robotic therapy after a few weeks after the acute event and identifying prognostic parameters of motor recovery to be provided to physiatrists in order to early identify the most suitable rehabilitative treatments for each patient.

Another robotic system for the upper limb rehabilitation of post-stroke patients, the “MEMOS” (Mechatronic system for motor recovery after Stroke), was designed and developed at the Scuola Superiore Sant'Anna in Pisa, Italy (Figure 3). It is currently used at the Fondazione Salvatore Maugeri in Veruno, Italy, where the clinical trials has already shown excellent results: a significant reduction of the upper limb impairment in chronic hemiparetic patients was observed (Micera et al., 2005; Colombo et al., 2005; Colombo et al. 2008).

The “MEMOS” enables patients to perform reaching movements using a simple system of mechanical guides: the dimensions of its workspace are 70 cm x 70 cm. Before starting the therapy session, the worktable can be tilted by the therapist according to the needs of the patient through a manual adjustment. To a greater simplicity in terms of mechanical structure compared to the “MIT-Manus”, the “MEMOS” adds the flexibility of a system that can be used for rehabilitation at home, supported in real-time by the remote control of physiatrists and therapists.

Fig. 3. The "MEMOS" system: a mechatronic system for the upper limb rehabilitation

4. Robotic systems for lower limbs rehabilitation

The objective of rehabilitation in paraplegic patients is to achieve maximum independence in the Activities of Daily Living (ADL). Over the past decades, the rehabilitation of locomotion in individuals with spinal cord injury (SCI) was largely developed and tested (Scivoletto & Di Donna, 2009; Barbeau & Rossignol, 1994; Barbeau et al., 1999; Barbeau et al., 2006).

Currently, the locomotion in these subjects is performed using standard wheelchairs, often without any training for the functional motor recovery of the lower limbs (i.e., the gait). An increasing evidence based on neurophysiological studies has demonstrated the ability to activate locomotion patterns in animals affected by a spinal cord injury through the use of systems for the body weight support (BWS) and a treadmill (Barbeau & Rossignol, 1987). Similar studies were performed on human subjects using a harness and variable BWS percentages on the treadmill: the locomotion activities in SCI subjects can be improved using such systems (Dietz & Colombo, 2004; Grasso et al., 2004; Edgerton et al., 2006; Scivoletto et al. 2007).

To activate the locomotor function using this approach, it is often necessary to help the progression of the lower limbs on a treadmill through a manual effort of two or more therapists. Therefore, the duration of the training is usually limited by the fatigue of the therapists and this causes a shorter duration of the sessions compared to the time needed to obtain a good rehabilitation outcome. To facilitate this type of rehabilitation and to ensure repeatability of the movements for locomotion, the "Lokomat" system (Hocoma AG, Volketswil, Switzerland), a bilateral robotic orthoses used in conjunction with a BWS system and a treadmill was developed (Figure 4) (Colombo 2000; Colombo 2001).

The joints in the "Lokomat" system, located in correspondence of the hip and knee joint, are moved by linear actuators which are integrated into the exoskeleton structure. A passive system of springs aimed at lifting the foot's sole induces an ankle's dorsiflexion during the swing phase. The patient's lower limbs, which are fixed to the exoskeleton structure

through adjustable stripes and settings, are moved in the sagittal plane according to a control strategy with pre-defined hip and knee trajectories which enables a safe patient-machine interaction (Riener 2005b; Riener 2006).
Up to now, different studies about the use of the "Lokomat" system in subjects affected by neurological diseases were published (Colombo et al., 2000; Jezernik et al., 2003; Lünenburger et al., 2005; Hidler et al., 2005; Lünenburger et al., 2006; Hidler et al., 2009; Hornby et al., 2008; Israel et al., 2006; Wirz et al., 2005).
Recent experimental studies analyzed the activation of different EMG patterns in healthy and spinal cord injured subjects during the "Lokomat" training using the treadmill, in different experimental conditions (Hidler & Wall, 2005). The comparison of the EMG activity between healthy and SCI subjects show that in a complete spinal cord injury, the adaptation to different speeds is still present (Lünerberger 2006).
An experimental study currently in progress, carried out through a joint collaboration among Scuola Superiore Sant'Anna, the Neurorehabilitation Unit and the Spinal Cord Injuries Departmental Unit at Cisanello Hospital in Pisa, Italy is aimed at assessing the changes in the muscle activation after a period of rehabilitation using the "Lokomat" system in subjects with incomplete spinal cord injury.

Fig. 4. The "Lokomat" robotic system for the lower limbs rehabilitation

To the current knowledge, the use of this device is still empirical: the choice of the variable parameters (BWS percentage, speed, driving force and duration) is not yet included in specific guidelines and the patterns of muscular activation of the robot-aided gait are not, for the time being, well defined.
Surface EMG signals from four muscles on each limb (rectus femoris, biceps femoris, anterior tibial and medial gastrocnemius) in healthy subjects and patients with incomplete spinal cord injury during the training with the "Lokomat" robotic system are recorded. In detail, three different treadmill speeds (1.0, 1.6 and 2.4 km/h) using two BWS percentages

(30% and 60%) and two different patient-cooperation modalities are used. The modalities are: (1) "passive", in which the subject does not contribute to the movement of the lower limbs that are mobilized by the robotic orthoses, and 2) "active", in which the subject accompanies the movement of the lower limbs according to his/her residual motor abilities.
Subjects with a spinal cord injury follow, after a first recording (pre-training), a training program with the "Lokomat" system of variable duration (i.e., 4-8 weeks), after which a further EMG recording is performed (post-training). Follow-up recordings at 3 and 6 months will be performed as well.
So far, the results obtained on a limited sample of patients affected by an incomplete spinal cord injury, which carried out a physical therapy using the "Lokomat" robotic system, showed an improvement of the locomotor function, due to enhanced recruitment of the lower limb muscles in the "active" condition: the assessment was based on the analysis of EMG signals recorded before and after the treatment, using specific clinical scales (i.e., 10-Meter Walk Test, 6-Minute Walk Test, Timed Up & Go Test) (Mazzoleni et al., 2008).

5. Mechatronic systems for the functional assessment and the movement analysis

Mechatronics is defined as the synergistic integration of mechanical engineering, with electronics and intelligent computer control in the design and manufacturing of industrial products and processes (Harashima et al., 1996).
A mechatronic approach has several benefits. In fact, mechatronic systems have greater flexibility, a better performance, higher quality, wide areas of applications and are less expensive.
The present paragraph focuses on the applications of mechatronics to the rehabilitation's area, according two main research fields: functional assessment and movement analysis.

A mechatronic platform for the functional assessment of the rehabilitation treatment using isometric force/torque during the execution of ADL tasks, in post-stroke subjects was designed and developed within the "Alladin" project, funded by the European Commission under the 6th Framework Program (IST-2002-507424) (www.alladin-ehealth.org).
The platform (Figure 5) was validated in three clinical centers in Europe:

- Mary Middelares Algemeen Ziekenhuis Sint-Jozef (Gent, Belgium),
- Szent János Hospital (Budapest, Hungary),
- Adelaide & Meath Hospital (Tallaght, Ireland).

In these centres, an experimental clinical trial with 270 subjects (150 hemiparetic subjects and 120 healthy control subjects) was carried out: the results contributed to identify six parameters related to the motor recovery of post-stroke patients, which can be used to perform a functional assessment after a short time after the acute event, in order to promptly address the choices by physiatrists and therapists about the most appropriate rehabilitative treatment for each patient (Mazzoleni et al., 2005; Mazzoleni 2006; Mazzoleni 2007a; Mazzoleni 2007b).

Fig. 5. The ALLADIN mechatronic platform for functional assessment of post-stroke subjects

In recent years, different wearable mechatronic systems for the movement analysis were developed. The “MEKA” (MEchatronic device for the Knee Analysis) system, designed and developed through a collaboration between the ARTS Lab at Scuola Superiore Sant'Anna in Pisa, Italy and the company Humanware Inc., is a mechatronic device that performs a real-time monitoring of the knee’s flexion-extension and varus-valgus angles (knee’s dynamic analysis) during the gait and other ADL. The recorded data can be displayed in a numeric and graphic format.

The system is composed of three main units:

1. a modular mechatronic device for measuring values from the knee’s flexion-extension and varus-valgus angles, through the use of Hall-effect sensors (Figure 6a);
2. a wireless system for the kinematic data acquisition and transfer to PC (Figure 6b);
3. a software tool for processing and displaying data.

One of the main advantages related to the use of the “MEKA” system is represented by the best cost/effectiveness ratio when compared to other similar devices aimed at performing a similar knee’s dynamic analysis.

The results of experiments carried out by using such mechatronic device highlighted different locomotor strategies, depending on the age and the difficulty of the required task (Micera et al., 2003; Micera et al., 2004).

(a) (b)

Fig. 6. The "MEKA" mechatronic system for the knee movement analysis

6. Open issues

In the field of robotics and mechatronic systems for rehabilitation some problems are still unsolved and require further developments to be addressed. As regards the clinical trials, the main issues are:

- the need for a greater number of patients to be recruited in clinical trials;
- the use of homogeneous groups of patients and control groups (i.e., RCT);
- the development of innovative clinical protocols;
- the definition of quantitative parameters related to the rehabilitation treatment (milestones) and prognostic parameters (markers);
- the identification of neurophysiological models of the recovery process;
- the detailed analysis of scenarios and definition of the roles of involved subjects (patient, physiatrist and therapist);
- the incremental innovation of devices already available and the design of new technological systems for rehabilitation.

A key aspect concerns the active role that the patient has to perform during the administration of robotic therapy: it should be an integral part of the requirements to be taken into account when designing new technological systems for rehabilitation. Furthermore, the integration between robotic systems and the techniques of brain imaging for the functional evaluation represents a fundamental area of research on which focusing efforts in order to define therapeutic approaches, tailored to the specific needs of each patient and the degree of recovery.

7. Conclusion

Robotic and mechatronic systems presented in this chapter are increasingly used in hospitals and rehabilitation centres as technological tools for the clinical practice. These systems are used to administer intensive and prolonged treatments aimed at achieving the functional recovery of people affected by neurological impairments, in sub-acute and chronic stage, with a potential improvement of the cost/effectiveness ratio. They can evaluate the effects of rehabilitation treatments in a quantitative way and contribute to increase the knowledge of motor control and learning mechanisms in humans.
Such systems have to be designed according to the ever-increasing knowledge in the neurophysiologic field, in order to improve the motor function through stimulating, entertaining exercises, able to promote patients' motivation.
The integrated use of robotic system for rehabilitation, mechatronic systems for the movement analysis and functional assessment and advanced brain imaging techniques enables to analyse the mechanisms of motor recovery for each patient and define customized rehabilitation treatments, towards an optimization of hospitalization's period and healthcare resources (Figure 7).
Furthermore, the development of low-cost robotic systems together with safe, reliable and robust telecommunications networks can also contribute to the validation of innovative tele-rehabilitation protocols, leading to potential high advantages:
(i) to continue the rehabilitation process at home or resident care (for the patient);
(ii) to reduce the costs associated with hospitalization and rehabilitation at the hospital (for the healthcare system).
Finally, the collaboration between physiatrists, therapists, patients and engineers, which has already shown important clinical and scientific results, has to be strengthened through research projects and specific programmes, at local and national level, as it is essential to guide the development of safe and effective technological systems for a patient-oriented robotics aimed at improving the quality of life of disabled persons.

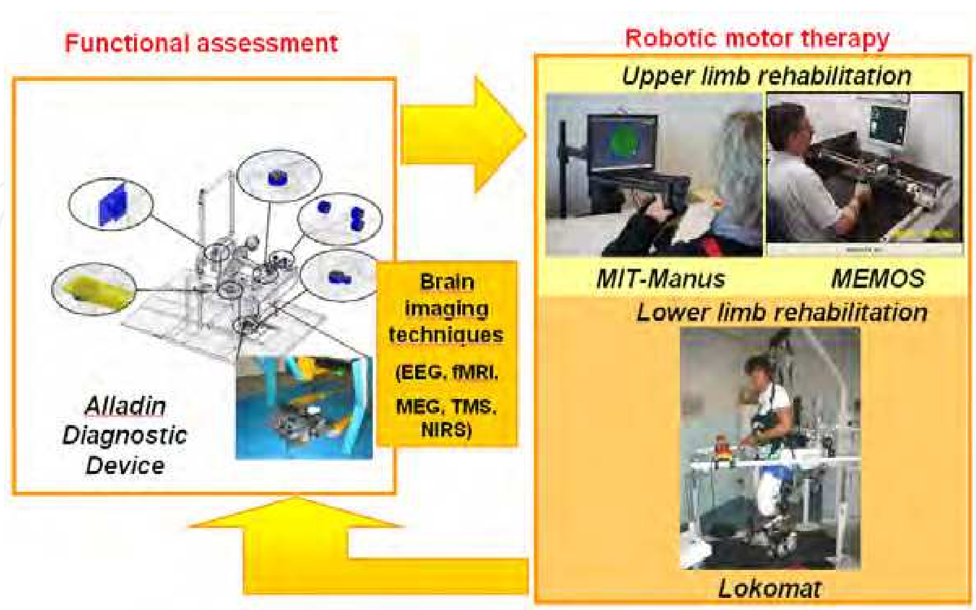

Fig. 7. Robotic and mechatronic systems for rehabilitation: an integrated approach

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Mechatronics, the synergistic blend of mechanics, electronics, and computer science, has evolved over the past twenty five years, leading to a novel stage of engineering design. By integrating the best design practices with the most advanced technologies, mechatronics aims at realizing high-quality products, guaranteeing at the same time a substantial reduction of time and costs of manufacturing. Mechatronic systems are manifold and range from machine components, motion generators, and power producing machines to more complex devices, such as robotic systems and transportation vehicles. With its twenty chapters, which collect contributions from many researchers worldwide, this book provides an excellent survey of recent work in the field of mechatronics with applications in various fields, like robotics, medical and assistive technology, human-machine interaction, unmanned vehicles, manufacturing, and education. We would like to thank all the authors who have invested a great deal of time to write such interesting chapters, which we are sure will be valuable to the readers. Chapters 1 to 6 deal with applications of mechatronics for the development of robotic systems. Medical and assistive technologies and human-machine interaction systems are the topic of chapters 7 to 13.Chapters 14 and 15 concern mechatronic systems for autonomous vehicles. Chapters 16-19 deal with mechatronics in manufacturing contexts. Chapter 20 concludes the book, describing a method for the installation of mechatronics education in schools.

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