

New generation emerging technologies for neurorehabilitation and motor assistance

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This paper illustrates the application of emerging technologies and human-machine interfaces to the neurorehabilitation and motor assistance fields. The contribution focuses on wearable technologies and in particular on robotic exoskeleton as tools for increasing freedom to move and performing Activities of Daily Living (ADLs). This would result in a deep improvement in quality of life, also in terms of improved function of internal organs and general health status. Furthermore, the integration of these robotic systems with advanced bio-signal driven human-machine interface can increase the degree of participation of patient in robotic training allowing to recognize user's intention and assisting the patient in rehabilitation tasks, thus representing a fundamental aspect to elicit motor learning

Key words: exoskeletons, EMG, EEG, human-machine interface, ADL, neurorehabilitation, motor assistance, emerging technologies

In the recent years we have assisted to a raising and growing interest in wearable technologies for neuromotor rehabilitation and assistance and in particular upper and lower limb robotic exoskeletons¹ that can provide autonomous walking to paraplegics after cerebrovascular stroke, spinal cord injury, or peripheral neuropathies.

In general (1, 2), a wearable device is defined as an active mechanism that: (i) is essentially anthropomorphic in nature; (ii) can be "worn" by an operator; (iii) fits closely to his/her body; (iv) works in concert with the operator's movements.

Robotic exoskeletons for rehabilitation and assistance

In developed countries, stroke affects 1/500 every

¹ From the greek ("exos" outside and "skeleton").

year, representing the 3rd cause of death (after cardiovascular diseases and tumours), and is the leading cause of long-term disability, with severe limitation in activities of daily living (ADLs). Motor recovery after stroke is still possible to different extents thanks to regain of function promoted by physical therapy and exercise, induced by changes in cortical reorganization according to the residual neuroplasticity. Four main factors are considered as the major determinants of motor recovery: early intervention, task-oriented training, amount and scheduling of practice and degree of participation (3, 4). In particular task oriented training stands for a repetitive training of functional (skill-related) tasks. Task-oriented training has been clinically tested for training locomotion (5), balance (6), arm-hand function recovery, motor control and strength in stroke patients (7). A fundamental principle in motor learning is that the degree of performance improvement increases with the amount of practice. Practice can be accomplished in a number of ways that are more effective than blocked repetition of a single task (massed practice). The degree of participation in patient represents a fundamental aspect to elicit motor learning, as volitional effort and active involvement is required to induce cortical reorganization (8).

In this regards, robotics represents a *key enabling technology* to enhance the recovery process and *minimize functional disability*, with consequent earlier reintegration in ADLs. Conventional neuro-rehabilitation appears to have little impact on impairment over and above that of spontaneous biological recovery (8). Robotic aided therapy has shown to be *more effective* than traditional physical therapy in providing high intensity of exercise, better movement controllability and measurement reliability, which makes robots ideal instruments to help neurologists and therapists in addressing the challenges in neuro-

rehabilitation. In fact, unlike conventional therapy, rehabilitation robots can deliver training at a much higher dosage (i.e., number of practice movements) and/or intensity (i.e., number of movements per unit time) with hundreds if not thousands of repetitions in a single session (8).

Several studies have already demonstrated the efficacy of the robotic treatment. In the article of Lo et al. (9) the authors have shown how robot-assisted therapy in upper limb rehabilitation led to significant improvements in motor capability and motor-task performance, as compared with usual care, and demonstrated how robot-assisted therapy is equivalent to an intensive conventional therapy. Recent available reviews of literature prove that patients who receive electromechanical-assisted arm training after stroke are more likely to improve their generic ADLs and may improve arm function (10).

Upper limb exoskeletons are typically used for rehabilitation of arm and hand function (11).

The ALEX exoskeleton developed at SSSA (12) is an example of a new exoskeleton device with unique properties in terms of kinematics and actuation: due to the adopted design the system can achieve a very light weight for actuating 4 degrees of freedom, thanks to a series elastic tendon transmission that guarantees intrinsic mechanical compliance. This compliance represents an important requirement for granting adaptability to patient movements on one side and high safety standards.

Lower limb exoskeletons, instead, offer patients' the freedom from a wheelchair, resulting in important positive aspects such as increased freedom to move and perform ADLs and hence improved quality of life; but also in terms of improved function of internal organs and general improved health status. The approach that makes use of robotic exoskeleton for gait assistance in disabled persons represents a revolution and a paradigmatic shift beyond traditional wheelchairs. Recent market estimates forecast the global exoskeleton market, in three markets (military, factory and rehab/healthcare), to grow at a 72.5% Compound Annual Growth Rate (CAGR) from 2014 through 2019.

Although robotic exoskeletons for lower limbs have attracted a strong attention from medical and patients' communities, they are still far from addressing the real needs of paraplegic persons. One aspect that needs to be further researched, it is that only a few of them are able to provide the balance of person by the device itself, but rather rely on the person to use crutches to keep the balance.

In 2012, it was estimated that worldwide over 185 million people use a wheelchair daily, and almost 20 per cent of the world's population is now aged over 65 years, and that is forecast to exceed 35 per cent by 2050. Accordingly, there is a growing need for devices that can assist the injured and elderly to enjoy a degree of independence and maintain a more active lifestyle.



Figure 1. The Alex 2 exoskeleton developed by Scuola Sant'Anna (commercialized by Wearable Robotics srl) integrated with a serious rehabilitation game.

At the state of the art (2, 13), the broad variability in mechatronic design, control and human-robot interface of these devices is due to differences in the targeted end-users and expected usage.

Among all the assistive devices emerging in the last decade, wearable robotic exoskeletons' were proposed as an innovative solution by many research centers active in the field of medical robotics to provide additional power for walking or stair-climbing to people affected by gait disorders. In such different human-robot interaction scenarios, the assistive torques contribute only partly to the body motion and, in the meantime, the exoskeleton must comply with the user's motion. Such a wearable medical exoskeletons require the patient to balance themselves which is in contrast to rehabilitation exoskeleton which are often equipped with a body weight support system.

The most of these devices use electric motors to actuate hip and knee joints and sometimes also the ankle joints.

Exoskeletons used for therapy are not portable and do not stand-alone mechanically (the so called treadmill-based exoskeletons). In fact, the main role of these robotic platforms is to support the patient weight and to generate symmetrical and periodic gait patterns for rehabilitation purpose only.

Finally, the impressive aspect of all described devices and tools is that all the outcomes and the developed technologies resulting from post-stroke research can be translated to neuromuscular rehabilitation and motor assistance since some medical needs and consequences of people suffering from dystrophinopathies are shared with post-stroke patients.

Biosignal-based interface for robotic tool control

One of the major challenges for tools for new generation rehabilitation is to produce devices able to recognize user's intention and assisting him/her in rehabilitation tasks. An effective approach for tool control is based on the use of bio-signals. Indeed, they allows to increase the degree of participation of patient in robotic training which has been demonstrated to represent a fundamental aspect to elicit motor learning, since volitional effort and active involvement are required to induce cortical reorganization, while passive movement driven by the robot along a trajectory does not result in learning (14).

Two increasingly used bio-signals in rehabilitation are Electromyography (EMG) (the electrical manifestation of the neuromuscular activation associated with a contracting muscle) collected from preserved or moderately impaired muscles and Electroencephalography (EEG) (the electrophysiological monitoring method to record electrical activity of the brain).

EMG-based interfaces

The "assistance as needed" rehabilitation paradigm (15) according to which the degree of assistance provided by the robotic tool is no more than the required one, has led to the development of adaptive controllers aimed to provide a rehabilitation protocol tailored to the condition of each patient. In particular, surface EMG-based (sEMG-based) control of robot represents a natural way to implement assistive controllers that provide assistance based on the level of muscle activation.

Most upper limb exoskeleton robots also use regression control approaches to map EMG signal features into torques either proportionally (16), or through a muscle model, or a neural network (17).

In triggered assistance, the subject initiates the movement without assistance, with the robot observing on-going performance and intervening taking full control when the task is not completed. On the other side in adaptive control strategies such as EMG-proportional, the power of the EMG signal is used to directly control the actuators (18). This is the case of probably the simplest case of model-free paradigm, the EMG-proportional approach, in which the assistance proportional to the EMG activation signal is provided through the robot.

To overcome these limitations, in more advanced model-free paradigms, sEMG signals are processed using machine learning techniques (17).

EEG-based interface

A Brain Computer Interface (BCI), or Brain Machine Interface (BMI), is a system that uses brain signals to drive external devices without the use of peripheral physiological activities (19).

Once the users' brain activity is recorded, it is decoded by means of an on-line classification algorithm and the output of the classifier is fed back to users allowing them to modulate their brain activity (20).

Depending on the aim of BCI application, two major approaches can be distinguished: assistive BCI and restorative BCI (21).

Assistive BCI systems aim at high dimensional control of robotic limbs or functional electric stimulation (FES) that specifically activate paralyzed muscles to assist in performing ADLs (22). These systems aim at having a large number of output commands and they often use mental strategy based on external cues such as Evoked Potentials (EP). For instance Ortner et al. (23) proposed the use of a Steady State Visual Evoked Potential (SSVEP) based BCI to control a two-axes electrical hand prosthesis.

The aim of Restorative BCI, instead, is to selective

induce use-dependent neuroplasticity to facilitate motor recovery. In neuro-rehabilitation, there are now sufficient evidences that non-invasive BCI (often based on EEG) may provide an advantage compared to traditional rehabilitation methods in patients with severe motor impairment (24).

For instance, BCI based on Motor Imagery (MI-BCI) can provide a valid substitute for active motor training as a mean to activate the motor network (25), thus influencing motor recovery in a positive way.

The combination of MI with a congruent and appropriate bio-feedback originated from the BCI system can provide a twofold advantage: it generates a normal afferent-efferent feedback loop (20), useful for neuro-rehabilitation purposes, and improves consistency of MI features detected by BCI (26). The development of restorative BCI systems is tightly associated with the development and successes of neurofeedback and its use to purposefully up-regulate or down-regulate brain activity.

The use of sensory feedback in BCI could improve the performances of the BCI itself and it allows to close the sensorimotor feedback loop (13).

Considering that BCI technology is based on feedback and exploits learning mechanisms, a logical step forward would be to design and develop specific BCI-protocols for patients.

Numerous research groups have recently provided evidence that this type of BCI leads to functional improvements in upper limb or hand function.

Motivations and benefits of the MI-BCI initiated rehabilitation systems have been discussed by several researchers so far and, currently, it might be concluded that BCI systems are a promising tool to add to the neuro-motor rehabilitation toolbox.

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