COMPUTER HAPTICS FOR NEUROMOTOR REHABILITATION

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Abstract: The paper proposes an approach for linking the analysis of the neural control of movement and motor learning with robot therapy in neuromotor rehabilitation. A new haptic workstation is described and a pilot study of robot therapy with hemiplegic patients is presented.

Keywords: computer haptics, neural control of movement, motor learning, robot therapy, neuromotor rehabilitation.

1. INTRODUCTION

The experimental investigation of the mechanical impedance of the hand [1,2,3] has made evident the strong anisotropic nature of the musculo-skeletal system and this is, at the same time, a cause of computational complexity for the neural control of movement and a source of sensorimotor affordances in the Gibsonian sense. Also the analysis of the interaction forces points in the same direction. On the other hand, this is in strong contrast with the substantial isotropy of the spatio-temporal structure of the reaching movements, described by Morasso [4].

A stiffness control hypothesis, as a general mechanism of compensation of self-generated disturbances and other elements of anisotropy, has been falsified by the measurements of the physiological levels of muscle stiffness, which appear to be too low to be an effective compensation mechanism. In this context we should consider the emergence of the concept of *internal model*, i.e. the idea that the brain is able to develop, over the years, a representation of its own dynamics and dynamic interaction with the external world. However, this is a difficult process to study in an experimentally controllable way because it occurs spontaneously in a variety of contexts and over a long time. Therefore, the next logical step [5] was to use the same type of technology (haptic robots) also for generating artificial dynamic environments, completely unfamiliar to the subjects: in this way, it is possible to study in a systematic, controllable way, the modality of acquisition and consolidation of internal models of control.

A number of recent investigation in primates and humans have provided evidence that the primary motor area as well as other frontal, parietal, and subcortical areas are involved in motor learning [6,7]. The high-level functions that underlie acquisition of motor skills require the integration of these various and distributed cortical areas.

An important mechanism for such large-scale integration might be the transient formation of dynamic connections among cooperating cortical areas. It is quite plausible that occurrence of such functional neuronal aggregations are associated with the synchronization of neuronal activity in different frequency bands. This may be regarded as a self-organization process that allows the appropriate selection and assembly of neural networks that evolve into adaptive control system.

This kind of knowledge is the necessary substrate for addressing neurorehabilitation topics, whose goal is to promote and speed up functional recovery processes, based on the exploitation of the intrinsic neural plasticity. Even in the adult age, the cerebral cortex retains its plasticity, that is the capability to reorganize itself in the case of brain lesions. The underlying physiological mechanisms are still scarcely understood but there is ground to assume that they are potentially capable of inducing a functional modulation of pre-existing and active neural pathways as well as calling into operation neuronal circuits, which in the intact brain are maintained in a state of functional inhibition.

The rehabilitation process of patients affected by alteration of the voluntary control of the upper/lower limb as a consequence of lesions in the central nervous system requires a phase of evaluation of the brain damage and the related disability. The functional evaluation is particularly important in rehabilitation, for the purpose of structuring and organizing the treatment and follow-up of the patients in the short, medium, and long terms. For this reason, a number of clinical evaluation scales have been defined for characterizing to which extent the patients are indeed able to carry out a certain number of activities of the daily life. Such scales have well known limitations due to their semi-qualitative nature: crude sensitivity, floor and ceiling effects and, in particular, the large margin of subjective judgment. On the other hand, these limitations are common to a number of areas, which require a clinical evaluation on the basis of measurements and procedures of analysis of the modifications in the status and behaviour of the patients. The need for a quantitative evaluation of motor abilities has contributed to the diffusion of instrumental techniques into contexts such as gait and posture analysis. Less research efforts have been devoted to evaluate the functionality of the upper limb and this work is a contribution in this direction.

Moreover, since functional recovery is obtained, mostly, by means of repeated physical exercises, with the aid of human therapists; why not using robots for the same purpose? Haptic workstations are indeed able to emulate the action of human therapists by helping the patients to carry out rehabilitation exercises in a controlled, repeatable, and quantifiable way. In others words, they allow us to precisely quantify the deficits determined by the pathological condition of a specific patient and to monitor the results of therapeutic actions, based on appropriate measurements.

Haptic interfaces

Haptic interfaces are devices that enable human-machine interaction via the kinesthetic and/or tactile sense. Typically, a haptic interface is designed as a manipulandum, i.e. a robotic manipulator that is equipped with a handle, which can be grasped by the user. The manipulandum applies forces, which can be programmed to vary with hand position, speed, or acceleration. In virtual reality or telepresence systems, this allows mimicking the dynamic behaviour of virtual or remote environments. Haptic interfaces have been successfully used in various domains, including telesurgery [8], medical and surgical virtual reality systems [9], micro-manipulation [10], and neuromotor rehabilitation. Although the different application areas share methodological and technological issues, the design constraints can be quite different. In this paper we focus on robot therapy for neuromotor rehabilitation, a field in which different systems have been designed and investigated: MIT-MANUS [11], MIME [12], KINARM [13], PFM [14] MEMOS [15], etc. Such devices can be used to guide or assist the movements of a patient and in close interaction with him, just like a human physical therapist. Among the advantages are lower costs, a better repeatability of the therapeutic exercise, the possibility of a more personalized treatments and of precisely monitoring the outcome of therapeutic actions. Here we report on a new robotic workstation for neurological rehabilitation, shortly named *Braccio di Ferro*. In comparison with existing devices, we had several design goals: 1) an extended range of forces, in order to match the natural capabilities of the human motor system; 2) back-driveability of the system, in order to have natural haptic interaction; 3) very low friction and inertia in order to enable experiments near proprioceptive thresholds; 4) mechanical robustness, taking into account the intended clinical usage of the device; 5) the possibility to operate in different planes; 6) an open programming environment.

2. DESIGN OF THE MANIPULANDUM

The structure of the manipulandum was designed by means of an optimization procedure that is based on the Global Isotropy Index. The procedure was applied to the four-bar linkage shown in fig. 1, under the working hypothesis that the workspace was approximated by a 40x80 cm ellipse The geometric parameters determined by the optimisation procedure are shown in the table. The table also shows important functional indicators that can be derived from the kinematic analysis of the device: isotropy index (1 in the ideal case), manipulability index (it should vary as little as possible in the workspace), and torque/force

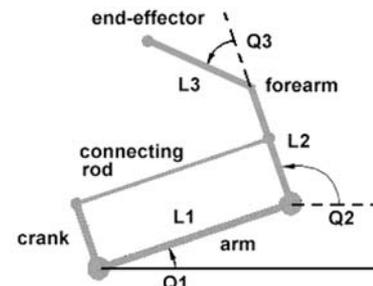ratio (it should be as small as possible), which is important for dimensioning the motors:

Figure 1.

Workspace (elliptical) (cm)	80 × 40
Arm rod & connecting rod L1(mm)	Length 550; tube ∅ 30; thickn. 7.
Forearm, segment 1 L2 (mm)	Length 187; tube ∅ 25; thickn. 3.
Forearm, segment 2 L3 (mm)	Length 283; tube ∅ 25; thickn. 3.
Bending angle (segments 1/2) (deg)	36.5
Isotropy index (f_{max}/f_{min}) (a.u.)	1.537 ± 0.2809
Manipulability index (m)	0.2257 ± 0.0195
Angular res. of encoders (bit/rev)	17
Continuous force at the HIP (N)	>50
Peak transient force at the HIP (N)	>200
Sampling frequency (Hz) 1000:	1000

For the motors we used a direct-drive approach and we chose two AC brushless servo drive systems (Ultract II series motors, Phase Motor Control spa), based on rare earth permanent magnets, which provide high levels of dynamic performance and torque density, even at very low speed.

3. CONTROL

The system is controlled according to the impedance control mode in which the motor torques are computed in real-time in accordance with the dynamic model of the mechanical impedance of the virtual haptic object and the actual movement of the subject (figure 2). The loop must be updated at least at 1000 Hz in order to satisfy physiological constraints of the haptic interaction.
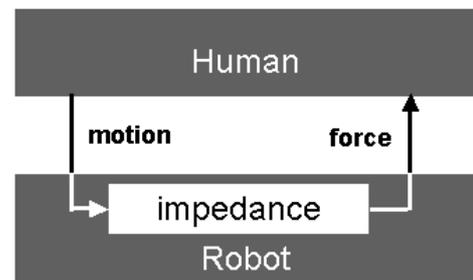

Figure 2.

The control software is organized according to the following architecture that uses two PCs: 1) Planning and application design software on PC1; 2) Real-time control on PC2. PC1 runs the RT-Lab® software package and operates as a Command Station. RT-Lab, among other functions, is a graphical user interface, which supports the user in the design of Simulink® models in order to implement specific real-time control applications. It also automatically translates Simulink models into C programs, which are then

compiled into real-time processes on a remote target computer (the QNX machine on PC2); the QNX machine carries out the actual haptic rendering scheme and other real-time functions. PC1 and PC2 communicate via Ethernet according to the TCP/IP protocol.

4. EXPERIMENTS OF ROBOT THERAPY

4.1 Methods and patients

Braccio di Ferro has been applied in the rehabilitation of hemiplegic subjects. As regards the most appropriate way to exploit the potential of the robot therapy in implementing rehabilitation paradigms, no consensus has been reached so far and this, in a sense, mirrors the lack of consensus among different schools of physical therapy. At present, the experimented approaches of robot therapy fall into three basic categories:

a. *Assistive approaches*: the robot provides assistive or restoring forces, which vary in proportion to the instantaneous difference between desired and actual movement [11] or on the basis of a force field converging to the intended target [16] or in the context of bimanual interaction [17].

b. *Perturbing approaches*: the robot generates disturbances with a variety of patterns while the subject is performing a movement or is maintaining a particular posture. This theory is supported by clinical and physiological observations [18,19].

c. *Adaptive training approaches*: the robot generates a force fields that adapts to the subject's response. This is a very general scheme that can be implemented in a number of ways. A representative approach has been explored by Patton and Mussa Ivaldi [20].

In any case, it is fair to say that we are still far away from a consensus on a general strategy for the optimal use of the robot therapy technologies.

Figure 3.

Frequently, hemiparetic patients with a severe impairment of the arm hold it in a flexed, adducted, and pronated posture and are unable to extend it for reaching objects at the limit of their workspace. In practice, these patients "forget" the affected arm, a phenomenon that mirrors, in the opposite way, the phantom limb syndrome of people with amputated arms. An approach for freeing these patients from the dominating flexion pattern is to use the robot companion for generating a force field that facilitates the achievement of the goal in an "active" way, without forcing a purely passive extension pattern. In particular, we used an attractive force field to the designated target that helps the patient to move the hand in the direction of the target. However, we took into account the requirement that the facilitating action should evoke a voluntary action not impose a passive movement. In order to achieve this goal, we programmed the activation of the force field in the following way:

- When a target is presented to the patient the field is activated in a smooth, progressive way;
- The field intensity is constant throughout the workspace, except in the area of the target;
- The intensity of the force field is selected by the medical personnel according to the general status of the patient as the minimum value capable to determine a detectable, although slow movement in the right direction.

In other words, the subject is required to generate reaching movements to targets that are presented to him/her at the same time in a visual way (in the computer screen in front of her/him) and in an haptic way (as a force applied to her/his hand). The physical assistance provided by the robot can be modulated during the rehabilitation process, with the purpose of making it as small as possible. Moreover, when using this type of assistance paradigm it is possible to carry out training sessions with or without vision for enhancing the proprioceptive contribution in the active control of movements. The implementation of these concepts used in the experiments consists of arranging the visual/haptic targets in three layers: a layer close to the body of the subject (layer A); a far layer requiring almost a complete extension of the arm (layer C); an intermediate layer (B). The target activation pattern is organized as a repetition of the sequence (A→C→B→A) with a randomisation of the selected targets at each layer. The emphasis is on the large A→C movements, which are the main object of the rehabilitation paradigm.

The pilot study reported in this paper was carried out as a collaboration between Neurolab-DIST at the University of Genova and the rehabilitation center ART srl in Genova. Ten hemiplegic subjects were selected among the patients under treatment in the center. They were all in chronic conditions and, at least in the three months before the initiation of the robot therapy sessions, their general performance was stable. During robot therapy the normal sessions of physical therapy were not interrupted and were continued according to the usual schedule. Of the 10 patients, 5 were very severely affected (Fugl-Meyer score – FM – below 10); 3 subjects were severely affected (10<FM<20) and 2 subjects were more slightly affected (FM>20). The research conforms to ethical standards laid down in the 1964 Declaration of Helsinki that protect research subjects. Before beginning, each subject signed a consent form that is conformed to these guidelines.

The subjects were requested to reach visual/haptic targets in the workspace under control of the manipulandum that acted, at the same time, as provider of facilitating actions and monitor of the on-going performance (fig. 3). It is important to note that we kept the level of assistance as low as possible, in order to be sure that the observed

responses were mainly driven by active patterns, not the robot actions. The subjects sat in a chair, with their chest and wrist restrained by means of suitable holders, and grasped the handle of the robotized haptic interaface. The height of the seat was adjusted so that the arm was kept horizontal, at the level of the shoulder joint. The position of the seat was also adjusted in such a way that, with the hand positioned in the centre of the workspace, the elbow and the shoulder joints were flexed about 90° and 45°, respectively.

The visual representation of the targets uses a large screen put vertically in front of the subject at a distance of about 1 m. The haptic representation of the targets is carried out by a force field generated by the robot companion according to the following impedance control equation:

$$T_m = J^T \left\{ \rho(F) \frac{(x_T - x_H)}{|x_T - x_H|} + \begin{bmatrix} B & 0 \\ 0 & B \end{bmatrix} \dot{x}_H + F_w(x_H, x_w, K_w) \right\} \qquad (1)$$

where x_T is the target position, x_H is the position of the hand/handle, F is the level of the force field, $\rho(F)$ is the activation function of the field (a ramp with a rise time of 1 s), J is the Jacobian matrix of the robot arm (the corresponding transpose matrix maps the desired force to be transmitted by the handle into the torque T_m that must be delivered by the motors). Eq. 1 also includes 1) a viscous term that tends to stabilize the arm posture (for the viscous coefficient B a value of 12 Ns/m was empirically determined as a trade-off between stability and dissipated energy) and 2) a term that emulates a rigid "wall" beyond the C layer of targets: we found indeed empirically that the patients were helped by receiving an additional haptic feedback provided by the haptic representation of the boundary of the workspace (a stiff virtual wall with a 1000 N/m elastic coefficient K_w).

The force level of the robot facilitation was selected by the physical therapist as the minimum value that evoked a functional response, i.e. a movement in the intended direction, independently of the target reaching time or the fact that the target could not be reached at all, as in the early phase of learning.

The basic trial consisted of the following steps:
1) from a starting position in the A layer, random select one of three C-targets (forward-left, forward, forward-right); turn on the visual and haptic representations of the target at the same time; when the target is reached, give an acoustic feedback, switch off the target (visually and haptically) and wait for a given time;
2) random select one of the B targets; turn it on; switch it off when is reached and wait for a given time;
3) random select one of the A targets; turn it on; switch it off when is reached and wait for a given time.

The duration of the wait and rise times was 1 s. The basic trial was repeated several times, in such a way to have 3 presentations of the seven C-targets, with a total 21+21+21=63 movements in a given block of trials.

We introduced in the protocol two types of trials, with open or closed eyes, respectively. In the latter case, the subjects could feel the target via the proprioceptive channel and the purpose was indeed to enhance the role of proprioception, which is likely to have a beneficial effect in

the further reduction of the pathological patterns and in the recovery of a memory image of the affected (and neglected) limb. The overall protocol consisted of four blocks of trials: open eyes, closed eyes, open eyes, closed eyes, using the same level of force. The therapist could decide, in accordance with the subject, to extend the session with additional blocks characterized by lower levels of force. The overall duration of the sessions ranged from 45 to 90 min. The training sessions took place one or two times per week, while the patients received their standard physiotherapy treatment.

Hand trajectories were reconstructed from the recorded sequences of joint rotation angles (sampled at 1000 Hz) and sub-sampled to 100 Hz. The x and y components were smoothed with the a 4th order Savitzky-Golay filter (with an equivalent cut-off frequency of about 6 Hz), which also allowed us to estimate the time derivatives.

4.2 Results

For all the patients there was a detectable improvement of performance over training. Figures 4 and 5 report this process in qualitative terms. They both refer to the same subject in the early and final phases of the training, respectively. For each figure, the top panel shows the trajectories to three targets in the three layers of the workspace (A→C→B→A) and the lower panel shows the corresponding time plots of the magnitude of the force field and the velocity trace of the hand.
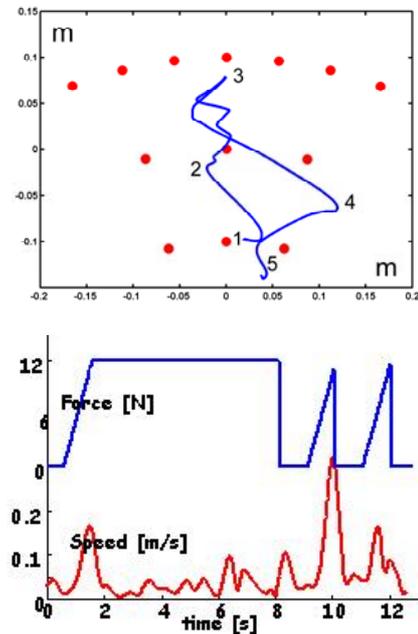

Figure 4.

It appears that initially the subject was unable to reach the external target in one shot, with the typical straight trajectory and bell-shaped velocity profile that characterizes normal people [4]. On the contrary, the movement was segmented in a number of attempts or sub-movements that eventually succeeded to reach the target but after a rather long time. In the later phase of training, the assistance level

was reduced (from 12N to 6N), the pattern was clearly improved and was more similar to the normal one. In other words, initially the assistance provided by the robot companion to outward reaching is sufficient to elicit voluntary movements in the right direction but it covers only part of the total distance, thus leaving a residual error that must be corrected by subsequent commands. The inward reaching movements, on the other hand, are carried out with a single command, which is characterized by a single peak. As a consequence, the duration of forward reaching is much longer than inward reaching. This observation suggested us, as expected, to concentrate the attention on outward movements for finding the changes of the pathological patterns.
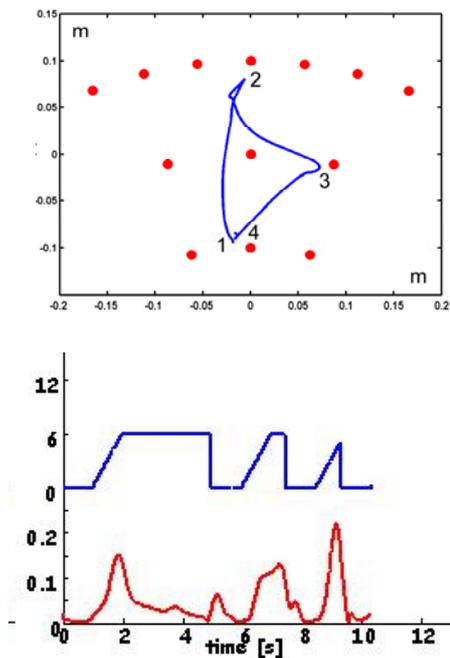

Figure 5.

The 10 therapy sessions were preceded by a test in which the physical therapist selected the level of force assistance appropriate for each subject. As shown in fig. 6, this level ranged between 25 N (subject 1) and 5 N (subjects 9 and 10). Each session always begun with two blocks of trials at this force level: one with open eyes and one with closed eyes. Each block included 63 movements (3 movements to each of the 7 external targets plus the associated return movements). After these two blocks the therapist, in agreement with the patient, could either repeat the same blocks or initiate a new pair of blocks with reduced force assistance. The procedure went on until the patient became fatigued and/or the therapist decided that it was appropriate to stop. Fig. 6 also reports the minimum force level reached for each session: it is apparent that all patients improve, requiring less and less assistance by the robot companion. It is clear that the subjects need different levels of force for working with minimally assistive robot training. Personalization of the treatment, in close cooperation with the human physical therapist, is a *conditio sine qua non* for a successful employ of the "robotic therapist".

Alternating OE and CE trials was well accepted by the subjects, although they reacted in a different way, in particular in the early phase of training. Some subjects, who work with higher values of force (more than 12 N), are more able to relax the arm with closed eyes, while patients who work with low levels of force (less than 9N) can have proprioceptive problems to feel correctly the force (S6) and, in the early recovery phase, they may need to work with greater forces with closed eyes than with open eyes (S8, S9).
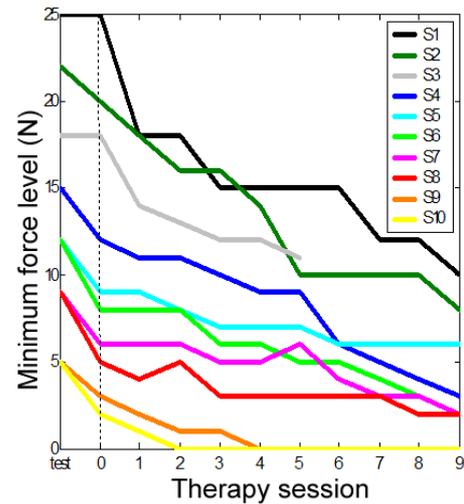

Figure 6.

Movement indicators and statistical analysis

The qualitative/morphological analysis was completed by introducing four quantitative indicators of movement performance, derived from the concept that overcoming the segmentation of reaching movements into sequences of sub-movements is an index of improved motor organization.
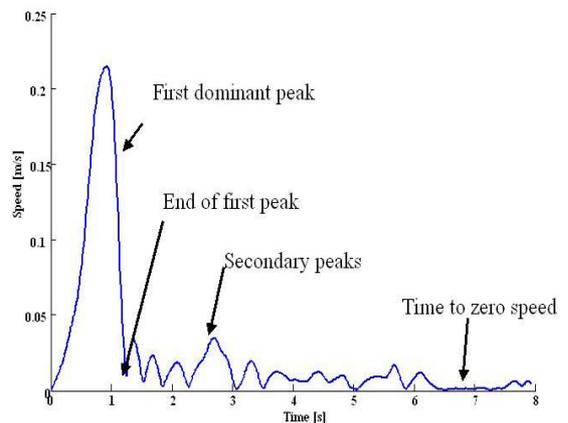

Figure 7.

Figure 7 shows a typical segmentation pattern of a reaching movement, with the first, dominant peak of the speed profile and the smaller, secondary peaks before reaching the target. From this we derived the following indicators:
1) Number of peaks of the speed profile (an indicator of the smoothness of the movement);
2) Average reaching speed;
3) End-point error after the first sub-movement;

4) Timing indicator of the first sub-movement (ratio between the duration of the first sub-movement and the total time to target).

The improvement of performance is consistent, with the only exception of subject 2, whose impairment level (FM score) was mild to start with :

1) the number of peaks of the speed profile goes down to 1 or 2 from an initial value that can exceed 10;
2) the mean speed in most of the subjects increases up to 10 cm/s;
3) the endpoint error goes down to the size of the target;
4) the T-ratio goes up to 0.9 or more.

We run a repeated-measures ANOVA of the control indicators with two factors: session (1-10) and vision (yes/no). We found significant effects of session for all indicators. The role of vision is somehow intriguing. The effect is marked in some subject and for some indicator. For example, the number of peaks indicator is much better (initially) with vision than without vision (S3) but for S10 it is just the opposite. In both cases, however, the difference between the two conditions tends to disappear as training proceeds. The consequence of such divergent behaviour among patients is that at the population level there is no statistically significant effect of the vision factor. However, there is a significant effect of the interaction between vision and session for two indicators: the number of peaks and the T-ratio. This can be attributed to the fact that differences of performance between the two conditions in the early phase of training are attenuated in the later phases. This is clearly a positive clinical sign, because it means that an effect of training is a *recalibration* of the sensory channels that are crucial for carrying out purposive motor actions.

5. CONCLUSION

The reported approach to robot therapy, which links the study of the neural control of movement to the application in neuromotor rehabilitation, appears to be promising and worth a large-scale application.

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