Robot therapy of the upper limb in stroke patients: preliminary experiences for the principle-based use of this technology

Maura Casadio, PhD
Psiche Giannoni, PT
Lorenzo Masia, PhD
Pietro Morasso, ME
Giulio Sandini, PhD
Vittorio Sanguineti, PhD
Valentina Squeri, PhD
Elena Vergaro, PhD

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Introduction

In spite of the fact that robots entered clinical practice more than a decade ago (1), a recent Cochrane review (2) gives a rather negative evaluation of the impact of this technology in the field of neuromotor rehabilitation of the upper limb in stroke. The aim of its authors was to assess the effectiveness of "electromechanical and robot-assisted arm training" for improving activities of daily living and arm function and motor strength in post-stroke patients. They reached the following conclusions: "...the role of electromechanical and robot-assisted training for improving arm function after stroke is unclear... arm training did not improve activities of daily living in people after stroke... electromechanical and robot-assisted 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..."

The problem, as remarked by Wade in a recent editorial (3), is that neuromotor rehabilitation is a complex multifactorial intervention that does not allow the separate, one-at-a-time analysis of the different factors that would provide reliable, quantitative assessments of the effectiveness of treatment protocols, whether they are provided by human therapists or robot therapists. Moreover, the variety of brain damage and the extent and variety of the resulting patterns of impairment are such that standard, unspecific treatment protocols are unlikely to be efficacious. On the other hand, the lack of agreed guidelines is the consequence of a purely empirical approach in which experiments and systems are characterized mainly in the absence of the theoretical basis that, as again remarked by Wade (3), is essential for the rational design of treatment protocols.

Our concerns are shared by Marchal-Crespo and Reinensmeyer (4), who recently reviewed control strategies for robotic movement training after neurological injury. In this paper, we summarize what we see as the theoretical bases necessary for the rational design and use of robotic systems and suggest a number of possible guidelines that are consistent with this framework.

Theoretical bases

Various suggestions for the rational design of robot therapy protocols have been advanced in the spheres of neurophysiology, neuropsychology and neuroimaging. Here, we briefly summarise some of these.
Functional recovery and neural plasticity

As demonstrated by different authors (5-7), referring to animal models of stroke and correlated human studies, functional recovery of motor patterns is obtained through the use-dependent reorganization of neural mechanisms, exploiting basic properties of neural plasticity. However, it is not movement per se, obtained for example by means of passive mobilization, which is effective in recruiting plastic adaptation. The key is movement associated with a task and a volitional effort, which suggests that the issue of neuromotor rehabilitation should be linked to the general topic of skill learning, typically addressed by neuropsychological research. Underlying neurorehabilitation, therefore, is the basic assumption that motor learning principles can be applied to motor recovery.

The schema theory of motor learning

A key concept is the schema theory of skill learning developed by Richard Schmidt (8-10). On the basis of a definition of motor learning as a set of “internal” processes, associated with practice or experience, leading to relatively permanent changes in the capability for responding, Schmidt argued that as people practise movements related to a well-defined problem-solving task, they do not learn specific movements per se. Rather, they construct generalized motor programmes that relate “control parameters” to “movement outcome”. Control parameters are modifiable features of a movement, for instance its duration or overall time, or the level of force that develops in the muscles that contribute to the movement. By scaling these parameters in the course of training, people experience different outcomes and are thus enabled to evaluate the functional relationship between parameters and outcome through recourse to some kind of best matching procedure. An important prediction of the theory of motor adaptation, verified by a number of experimental studies, is that people more quickly learn the relationship between the manipulation of control parameters and the achievement of a desired movement outcome if they practise a task in wide variety of situations and experience errors in the process, accumulating a large and broad scatter of data points. Another prediction of the theory is that practice that lacks variety, but is instead precise or repetitious, must be provided, without either stressing the subject or impeding the emergence of voluntary control.

From the schema theory to optimal modulation of assistance

The schema theory of motor learning can be taken as a general framework for designing optimal patterns of assistance in robot therapy. By “assistance” we here mean a force field generated by the robot with the purpose of facilitating the emergence of voluntary control in task-oriented movements (Fig. 2). When a patient is assisted by a robot in carrying out a task, we may assume that a measured performance parameter is a function of both the assistance A and the residual voluntary control C:

\[ P = f(A + C) \]

A profile of assistance may be defined “optimal” if, with the constraint that a given performance level be reached, it succeeds in maximizing the amount of voluntary control. The following list of rules for the optimal modulation of assistance patterns is compatible with the general framework of the schema theory of motor learning. In particular, the assistance force should be:

- **great enough** to allow the subject to complete the task, even in an imprecise and/or slow manner (in order to avoid frustration);
- **small enough** to motivate the subject to contribute as much as possible to the outcome (in order to avoid laziness);
- **reduced from trial to trial** as performance improves (in order to promote the emergence of voluntary control);
- **boosted at the beginning of each session**, thus implementing **non-monotonic modulation** of assistance over the treatment protocol (in order to allow memory consolidation).

The equilibrium point hypothesis and motor imagery

Another general concept that can provide a solid basis for the optimal design of assistance in neuromotor rehabilitation is the equilibrium point hypothesis (EPH)
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(15,16), and its strength derives from its ability to solve the “degrees of freedom problem” as formulated by Nikolai Bernstein. The main idea is that posture is not directly controlled by the brain in a detailed way but is the “biomechanical consequence” of the balance between a large set of muscular and environmental forces, including the forces of interaction between a patient and a therapist. From this perspective, “movement” can be seen as a symmetry-breaking phenomenon and thus as the equivalent of the transition from one state of equilibrium to another. This mechanism of trajectory formation works because muscles are not pure force generators, but rather devices capable of storing and releasing mechanical energy. In this sense, controlling movements can be equated with controlling the flow of mechanical energy.

Generally speaking, the EPH, as well as the literature on force field adaptation (12), suggests that the brain understands the “language of force fields”; thus it provides a theoretical basis for an approach to robot therapy based on the use of force fields. This assumption is further strengthened by recent research into motor imagery, which has been defined by Crammond...
(17) as a specific type of mental imagery that consists of the mental rehearsal of a motor act in the absence of overt motor output. Experimental results (of EEG, fMRI, PET, NIRS studies) generally support the idea of common underlying functional networks subserving both the preparation for execution, and the imagery, of movements. They also provide a broader context for this notion by revealing similarities in cognitive components associated with movement tasks (18,19). Marc Jeannerod (20) has taken these ideas a step further, formulating a mental simulation theory, which posits that cognitive motor processes (e.g. motor imagery, movement observation, action planning and verbalization) and motor execution share the same representations. The corresponding neural activation patterns include not only premotor and motor areas such as the PMC, SMA, and M1, but also subcortical areas of the cerebellum and the basal ganglia (21). The motor imagery theory suggests that if physical force fields are a general language for understanding neuromotor control, motor learning and physical interaction, then the internal control models, which are operant during actual movements as well as in imagined movements, can be analyzed in terms of “computational force fields” that characterize the attractor dynamics of interacting neuronal assemblies (22,23).

In short, we can say that, in terms of force fields, the planning, preparation, and execution of purposive movements works in a similar way. This is the reason why the application of suitable external force fields, either by a human physiotherapist or a robot therapist, has a chance of promoting the (re)formation of internal control models and thus the recovery of lost sensorimotor functions.

Suggested guidelines for the best use of robot technology

The conventional wisdom about stroke patients is that there is little scope for functional recovery when, a few months after the ictus, they become chronic. Damage to the CNS is the primary cause of motor dysfunction after a stroke, and because of the interactive nature of the nervous system, many different areas receive reduced input and have altered function following a stroke (5,6,24). All this produces a deficit of motor control and sensory-perceptual changes. A lack of postural control induces greater endurance and greater strength.

iii) Robot therapists must adhere to a minimal assistance level of force criterion. This criterion is motivated by the requirement of compatibility with the schema theory of motor learning. It has also been formulated as the “assist as needed principle” (36) or the “minimal assistance strategy” (34). It implies, among other things, that assistance given must be sensitive to the actual performance of the subject and must not be delivered in an open-loop manner according to a passive mobilization strategy. Different schemes of assistance have been proposed. An important discrimination is the one made between two control strategy categories: a) strategies that are based on the “desired trajectory” concept and that thus provide assistance as a function of the “error” between the actual and the nominal trajectory (“impedance-based assistance”, characterized by an error threshold); and b) strategies that do not impose a specific law of motion on the patient, in which assistance is instead directed only at the task of reaching the target, leaving the patient total freedom as regards the trajectory actually followed. Moreover, assistance is not the only form of haptic interaction between robot and patient. Another form might be a control strategy, still compatible with the principles of the schema theory, based on the “amplification of errors” by means of suitable force fields (37). A resistive strategy is also possible; this consists of therapeutic strategies that offer resistance to the subject's hemiparetic limb.
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movements during exercise, on the basis of the accumulating evidence that higher effort on the part of the impaired limb can indeed help to improve motor function following a stroke (38, among others). However, non-assistive strategies are feasible only if the subject is capable of carrying out the task, even if in a slow and poorly coordinated manner, i.e., if the level of impairment is sufficiently mild. Therefore, robot assistance strategies remain the basic building block, upon which it is possible to formulate more sophisticated treatment schemes.

iv) Robot therapists must promote the improvement of proprioceptive awareness. It is necessary to consider the fact that motor deficits are almost always associated with proprioceptive deficits or deficits of spatial representations that affect the integrity of the body schema. In many cases such deficits are even more invalidating than the purely motor deficits, but are not adequately taken into account. One need only think, for example, of the phantom limb phenomenon. Traditionally, the presence of a phantom limb resulting from a cerebral lesion is reported as a rare event. However, a recent study (39) demonstrated that over 50% of stroke patients exhibit this kind of impairment of proprioceptive awareness. The problem is that proprioceptive deficits are typically masked by visual feedback (one of the various compensatory mechanisms that patients tend to use) and thus treatment protocols that rely on vision (as do the great majority of systems currently employed) are unable to improve proprioceptive deficits. This suggests that there is a need to design treatment protocols that can operate with or without vision, for example by focusing the attention of the patient on the orientation of interaction forces. Again, for this to be possible, the robot must be highly compliant and must not impose passive motion. The beneficial effects of this strategy have been described in a pilot study (40). In this context, it is also worth remarking briefly on the compensatory mechanisms frequently adopted by stroke patients in order to perform their activities of daily living. These mechanisms develop because of the subject’s lack of proprioceptive awareness and consequent poor dynamic stability on attempting to carry out a task. The problem is that inappropriate compensatory behaviours will prevent the acquisition of other, efficient behaviours and limit the recovery of spared neural mechanisms (41-44). Inappropriate compensatory strategies can also influence the cardio-respiratory function and alter the normal properties of tissues, leading to reduced muscle endurance (45,46). The question is, should treatment protocols favour or resist compensatory strategies? It is a trade-off between short-term gains and long-term impairment. However, we believe that in many cases recovering some degree of proprioceptive awareness is crucial for improving the prognostic outlook as regards the quality of motor control (and thus for avoiding dangerous compensatory patterns) and this justifies the requirement that robot therapists be able to deliver treatment which favours proprioceptive awareness. This part of the suggested guidelines should also cover the issue of “neglect”, which is almost totally ignored in the literature on robot therapy. We believe that evaluation of neglect, with particular emphasis on the poorly studied “motor neglect”, should be included in the capabilities of the robot therapist and should be taken into account in the design of robot control strategies.

v) Robot therapists must have a high degree of motor intelligence. This, in a sense, is a consequence of the previous requirements and it implies that the controller of the robot therapist must be complex, in such a way as to obtain a “humanoid robot” with perceptual, motor, and cognitive capabilities. Figure 3 summarizes the basic elements that characterize the flow of information: 1) a haptic robot; 2) a force field generator; 3) a performance evaluator; 4) an adaptive controller. In other words, an efficient robot therapist must not be a purely executive electromechanical device but must provide the patient with a rich interactive environment. The haptic robot, coupled with the force field generator, provides a bi-directional interaction: the force applied by the robot is added to the force applied by the subject in the course of the task, without imposing a specific movement trajectory. Performance evaluation can be carried out according to different timeframes: instant by instant, trial by trial or session by session. Also, adaptive assistance strategies can be modified according to the same timeframes. This means that the robot must possess short-term and long-term memory of performance in order to be able to personalize the treatment profile and optimize the prognostic outlook. Most robots in current use are rather “stupid” in this respect and fail to show sufficiently adaptive interaction with the patient. Evaluation of performance in quantitative terms is one of the strong features of advanced therapy robots and we believe that ultimately designers of robot control strategies should look beyond empirical performance parameters (such as speed, length, smoothness, see for example 47) which, although useful, are somehow removed from what really matters: the level and quality of the voluntary control commands. These are “hidden” variables, which cannot be measured in a direct way, but model identification techniques can be used in order to evaluate them. We recently made a preliminary contribution on this topic (48).

vi) Robot therapists must be designed in a modular way. We believe that the complexity of a therapy robot, in particular the number of degrees of freedom employed, should be chosen specifically for each patient and, in general, should be as small as possible. Training can be

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Figure 3 - Robot training by means of the self-adaptive haptic interaction between patient and robot therapist.
effective providing the subject is not confused by an ex-
cessively complex interaction scheme. Complexity, if
necessary, should be added to the therapy in an in-
cremental way also taking into account the use of tele-
communications technology in rehabilitation (49). It follows,
from this philosophy, that robot systems need to be de-
designed and organized in a modular way, in order to allow
easily assembling of the system so that it best fits the in-
dividual requirements (consider, for example, 50,51).
Modular robot systems should also make provision for
bilateral configurations that allow the paretic arm to in-
teract with the unimpaired arm (52-54). The problem, in
this case, is to design control strategies in which there is
real synergy between the two arms, avoiding the poten-
tially counterproductive situation in which the paretic
arm is passively mobilized by the movements of the oth-
er arm. Along the same lines, it is, in our view, highly de-
sirable to use open-source software architectures that
allow interactive applications to be transported from
one robot platform to another, and different research
groups to share their experiences and speed up the
growth of shared best practices. A very good example,
in this respect, is provided by H3D (www.h3d.org) which
offers an open source haptics software development
platform: H3DAPI. This platform uses the open stan-
dards OpenGL and X3D with haptics in a single unified
scene able to handle both graphics and haptics.

vii) Robot therapists must facilitate synergy between
physiotherapy and robot therapy. The general principle
is that robot therapy and physiotherapy should not work
in opposition to each other, but rather cooperate ac-
cepting the unimpaired arm. The problem, in
this case, is to design control strategies in which there is
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Concluding remarks

We have already underlined the importance of synergy
between intelligent robot therapy and physiotherapy for
functional recovery and, in particular, for fighting the
"learned non-use" of the impaired hand (57). Constraint-
induced therapy (CIT), which forces the use of the af-
fected limb by restraining the use of the other limb, was
specifically developed to reverse learned non-use and
has been shown to be effective in the recovery of arm
and hand functions after stroke in randomized clinical tri-
als (58). However, CIT is applicable to only a fraction of
stroke patients with quite mild impairment.

As suggested by Han et al. (59) functional recovery can
be characterized as a dynamic process with a threshold:
if retraining after a brain lesion increases spontaneous
arm use above this threshold, performance will keep on
increasing, as each attempt to use the affected arm will
act as a form of motor relearning. The patient will then
enter a virtuous circle of improved performance and
spontaneous use of the affected arm. By contrast, if this
threshold is not reached a negative cycle could be trig-
gered, promoting the emergence of compensatory
strategies with greater reliance on the less affected limb.
In this framework, intelligent robot therapy, emerging as
a mechanism for improving the patient’s sensorimotor
synergies up to the threshold beyond which CIT and
self-supported spontaneous improvements can occur,
clearly has a key role to play.

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