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Desirable features of a "Humanoid" Robot-Therapist

Pietro Morasso, Maura Casadio, Psiche Giannoni, Lorenzo Masia, Vittorio Sanguineti,
Valentina Squeri, Elena Vergaro

Abstract—**In relation with a recent Cochrane review, the paper discusses desirable features of a "humanoid" robot-therapist: 1) high mechanical compliance, 2) large range of force, 3) minimum assistance level, 4) soft haptic interaction for proprioceptive awareness, 5) adaptative assistance properties. It also proposes a framework for addressing optimal assistance and learning paradigms in view of a consensus in the community of rehabilitation engineers about shared principles and common standards.**

I. INTRODUCTION

A recent Cochrane review [1], aimed at assessing the effectiveness of "electromechanical and robot-assisted arm training" for improving activities of daily living and arm function and motor strength of patients after stroke, identified 11 controlled trials that evaluated this type of therapy. The conclusion was that "…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 … however, 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 …"

This rather negative evaluation of robot therapy by the clinical users is not mitigated by the consideration that quite similar negative evaluations could be formulated for the variety of human-delivered arm rehabilitation techniques: in fact, no comprehensive Cochrane review is available on this matter and the very few clinical trials that attempted to provide quantitative evaluations about the efficacy of different rehabilitation approaches [2,3,4] only performed pair-wise comparisons with rather marginal results. This is not enough to conclude that physical therapy, whether delivered by a robot or a human, is basically a waste of time because, as some clinician says, the main factors in the recovery of the upper limb functions are the plasticity of the human brain and the subjective motivations of each subject. Rather, we think that the main message coming from this state of affairs, for the designer of robot systems as well as for the human therapist who directly provides treatment or uses a robot to do so, is that unless treatment is highly personalized and capable to exploit in an "optimal way" the residual capabilities of each patient, the foreseeable functional gains are likely to be marginal. This implies a kind of paradox: in order to be effective, rehabilitation treatment cannot be standard and thus controlled clinical trials in the traditional sense are impossible, unless aimed at very specific and narrow groups.

However, the main worry for the designer of robot-therapy systems, coming the Cochrane review's criticism, is that the clinical establishment views "electromechanical and robot-assisted arm training" as a single and homogeneous field. This is somehow justified by the fact that the community of rehabilitation engineers has failed so far to provide a comprehensive and agreed framework for the classification of systems in functional terms, in order to be comprehensible by a clinician as well as a neuroscientist. Thus, it is not surprising that "electromechanical systems" and "robots" are perceived as members of the same category and averaging efficacy estimates throughout a dis-homogeneous variety of situations yields marginal gains.

We hope that the community of rehabilitation engineers finds a way to start a consensus process about a set of guidelines that may allow to differentiate in a reliable way between "electromechanical systems" and "robots" and, in the class of robots, among different, functionally defined classes. This paper is intended as a small contribution in this direction by focusing, in particular, on the desirable features of the high-end group of the larger class of robotic systems, which we may call, for simplicity, "humanoid robot-therapists". "Humanoid" is not intended here in the sense of humanoid robots, i.e. robots that resemble humans and have tens of degrees of freedom; rather, means that the robot-therapists of this category must share with human therapists some functional features, mainly from the haptic and cognitive points of view. Other implementation features, are not considered in this context.

II. THE HUMANOID ROBOT-THERAPIST

We start with the suggestion, formulated by Wolbrecht et

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P. Morasso (corresponding author) is with Unige-DIST (University of Genoa, Dept. of Informatics, Systems, Telecom.), Via Opera Pia 13, 16145 Genoa, Italy and with IIT-RBCS (Italian Institute of Technology, Dept. of Robotics, Brain and Cognitive Sciences); phone: +39 0103532749; fax: +39 0103532154; e-mail: pietro.morasso@unige.it.

M. Casadio is with Unige-DIST and IIT-RBCS; e-mail: maura.casadio@unige.it

P. Giannoni is with ART Education and Rehabilitation Center, Genoa, Italy; email: psichegi@tin.it

L. Masia is IIT-RBCS; e-mail: lorenzo.masia@iit.it

V. Sanguineti is with Unige-DIST and IIT-RBCS; e-mail:: vittorio.sanguineti@unige.it

V. Squeri is with IIT-RBCS; e-mail: valentina.squeri@iit.it

E. Vergaro is with Unige-DIST; e-mail: Elena.vergaro@unige.it

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al [5], that there are three main desirable features for a controller of robot-aided movement training following stroke: A) high mechanical compliance, B) the ability to assist patients in completing desired movements, and C) the ability to provide only the minimum assistance necessary. We further elaborate on this by adding other items that express the general concept that a humanoid robot-therapist must have *haptic* properties similar to those of a human (therapist) and at least some *cognitive* capabilities.

A. *High mechanical compliance*

The requirement of high mechanical compliance does not come only from the rehabilitation field but also from the general area of the neural control of movement and sensorimotor learning by using compliant robots. These robots are typically used for evaluating the geometric and dynamic features of the arm mechanical impedance, the adaptation to structured dynamic environments, etc.

Industrial robots as well as therapy robots conceived with the same design criteria are characterized by very stiff positional controllers. In this way the patient's limb is moved along a desired trajectory with a prescribed timing. The main problem with this approach is that a stiff controller limits kinematic error, the stiffer the controller the smaller the error. If this is exactly what is expected of a precise industrial robot, in the case of robot therapy it is quite undesirable because eliminating the error destroys the causal relationship between effort and error that is important for motor learning [6]. Moreover, a stiff controlled robot can carry out the required task without any active participation of the subject and this, by itself, is very likely to reduce to a great extent the therapeutic effect of training. In general, we suggest that a humanoid robot-therapist should have all the dynamic features that are required by the ongoing research on motor learning because, for the foreseeable future, it is quite likely that clinical research on better robot therapy and neuromotor research on motor learning will mutually influence each other, more easily if they use similar experimental tools. The requirement of low stiffness should also be associated with low inertia and low friction, in comparison with the analogous features of the human arm. This suggests, among other things, to prefer direct-drive actuation vs. indirect actuation through high-ratio reduction gears and force control vs. position control. Last, but not least, a low-stiffness robot is potentially less dangerous than a high-stiffness robot in the interaction with the patient.

B. *Large range of force*

The force assistance that a robot is supposed to deliver has intrinsically a very large range of variation, because the distribution of impairment levels in the population of stroke patients tends to be bimodal. Moreover, the assistance force required of the robot in order to allow the patient to achieve the goal varies widely in the treatment process. Thus, the robot must be strong and delicate at the same time, and must be able to deliver precise force vectors independently of movement kinematics. This means that the range of available force must be wide and must not be constrained by the kinematics of natural movements.

C. *Minimum assistance level*

The common wisdom coming among rehabilitation practitioners [7,8] is that when helping a patient to perform a movement the therapist should apply the minimal amount of manual assistance possible, in order to facilitate the emergence of voluntary, purposive control patterns. Shortly phrased this can be formulated as an assist-as-needed principle [5] or minimal assistance strategy [9]. A possible implementation of this concept can be labeled "triggered assistance": the idea is that for each trial (e.g. reaching a target presented on a computer screen) the robot is initially passive and starts applying an assistive force only later on, if "triggered" by some criterion of "failure" (e.g. amount of time, error size etc.), forcing the patient to complete the movement, without any attention to the voluntary aspects of the movement. Different versions of this concept have been investigated, with mixed results. However, the intrinsic limit of "triggered assistance" is that it has a discrete nature, which tends to break down the movement into two parts, with a jerky transition from the patient-driven initiation to the robot-driven termination. Moreover, the robot-driven part is typically characterized by a relatively stiff control in order to achieve the required goal, hence robot-assistance is provided in a low-compliance condition. On the contrary, we think it is crucial to provide a seamless level of robot assistance to subject-driven motion by applying from the start of the movement an assistive force that is sufficient to promote the emergence of voluntary control patterns from the background "noise", including in this term muscle hypertonus, exaggerated segmental or suprasegmental reflexes etc. This assistive force is not supposed to fulfil the purely mechanical function of "winning" the peripheral resistive muscle forces but mainly to send an informative message to the cortical areas through the proprioceptive channel. Thus the assistive force should constrain as little as possible the trajectory and the timing.

D. *Soft haptic interaction for proprioceptive awareness*

Although the motor deficit of stroke patients is the more evident aspect of the pathology, proprioceptive deficits may be as important, although somehow hidden and difficult to measure. However, it is quite clear that if functional recovery is achieved this is not restricted to the motor side (force increase and coordination improvement) but also to the improved awareness of the affected part of the body, mainly through the proprioceptive channel. Therefore, we think that a humanoid robot-therapist, in addition to be able to provide assistance in a highly compliant environment, with a large range of forces, according to a minimal assistance strategy, must also be able to enhance the haptic communication with the patient. A way for addressing this goal [10] is to overcome the typical design of robot exercises as videogames: this is limiting the range of possibilities, also because the visual channel tends to dominate the other channels and thus inhibit the emergence of proprioceptive improvements. In general we think that humanoid robot-therapists should be able to switch between standard paradigms of visual virtual reality and new paradigms of haptic virtual reality.

E. Adaptative assistance properties

Since the treatment of stroke patients should be tailored on the specific patient in order to exploit in an "optimal way" his/her residual capabilities, the humanoid robot-therapist must have sensorimotor intelligence and adaptive/cognitive capabilities (consider the simplified block diagram of fig. 1).

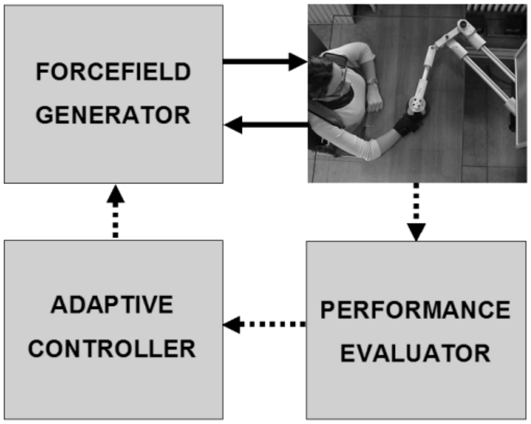

Fig. 1. Simplified block diagram of a humanoid robot-therapist.

The "force field generator" is the haptic part of the system that carries out a high-compliance rendering in the continuous-time, bi-directional robot-patient interaction. In general, haptic-rendering can be viewed as the problem of shaping a forcefield landscape in a task-dependent manner. A "performance evaluator" monitors in real-time the evolution of the robot-patient interaction, extracting task- and subject-related parameters that are transmitted to an "adaptive controller" in order to compute "optimal" control parameters of the haptic, human-robot interface. A relevant practical consequence of this framework is that a humanoid robot-therapist cannot be characterized by a pre-programmed set of exercises but must be based on an open software architecture and a user interface that allows two flexibility levels: 1) to adapt the task to the patient, 2) to adapt the robot to the task.

III. LEARNING AND OPTIMAL ASSISTANCE

Given a task, suppose that we can measure the evolution of the performance level (P) over a series of "trials": $\{P_1, P_2, ...P_n\}$, in relation with an ideal or reference performance $\hat{P}$. The implicit or explicit goal of the subject is to learn a control law $\hat{C}$ that minimizes the distance between P and $\hat{P}$ in the shortest possible time:

$$\hat{C} = \arg\min_{C} \left|\hat{P} - P(C)\right| \tag{1}$$

In an informal learning situation, in which the subject "plays" by alone or with an external trainer/audience that only interacts in a verbal manner, the learning/optimization scheme is essentially a reinforcement learning paradigm, in which the reinforcement signals by the "critic" are only provided "after" the action, not "before" and/or "during".

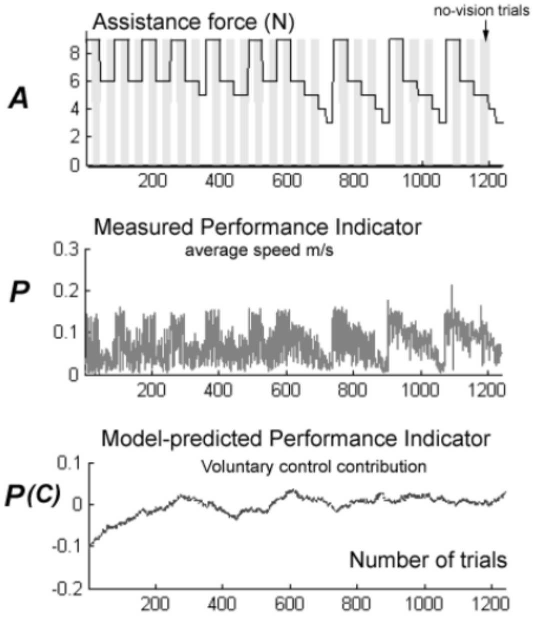

Fig. 2. Emergence of volitional control as a function of adaptive robot assistance. Note the non-monotonic inter-session profile of assistance force.

If the task is very complex and/or the subject has a significant impairment level, it is quite likely that the subject will only be able to learn a suboptimal control, with a great residual error. This is due to the fact that in the space of feasible control laws the landscape of the criterion $J(C) = \left|\hat{P} - P(C)\right|$ is likely to have a large number of deep local minima and the reinforcement learning scheme, by alone, is bound to get stuck in some inefficient local minimum if the initial control is far from optimal. However, we can supplement the internal/voluntary control C with an assistance A and thus we can substitute eq. 1 with eq. 2:

$$\hat{C} = \arg\min_{C} \left|\hat{P} - P(C + A)\right| \tag{2}$$

The rationale is that if the assistance is "appropriate" then the search of the learning process will be restricted to a region closer to the global optimum and thus the danger of getting stuck in an inefficient local minimum will be greatly reduced. But how can we choose an "appropriate" assistance? First of all we can identify a feasible range, which goes from absence of assistance $A = 0$ to a maximum level of assistance $A_{\max}$ which forces the subject to achieve the ideal performance in a "passive" way. Both extremes must be avoided because both are not functional. The latter one, in particular, does not give any chance to the learning mechanism because, by definition, $A_{\max}$ forces the optimum performance whatever the control C. Therefore, a smart choice is to adopt values of assistance somehow in mid-range between $A_{\min}$ and $A_{\max}$ according to a suitable profile of A over trials. But what is a reasonable choice for a "suitable profile of *A*"? We should consider that in most cases (certainly in the case of neuromotor rehabilitation) training takes place across several sessions and that learning a functional/optimal control is similar to consolidating a memory trace. It is known from the psychology of procedural memory that between one session and the next one the memory of the control partly fades away. Therefore, an empirically assistance strategy, compatible with such considerations, can be formulated according to the following pseudo-code, that we implemented scheme in some pilot studies [9-11]:

```
Initial_Session: evaluate empirically the minimum value
    of $A$ capable to solve the task, whatever the required
    time, and store it in $A_s$.
Session: recover $A_s$
    Trial: perform trial & evaluate quantitatively $P_i(A)$
     if $(P_{i-1} - P_i) > THR$ then reduce $A$
     if session is not over then goto Trial else
     store a "slightly" reduced value of $A_s$
     goto next Session unless training is over
```

The strategy above, which is characterized by a non-monotonic assistance profile, allows the learning process to operate as close as possible to the global optimum but with the lowest possible value of assistance in such a way that, ultimately, the control will be able to solve the task very close to the ideal performance. In particular, we may posit that the assisted subject is implementing the minimization (2) as a gradient descent which yields a recursive equation in the control law from trial to trial:

$$C_{i+1} - C_i \propto (\hat{P} - P(C_i))\frac{\partial P}{\partial C} \qquad (3)$$

A specific model of this learning equation is described in [12] with respect to the pilot study reported in [9]. The model is successful in explaining the evolution of performance and it provides insight on the emergence of volitional control: the top 2 panels of fig. 2 show the trial-by-trial & session-by-session evolution of the assistance force (*A*) and the performance (*P*) expressed as average speed of the reaching movements, including the alternation of vision & no-vision trials. The bottom panel shows the evolution of the performance portion that can be attributed to volitional control rather than to assistance. We can interpret these findings by saying that in the optimization of performance that implements the minimal assistive training strategy there is a division of labor between the robot and the patient: the robot optimizes the haptic environment adapting it to the patient and the patient optimizes volitional control in the framework of such environment.

An alternative approach is described in [5]: the goal of providing optimal "as needed assistance" to a patient in a highly compliant manner is formulated as an adaptive, optimal controller that learns in real time a dynamic model of the patient's arm as well as a model of the patient's ability and effort. This model of assistance is more powerful and more complex than the previous one and it is an interesting research problem to investigate the pros and cons of each of them. In any case the two methods for the delivery of optimal assistance are two good examples of the cognitive features that should characterize what we have named a humanoid robot-therapist.

IV. CONCLUSION

As a concluding remark, we wish to express our agreement with the opinion [13] that there is a deep similarity between the problem of optimal assistance for a humanoid robot-therapist and the haptic assistance for training sensorimotor skills in normal subjects. This is also the subject of a new EU-funded project (HUMOUR) that aims, among other things, at developing an open robot-independent software platform for "humanoid" robot-training.

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