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Training stroke patients with continuous tracking movements: evaluating the improvement of voluntary control

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Abstract—**We report on a pilot study of robot therapy with stroke patients. Patients were requested to track a continuously moving target according to a figure-of-eight. Assistance was provided by an attractive force field, whose magnitude was regulated according to a principle of minimal assistance and a principle of consolidation of the learned memory trace. From the analysis of the assistive forces, we show that subjects improve their degree of voluntary control.**

I. Introduction

THE purpose of this study is to evaluate the improvement of voluntary control in stroke patients trained by a haptic robot, according to an innovative exercise protocol characterized by the following elements:

- Continuous movements as opposed to point-to-point movements, which characterize the great majority of trained movements in robot therapy. There are several reasons for this choice: it promotes motor smoothness, which is known to be important in motor recovery; it facilitates coordination in all movement directions, not just a few; it provides a richer proprioceptive feedback; it trains the patient to integrate feedback and feedforward control, which is known to characterize visuo-manual tracking tasks [1, 2].
- High-compliance haptic environment in most part of the state space, obtained by a non-linear attractive field; this is meant to enhance the freedom for the patient in shaping the spatio-temporal patterns of the tracking movements. This is in agreement with the general notion that motor learning is made possible by the experience of error in a wide variety of situations [3].
- Automatic regulation of assistance, according to a trade-off of two basic principles: 1) minimization of the level of assistance (or "assist as needed" [4]) by means of a progressive, performance-related decrease of the assistance "gain" in the course of a given session; 2) consolidation of the memory traces of newly acquired control patterns, by restoring higher assistance values at the beginning of a new session (non-monotonic time-course of assistance).
- Enhancement of proprioception, by alternating blocks of trials performed with or without visual feedback.

Parts of the protocols were investigated in previous studies: non-monotonic assistance patterns [5], proprioception enhancement [6], and continuous tracking movements [7].

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II. Experimental Methods

A. Experimental setup

Subjects sat on a chair, with their torso and wrist restrained by means of suitable holders, and grasped with their plegic hand the handle of a planar manipulandum [8] characterized by low friction, low inertia, zero backlash, large elliptical workspace (80×40 cm) actuated by a pair of direct-drive brushless electric motors. A lightweight support allowed low-friction sliding of the forearm on the horizontal surface of a table. The position of the seat was also adjusted in such a way that, with the cursor pointing at the center of the workspace, the elbow and the shoulder joints were flexed about 90° and 45°, respectively, and the arm was kept approximately horizontal, at shoulder level. A 19" LCD computer screen was placed in front of the subjects, about 1 m away, at eye level. The current position of the hand was continuously displayed, as a color icon (a vehicle, see Fig. 1). Target was also displayed as a round red circle (diameter 2 cm). The visual scale factor was 1:1.

B. Subjects

Ten stroke subjects volunteered to participate in this study (table I). They were recruited among outpatients of the ART Rehabilitation and Educational Center - Genova. Inclusion criteria were (1) diagnosis of a single, unilateral stroke, verified by brain imaging; (2) sufficient cognitive and language abilities to understand and follow instructions; (3) chronic conditions (at least 1 year after stroke), (4) stable clinical conditions for at least one month before entering robot therapy.

Subjects ranged in age from 32 to 74 years (53 ± 15) with an average post-stroke time of 4 ± 2 years and with a majority of ischemic etiology (7/10). As regards the degree of impairment (table II), the majority of patients (6/10) had a Fugl-Meyer score (arm section: FMA) smaller than 25/66.

The other 4 patients had a more moderate score (25<FMA<45).

The research conforms to the ethical standards laid down in the 1964 Declaration of Helsinki for the protection of research subjects. Each subject signed a consent form that conforms to these guidelines.

C. Task and protocol

The task consists of tracking a moving target, which moves along a figure-of-eight shape (trajectory length = 90cm), with the following law of motion: $[x_T = A\sin\Omega t, y_T = B\sin 2\Omega t]$, where A=0.16m, B=0.07m, Ω=0.42 rad/s, T=15s, which corresponds to an 8-shaped path.

Training sessions are divided into *blocks*, each of them containing 10 repetitions of the 8-shaped path: 5 turns in the direction "clockwise-right/counterclockwise-left", plus 5 turns in the direction "counterclockwise-right/clockwise-left" (figure 1). The nominal duration of a block (for an ideal subject) is 10×15 = 150 s and the corresponding path length is 10×0.9 = 9 m. Each block of trials was carried out in one of two experimental conditions: open-eyes condition and closed-eyes condition (vision vs. no-vision). The two conditions were alternated in a given session. The approximate duration of each session was 1 hour min (or less if the patient appeared to be fatigued).

TABLE I
SUBJECTS' ANAGRAPHIC AND CLINICAL DATA

Subject	Age	Sex	Dis. dur.	Etiol.	Hand
S1	74	M	4	I	L
S2	48	F	4	H	L
S3	36	F	4	I	R
S4	56	F	2	H	L
S5	32	F	3	I	L
S6	59	M	5	I	L
S7	71	F	4	I	H
S8	34	F	2	I	H
S9	57	F	8	H	L
S10	62	M	1	I	L

Age (y); Sex (Male/Female); Dis. dur. (disease duration: y); Etiol. (Etiology: Ischaemic/Hemorragic); Hand (paretic hand: Left/right).

TABLE II
CLINICAL EVALUATION OF THE THERAPY.

Subject	Sess	FMA_{ini}	FMA_{fin}	ΔFMA	Ash
S1	11	4	8	4	3
S2	12	13	16	3	2
S3	10	25	31	6	1+
S4	12	36	38	2	1
S5	10	9	11	2	2
S6	10	22	23	1	3
S7	10	27	34	7	1+
S8	9	43	46	3	1
S9	6	44	48	4	1
S10	10	11	13	2	1+

Sess (no. of sessions); FMA_{ini}, FMA_{fin} (Fugl Mayer score, arm section, at the beginning and at the end of the training); Ash (Ashworth score).

D. Control of assistance

Fig. 2 shows the assistance control scheme, which includes three basic modules:

- Force field generator, which assists tracking movements with an attractive force, proportional to the square root of the distance $d=|x_T-x_H|$ between the target and the hand: $F = K\, v_{HT}\,(d)^{1/2}$ where v_{HT} is the unit vector connecting the hand to the target. The force field is modulated by the gain *K,* which is transmitted to this module by the Adaptive Controller. It operates in real-time, with an update rate of 1000 Hz. The initial values of the force field K the is selected as the minimum level capable to induce the initiation of movement of the paretic limb, it ranges between 7 N and 27 N and it is generally higher for more severe patients.

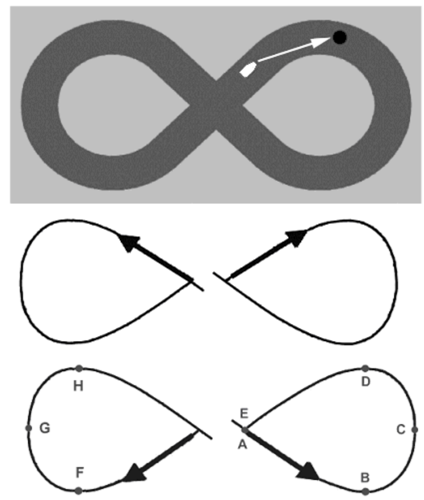

Fig. 1. Trajectory of the target, as presented on the computer screen (top panel). Tracking directions and "control points" (middle and bottom panel).

- Performance evaluator, which computes two performance parameters at the end of each block, a tracking error parameter P_1 and a timing parameter P_2. P_1 is defined as the number of times in which the tracking error is greater than 2 cm, in relation with the 8 control points of fig. 1. P_2 is the duration of each block, relative to the nominal duration of 150 s. The two parameters are transmitted to the Adaptive Controller module.
- Adaptive controller, which (i) supervises the protocol sequencing, (ii) controls the motion of the target, and (iii) modulates the gain of the assistive field. The law of motion of the target is sampled with the 1000 Hz frequency as long as the tracking error is less than the tracking threshold of 2 cm. If the error becomes greater, target motion is blocked; it reactivated when the error goes below that threshold. The gain of the assistive field, *K,* is reduced by a fixed amount Δ*K* at the end of the current block if both indicators (P_1 and P_2) are below threshold. In this way, the intensity of the assistive force is gradually reduced during a session as soon as performance improves. The final value of the gain *K,* reached at the end of the current session is then used as

the initial value in the next session. This implements the previously mentioned non-monotonic assistance strategy.

E. Data analysis

For each turn of the 8-shaped path, we computed the average magnitude of assistive force. For each subject, the sequences of forces for each session resulted in two different time series, one for the "vision" condition $[f_1, f_2, \ldots\ldots f_N]_V$ and one for the "no-vision" condition $[f_1, f_2, \ldots\ldots f_N]_{NV}$.

Both time series were fitted with an exponential model:

$$f_k = A_0 e^{-\alpha k} + A_1 \quad (1)$$

The parameter A_1 is the asymptotic magnitude of the assistive force (after an infinite number of training sessions); A_0 represennts the variation of assistance between the first and the ∞-th trial (thus indirectly specifying the initial assistance level, $A_{i=} A_0+A_1$); α is the rate of decay of assistance (its inverse $1/\alpha$ can be interpreted as a time constant, expressed in number of 'turns').

Based on this model, an Indicator of Voluntary Control (IVC) can be defined by assuming that (as a first approximation) the observed performance (P), e.g. the average tracking error, results from the summation of an (unknown) level of voluntary control (C) and an assistive (A) component:

$$P = A + C \quad (2)$$

As the regulation of assistance has been designed to keep the tracking error P approximately constant, then we can say that, between the initiation and the termination of the treatment $\Delta C \approx -\Delta A$. A normalized IVC is then defined as:

$$IVC = \Delta C / A_i \cdot 100 \quad (3)$$

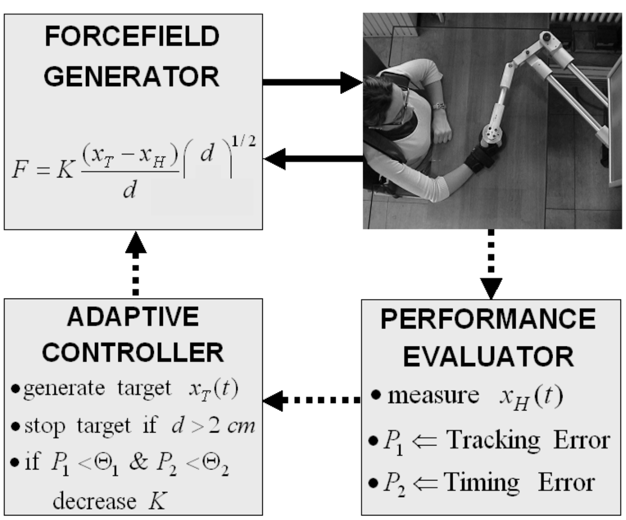

Fig. 2. Scheme of the self-adaptive assistance mechanism for a continuous tracking task; x_T and x_H are the trajectories of the Target and the Hand, respectively; d is the current distance between the target and the hand; P_1 and P_2 are the two performance parameters, evaluated at the end of the current block of 10 turns; Θ_1 and Θ_2 are the thresholds for the two parameters; K is the assistance gain.

III. RESULTS

In all subjects, we found a positive the decay rate, α and a positive A_0. This means that the self-adaptive regulation mechanism consistently leads to a gradual reduction of assistance.

The consistency of the assistance regulation mechanism is also confirmed by the relationship between the assistive force and the FMA and Ashworth score, at the beginning and at the end of treatment: the more severe patients (those with a lower FMA and higher Ashworth score) needed an initially greater assistance (A_i). Likewise, they needed a greater assistance at the end of the training (A_f); see Figure 3

The specific profiles of assistance differ from patient to patient. Figure 4 shows typical patterns. The patient (S1) depicted in the top panel has a high impairment level (FMA=4, ASH=3), which is reflected in the large force assistance needed at the beginning of the treatment (more than 14N in both vision & non-vision conditions).

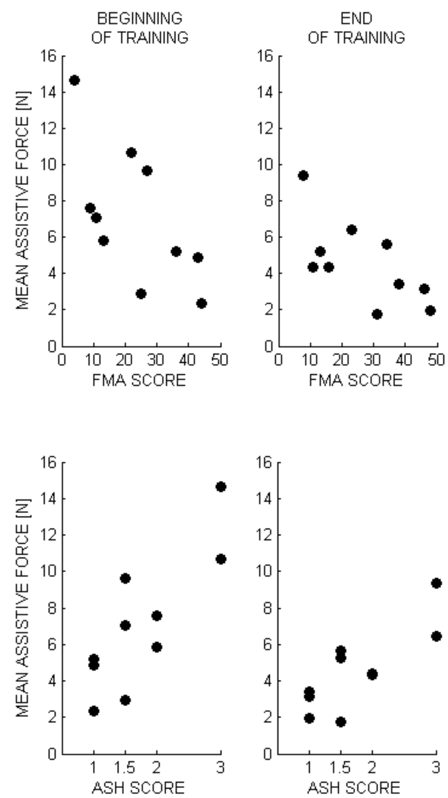

Fig. 3. Top: Assistive force (average between vision and no vision data sets) vs FMA score. Bottom: Assistive force vs Ashworth score.

In this patient there is a steady improvement in both conditions (vision and no-vision) and the learning time constant is smaller in no-vision condition. In both conditions, however, the trend suggest that the patient did not yet reach a steady state performance but, on the contrary, could have improved further with additional training sessions.

The patient (S7; FMA=27, ASH=1+) in the middle panel appears to have an even shorter time constant for the no-vision condition, suggesting he/she could benefit from a continuation of the training under the vision condition.

The patient (S6; FMA=22, ASH=3) in the bottom panel has similar time constants for both conditions. In this case, it appears that the amount of assistance reached a plateau for both experimental conditions.

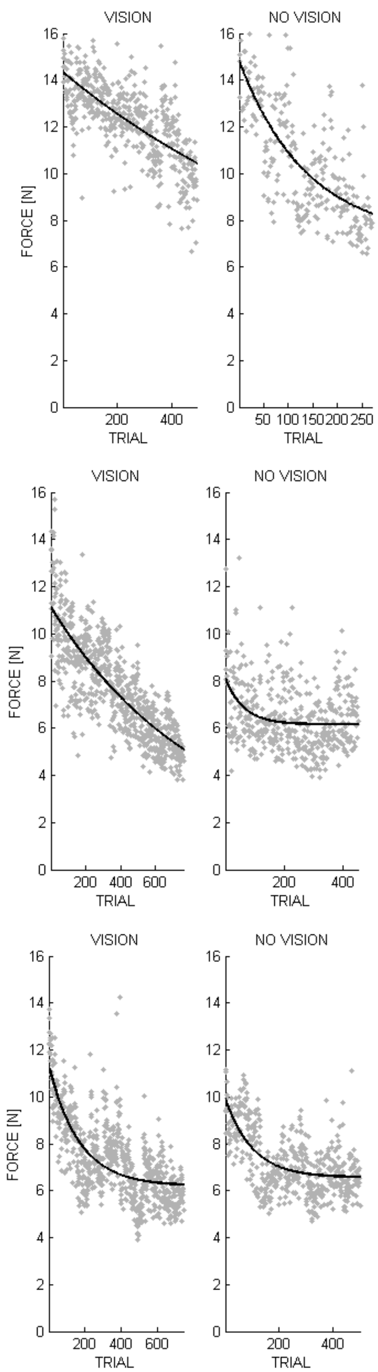

Fig. 4. Evolution of force assistance during each turn of the figure-of-eight (gray dots), with the corresponding assistance trend function (black curve), for the vision and no-vision block of trials. Top: subject S1 (FMA=4, ASH=3). Middle: subject S7 (FMA=27, ASH=1+). Bottom: subject S6 (FMA=22, ASH=3)

Table III reports, for all subjects, the model's parameters A_0, A_1 and the "time constant" $1/\alpha$ of the decay (number of turns), and the IVC index.

TABLE III
ASSISTANCE MODEL PARAMETERS

	VISION				NO-VISION			
Subj	A_0	A_1	IVC	$1/\alpha$	A_0	A_1	IVC	$1/\alpha$
S1	10.7	3.6	27	1082	7.6	7.2	44	136
S2	2.6	2.5	13	3130	6.5	0	35	1138
S3	1.5	0	34	1076	1.9	2.4	43	63
S4	4.5	0	55	1115	1.4	4.5	19	305
S5	2.7	4.1	39	101	3.8	4.6	46	80
S6	5.2	6.2	45	166	3.4	6.6	34	99
S7	10.3	0.8	54	862	1.9	6.1	24	61
S8	1.8	0.9	11	2932	3.1	3.9	44	12
S9	1.1	0.5	34	628	1.6	1.5	8	2292
S10	3.5	5.1	40	19	0.6	4.7	1	3331

A_0 (N), A_1 (N), α (dimensionless): model's parameters; IVC: Indicator of Voluntary Control (%).

In our population of patients, IVC ranges between 11 to 55 with visual feedback, with a mean value of 35. With no visual feedback, IVC ranges between 1 and 46 with a mean value of 30.

IV. CONCLUSION

In addition to provide useful information for the design of future large scale controlled clinical trials, the results of this preliminary study suggests that the personalization of robot therapy by means of suitable self-adaptive interaction strategies can be effective and practical.

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