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Characterizing the human-robot haptic dyad in robot therapy of stroke survivors

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Abstract

Purpose – The working hypothesis, on which this paper is built, is that it is advantageous to look at protocols of robot rehabilitation in the general context of human-robot interaction in haptic dyads. The purpose of this paper is to propose a new method to detect and evaluate an index of active participation (*AC* index), underlying the performance of robot-assisted movements. This is important for avoiding the slacking phenomenon that affects robot therapy.

Design/methodology/approach – The evaluation of the *AC* index is based on a novel technique of assistance which does not use constant or elastic forces but trains of small force impulses, with amplitude adapted to the level of impairment and a frequency of 2 Hz, which is suggested by recent results in the field of intermittent motor control. A preliminary feasibility test of the proposed method was carried out during a haptic reaching task in the absence of visual feedback, for a group of five stroke patients and an equal group of healthy subjects.

Findings – The *AC* index appears to be stable and sensitive to training in both populations of subjects.

Originality/value – The main original element of this study is the proposal of the new *AC* index of voluntary control associated with the new method of pulsed haptic interaction.

Keywords Human-robot haptic interaction, Robot therapy, Stroke survivors

Paper type Research paper

1. Introduction

Robot therapy is slowly emerging as an acceptable technique for the routine treatment of people affected by neuromotor diseases like stroke (Mehrholz *et al.*, 2012; Krebs and

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Hogan, 2012). However, there is still little agreement on the theoretical background that is necessary for overcoming the current empirical approaches, which have prompted a large variety of designs and control strategies. These include robots that move limbs rigidly along prefixed paths, robots that take action only if the patient's performance fails to stay within some spatial or temporal boundary, etc. (Hesse *et al.*, 2005; Marchal-Crespo and Reinkensmeyer, 2009).

After the studies on animal models of stroke by Nudo (2006, 2007), it has become clear that beyond time-dependent spontaneous neurological recovery, the principal process responsible for functional recovery is the use-dependent reorganization of neural mechanisms made possible by neural plasticity. The requirement of use-dependent reorganization, highlights the fact that promotion of active movements should be preferred to passive mobilization for inducing re-learning and functional recovery. This is not to say that passive mobilization should be always avoided: it is known indeed that it can help contrasting the deterioration of the tixotropic properties of the collagen matrix of the muscle tissue that is a secondary consequence of the functional immobilization of the paretic limbs of the stroke patient. Thus, some degree of passive mobilization is acceptable in a treatment routine, considered as a technique of dynamic splinting. However, the core of the treatment should be based on adaptive haptic interaction between the robot therapist and the patient, capable to recruit neural plasticity by inducing active participation of the subjects. The rationale of emphasizing the patient's active participation to the treatment process comes also from the discovery that during motor adaptation human subjects behave as greedy optimizers (Emken *et al.*, 2007), in the sense that they tend to decrease the active participation as a function of the degree of assistance, what is described as slacking behavior (Wolbrecht *et al.*, 2008).

As a matter of fact, one of the main cybernetic effects of brain damage after stroke is to break the intrinsic coherence of purposive actions, namely the causal relation or volitional loop between "intended actions," "actual movements," and the corresponding "feedback reafference": the motor program that drives the muscles in agreement with a given task can successfully unfold its control patterns only if the sensory consequences of them (the sensory reafferences) match the expected motion patterns. In severely impaired subjects, who are unable to carry out simple reaching movements (e.g. center-out movements to distant targets, on the border of the workspace) or have a strongly reduced range of motion these movements must be supported by carefully regulated assistance. The purpose of such assistance is not to carry out the movements in place of the subject. On the contrary, robot assistance must help recreating the volitional loop mentioned above. This means that the assisting force must be generated and modulated by the robot as a function of some indicator of the subject's intention to move in such a way to complement the voluntary neuromuscular commands in order to induce physiologically consistent reafferent signals. In other words, the relation between the stroke patient and the robot/human therapist can be viewed as a haptic dyad and we believe that significant advances in robot therapy will be facilitated by taking into account the results coming from haptic dyad studies in human-robot interaction.

According to Gibson (1966), the human haptic system is the sensibility of the individual to the world adjacent to his body by use of his body. This implies a close link between haptic perception and body movement, suggesting that haptic perception is not a passive sensory modality but, different from the other modalities, is intrinsically active, integrating sensory and motor aspects at the same time. Force as well as touch is indeed a constituent element of haptic perception and it is well known that both afferent and efferent signals contribute to force perception (Jones, 1986). Although many studies of the human perception of the force magnitude can be found in the literature (Jones, 1986; Pang *et al.*, 1991) less attention has been devoted on the perception of the force direction. In particular, it has been found that the discrimination threshold of force direction is significantly affected by visual information (Barbagli *et al.*, 2006). In another study (van Beek *et al.*, 2013) a marked anisotropy in perception of force magnitude and direction was found: normalized force magnitude data showed a consistent elliptical pattern, with its minor axis pointing roughly from the subject's hand to his/her shoulder, which is consistent with the known arm stiffness or manipulability patterns. This means that forces in the direction of highest stiffness and lowest manipulability are perceived as being smaller; moreover in other directions such anisotropy induces a distortion of the perceived force direction. The accurate perception of force direction is crucial in several applications, e.g. the design of skill transfer systems that rely on a haptic interface (Endo *et al.*, 2010). Few studies have attempted to discriminate the relative role of the kinesthetic and cutaneous components of haptic feedback during acquisition of a new skill. In a recent work (Rosati *et al.*, 2014) it was found that kinesthetic stimuli play a primary role during motor adaptation to a viscous field. Although it remains to be seen whether these results can be generalized to other tasks, this is a quite relevant finding for the design of effective protocols of robot therapy.

Haptic dyads are very common in human activities, like physical collaboration in handling bulky objects (Reed and Peshkin, 2008; Van der Wel *et al.*, 2011) or in visual and performing arts, such as dancing (Shaw *et al.*, 1992; Gentry and Murray-Smith, 2003). It has been found that dyads produce much more overlapping forces than individuals, especially for tasks with higher coordination requirements (Van der Wel *et al.*, 2011; McAmis and Reed, 2013), thus suggesting that dyads amplify their forces to generate a haptic information channel. Reed and Peshkin (2008) showed that the workload sharing between two humans changes during task execution and that they take over different roles: thus, we may expect cooperative haptic assistants to lead to reduced effort and failure rates and a higher acceptance by the human operator. But how do the resources of two agents combine to complete a task or how can this knowledge be exploited in human-robot cooperation? A positive answer to this question is still away and more research is needed in this respect. In a study by Corteville *et al.* (2007), a human-inspired robot assistant for fast point-to-point movements is investigated: the robot scales the offered level of assistance in order to give the operator the opportunity to gradually learn how to interact with the system. The results of the study show a bidirectional, synergistic influence: while the robot is programmed to adapt to the human motion, the operator also adapts to the offered assistance, inducing a highly natural type of interaction. In a shared virtual object manipulation task, performance-related energy exchange in haptic dyadic interaction has been analyzed and the results indicate that the interacting partners benefit from role distribution which can be associated with different energy flows (Feth *et al.*, 2009). On the other hand, in physical collaborative tasks it has been found that it may be beneficial to switch continuously between two distinct extreme behaviors (leader and follower), thus creating an implicit bilateral coupling within the dyad (Evrard and Kheddar, 2009). In a similar vein, Oguz *et al.* (2010) showed that in order to facilitate the arousal of a natural sense of collaboration in a robot guidance mechanism it is appropriate to supplement the haptic guidance with a role exchange mechanism, which allows the computer to adjust the forces it applies to the user in response to his/her actions. In general, a recent review on bilateral haptic interaction systems (Passenberg *et al.*, 2010) shows that the incorporation of environment, operator, or task-specific information in the controller structure can improve robustness and performance but such benefits are application dependent to a large extent.

Another way of looking at the development of haptic interaction in a dyad during the teaching/learning of a task is to evaluate the sense of agency, namely the subjective experience of the learner of being in control. Two formulations of this phenomenon have been proposed: one is the theory of apparent mental causation (Wegner *et al.*, 2004), which assumes that this experience is established after the action has been completed, taking into account the temporal relation between the mental representation of an action and the action itself (priority, exclusivity, and consistency); the other formulation is based on the forward model theory of action control, namely the idea that the sense of agency is driven by the degree of match between the predicted sensory consequences of a voluntary action and the actual sensory consequences or reafferences of that action (Frith *et al.*, 2000). Both theories capture different parts of this sensorimotor experience of dyadic interaction (van der Wel *et al.*, 2012), although more research is needed particularly on patient-therapist or patient-robot interaction in neuromotor rehabilitaton.

On a lower cognitive level than the sense of agency, but clearly related to it, is human interaction in the physical cooperation between (human or robotic) partners necessary to perform a cooperative manual task, including shared control of a complex task/equipment. Physical cooperation or kinesthetic interaction (Reed *et al.*, 2005) represent indeed a communication channel equally important to typical social mechanisms like speech, gesture, and facial expression. In particular, the hands-on interaction between physical therapist and patient is characterized by micro-gestures capable to communication to the therapist a number of important physiological variables such as muscle tone, muscle stiffness, activity vs passivity of motion patterns. This information should then be exploited by the therapist for delivering assistive/resistive forces aimed at enhancing the capability of the patient to generate goal-oriented voluntary control patterns. A related field of research on haptic dyads is that on haptic assistants, which indeed have been used in a large number of applications, from aviation or automotive systems to motor skill learning and rehabilitation. In most cases, as observed by (Passenberg *et al.*, 2013), a fixed assistance level was used, which was selected heuristically with respect to the specific task design. However, the assistance level should be selected carefully, as a too small level does not facilitate the task and a too large level discourages the user from remaining in control (van Asseldonk *et al.*, 2009). Moreover, O'Malley *et al.* (2006) showed that the user becomes easily dependent on a constant assistance level and (Passenberg *et al.*, 2013) demonstrated that smart adaptive assistance policies can outperform constant assistance policies.

Our work on robot therapy of stroke patients is based on the assumption that the robot therapist should be designed and controlled in such a way to establish a bidirectional, adaptive kinesthetic communication channel, somehow mimicking the human therapist, in such a way to avoid passive mobilization and thus enhancing the degree of active participation of the patient. Of course, mimicking the human therapist is difficult also because there is no specific, accepted protocol of physical therapy. Moreover, there is a quite relevant difference between haptic dyads used in therapy and cooperative handling: in the latter case, we may assume that the human part of the dyad has intact sensorimotor capabilities, thus simplifying the learning/adaptation process between the human and robot without any danger of slacking because with insufficient participation by the human partner cooperative tasks could not be carried out successfully; in contrast, in the clinical case the human is the weak part of the dyad, unable to carry out the task by itself, and thus the robot must do most of the job but in a clever way, i.e. by avoiding slacking and promoting the emergence of active participation.

Such general concepts are summarized in Figure 1. In the dyadic interaction the robot plays the role of an impedance and the patient the role of an admittance. The robot provides assistive force patterns related to the assisted movement. The forces activate tactile and kinesthetic channels of the patient, who is required to estimate from them the intention of the robot therapist. The assisted movements measured by the robot are analyzed in order to estimate an index of active contribution and from this the assistive force generation module can be modulated for reinforcing active and precise control of the patient. In this study we focus on a specific point that we think is crucial in the dyadic interaction between robot and patient: on-line evaluation of an index of active contribution (*AC* index). The computation of this index is based on a novel method of generation of assistive forces, namely a pulsed assistive mechanism which uses trains of small force impulses. In a recent paper (De Santis *et al.*, 2013) preliminary experiments were carried out with the goal of comparing continuous and pulsed assistance. The results show that pulsed assistance allows patients to reach a similar performance level as compared to continuous assistance after single-session training, while lowering to a significant degree the average force level. Here we focus on the analysis of the *AC* index, also including a control group of healthy subjects. Most experiments were performed in the absence of vision, taking into account previous studies (Casadio *et al.*, 2009a, b; Vergaro *et al.*, 2010) which show that robot therapy can work quite well in absence of vision, when training patients to perform reaching or tracking movements with pure haptic guidance. Moreover, Piovesan *et al.* (2013) demonstrated that in the same experimental context, assisted movements performed in the absence of visual feedback are characterized by lower stiffness than when visual information is available.

2. Methods

Two types of experiments were carried out: haptic reaching in healthy subjects and haptic assisted reaching in stroke patients. In the first experiment the subjects were blindfolded

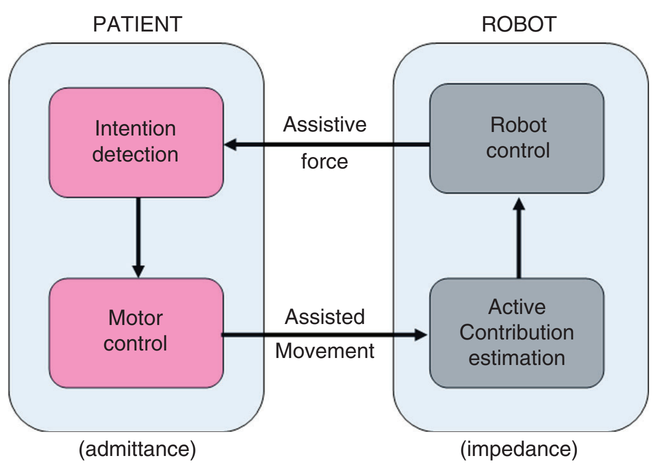
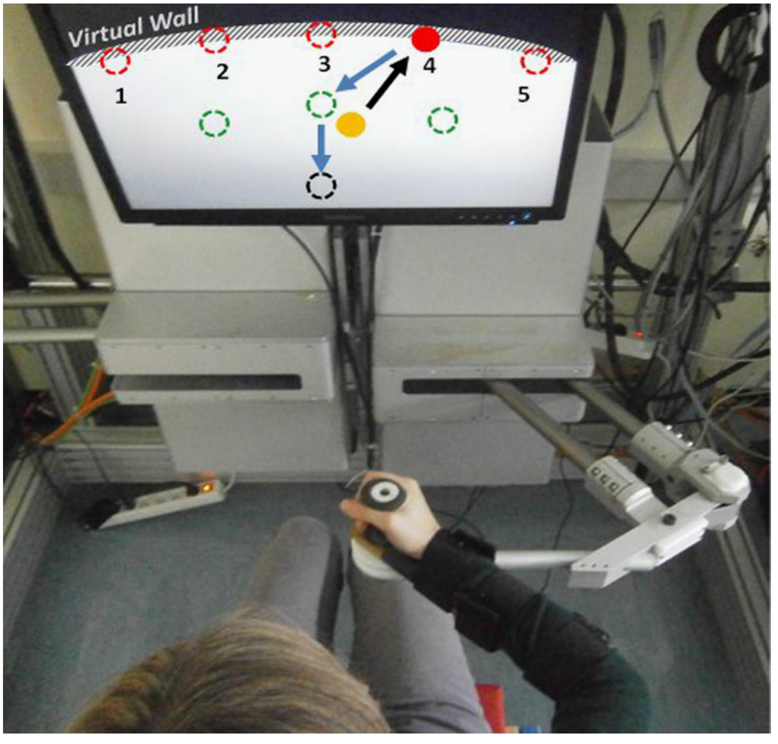


Figure 1.
Main processing blocks in the bidirectional haptic interaction in robot therapy

and haptic information about the target (a train of small force impulses) was provided by a planar manipulandum (Braccio di Ferro, Celin srl, La Spezia, Italy). The manipulandum, which has a very low friction and inertia (Casadio *et al.*, 2006) is directly controlled in force and can generate accurate force vectors (in amplitude and direction). The experiments with control subject were intended to provide a reference background information on the human capability to carry out reaching movements solely with haptic feedback. In the experiment with patients, the pulsed haptic feedback was mixed with continuous haptic assistance. Moreover, in alternated trials patients were also provided with visual feedback, by allowing them to see on the screen the real-time position of both the hand and the target. Subjects sat in front of the robot with their shoulders strapped to the chair, holding the end effector of the robot with the hand (the dominant hand in the case of controls and the impaired hand in the case of patients). The hand and the shoulders were securely fastened using a custom made cast. Figure 2 illustrates the setup.



Notes: In the first experiment (control subjects) the subject was blindfolded and the target was communicated only haptically by a train of small force impulses applied by the manipulandum to the hand (the yellow circle in the figure) and directed to the current target (the red circle in the figure). In the second experiment (stroke patients) the subject received the same haptic feedback, with or without visual feedback (in Vision or No-Vision trials, respectively). The target layout of the figure corresponds to the second experiment (patients). In the first experiments (controls) there were seven target aligned on the wall and a single starting target (black, dashed in the figure), without intermediate (green) targets

Figure 2.
Experimental setup: the subject sits in front of a screen, holding the manipulandum

2.1 Haptic reaching in healthy subjects

In this experiment, seven targets were used, equally spaced on a circle at a distance of 26 cm from a starting position, close to the chest. The inter-target angular displacement was 12.5 deg and the inter-target distance was 5.65 cm. For each trial, with the hand positioned in the starting position, one of the seven peripheral targets was selected randomly. The direction of the target was communicated to the subject by applying a train of short force impulses, oriented to the target, with a smooth minimum-jerk profile, a peak amplitude of 3 N, a duration of 200 ms, and a frequency of two pulses/s. After each impulse, the force transmitted to the hand of the subject by the robot went down to 0. The amplitude of the impulses was chosen in such a way to be close to the perceptual threshold. If applied in isolation with the task of maintaining the initial posture in a relaxed condition, a single impulse would temporarily displace the hand by an amount of the order of a centimeter, with an elastic return to the initial position at the end of the impulse. In this experiment, the task of the subject was not to maintain the initial posture but to direct the hand in the perceived direction up to the boundary of the workspace where the haptic targets were collocated. The boundary of the workspace was represented by an elastic wall, with a stiffness of 1,000 N/m, thus providing to the subject a haptic feedback that the wall was reached. When the hand overcame a distance of 10 cm from the initial position, the pulsed force field was turned off and the remaining part of the movement, up to the wall, was driven by the subject on the basis of the estimated target position. A go-sound (S0) signaled the beginning of a new trial and other sounds (S1, S2, S3), delivered after hitting the wall, informed the subject about the final reaching error: S1 corresponded to an error smaller than 2 cm; S2 to an error between 2 and 5 cm; S3 to an error >5 cm[1]. To start a new trial, the robot carried back the hand and maintained it on the starting position for 1 s. The protocol consisted of four target-sets of 84 movements each. The same protocol was applied to both hands. In this experiment, the force generated by the robot is only meant to give the subject a haptic representation of the target, to be transformed in an active command by the subject in an autonomous way.

Five subjects (28.5 ± 2.8 years old, all right-handed) took part in the experiment. In addition to the *AC* index, which is formally defined in Section 2.4 and is a quantitative measure of the subject's ability to sense and coherently move in the actual direction of the force perturbation, we also carried out two evaluations of aiming accuracy by computing the aiming error, namely the angular difference between the origin-target line and the origin-hand line, at two time instants:

(1) E_{10} (deg): when the hand reaches the 10 cm distance from the origin, i.e. the time instant at which the haptic feedback is turned off.

(2) E (deg): when the hand reaches the wall of the workspace.

2.2 Haptic assisted reaching in stroke patients

In this experiment we used five peripheral targets, placed on the circular wall (inter-target distance 20 deg), and three intermediate targets at middle distance, plus the initial target position. A single trial started from the initial position, then a peripheral target was randomly selected, followed by an intermediate target and finally a return to the initial target. The stepping from one target to another was triggered by the acquisition of the current target (target size = 2 cm): an acoustic feedback signaled that a reaching movement was completed and a 1 s delay was introduced before presenting a new target in the sequence. The focus of the analysis was on the center-out movements, which require extension patterns of shoulder and elbow and are typically more difficult for stroke patients; in contrast, the two return movements of each trial are favored by the pathology and thus are less relevant from the point of view of adaptation and learning; the intermediate targets were introduced for reducing the intensity of the flexion patterns required by such movements. As in the experiment with control subjects, the direction of the target was communicated haptically to the subject by applying to the hand a train of short force impulses, oriented to the target, with the same duration and frequency. However, the force field generated by the robot in this case has also the purpose of assisting the patient to carry out the reaching movement because the selected subjects would be unable to complete the movement without assistance, including the capacity to maintain the hands stable in different positions of the workspace. Therefore, the force profile generated by the robot in the experiments with stroke patients had a continuous component or bias force on top of which there was a sequence of force impulses with the same duration and frequency. The amplitude was adapted to each patient as explained in the following. First, we evaluated the bias force, specifically for each patient, in evaluation blocks included in the protocol. During these blocks, the subjects were positioned passively by the robot in the points of the workspace used as targets in the training trials. The robot held such positions for 1 s, averaging the corresponding holding forces. The overall averaged holding force F_A was used as the bias during the assisted experiments, different for each patient. The peak amplitude of the force impulses on top of the bias force was equal to F_A. The bias force was activated when the new target was selected but was applied in a smooth way, in order to avoid jerky movements of the patient, according to a ramp-and-hold profile (rise time = 1 s).

Five patients participated to these experiments. Demographic and clinical data are reported in Table I. Subjects were recruited among those followed as outpatients of the ART Education and Rehabilitation Center in Genoa. The patients were selected according to the following criteria: first, diagnosis of a single, unilateral stroke verified by brain imaging; second, sufficient cognitive and language abilities to understand and follow instructions; third, chronic condition (at least one year after stroke); fourth, stable clinical conditions for at least one month before being enrolled in this study. This preliminary clinical study did not include a control group and thus is not a randomized, controlled clinical trial. However, the functional assessment was blinded. The research conforms to the ethical standards laid down in the 1964 Declaration of Helsinki, which protects research subjects, and was approved by the ethics committee of the regional health authority. Each subject signed a consent form conforming to these guidelines. The robot training sessions were carried out at the Motor Learning and Robotic

Subject	Age	Paretic hand	FMA (0-66)	ASH (0-4)	F_A (N) ini-fin
S1	37	L	15	2	8.63-7.24
S2	39	R	28	1+	4.90-6.14
S3	63	L	55	1	3.87-3.60
S4	58	R	33	1+	4.94-4.98
S5	31	L	21	2	9.79-6.34

Notes: Age, years; FMA, arm portion of Fugl-Meyer score (0-66) at the time of the study; ASH, modified Ashworth scale of muscle spasticity (0-4); F_A, holding force, evaluated at the beginning (ini) and at the end (fin) of the training sequence

Table I.
Demographic and clinical data of the stroke subjects

Rehabilitation Lab of the Istituto Italiano di Tecnologia (Genoa, Italy), under the supervision of experienced clinical personnel and engineers. All subjects underwent clinical evaluations before starting the present study to ascertain their degree of spasticity and residual functional level.

The protocol included two sessions on two separate days. For each session, after an initial familiarization routine, there was a training sequence that comprised two evaluation blocks (a block at the beginning of a session, in order to select automatically the level of assistive bias force, and a block at the end) and two training blocks, one with and the other without visual feedback. In the training blocks of trials the subjects had to complete a total of three target-sets; each target-set consisted of 30 center-out movements and 60 return movements, for a total of 90 movements. The experimental blocks with vision were meant to provide a qualitative evaluation of the role of visual feedback in assisted reaching movements. The performance of the patients was evaluated by means of the three following indicators, applied only to the center-out movements:

- active contribution index (*AC*, dimensionless, normalized between 0 and 1);
- mean speed of movement (V_m; in m/s): it is the mean value of the speed computed by the time of target presentation considering a speed threshold on 0.01 m/s, to the instant in which the target is reached; and
- endpoint error after the first submovement (E_1; in cm): it is measured as the distance between the target and the hand position at the end of the first submovement, which is identified on the speed profile by two consecutive minima, one before and one after the first point of peak velocity. It ranges from 0 to 26 cm.

2.3 Haptic control

The manipulandum, which is activated by two brushless motors with direct drive, is controlled in current in order to generate a target-directed force field. The robot can measure the trajectory of the hand with high resolution (better than 0.1 mm) and is smoothly impedance controlled in order to generate continuous force fields that can range from fractions of 1 N up to 50 N. The control architecture is based on the real-time operating system RT-Lab and includes three nested control loops: first, an inner 16 kHz current loop; second, an intermediate 1 kHz impedance control loop; and third, an outer 100 Hz loop for visual/acoustic rendering and data storage. The robot has a very low friction and a low, almost isotropic inertia (Casadio *et al.*, 2006).

The total force field F used in the described experiments was generated in real-time according to the following control law, which is valid for both types of experiments:

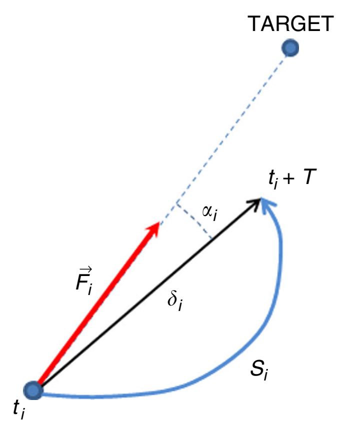
$$
\begin{aligned}
&F(t) = P(t) - B\dot{x}_H - K_W(x_W - x_H)\\
&P(t) = [F_{PEAK} \cdot I_{\Delta t}(t) + F_A]\frac{(x_T - x_H)}{\|x_T - x_H\|} \cdot R(t) \cdot S(x_H)\\
&S(x_H) = \begin{cases} 0 & \text{if healthy} - \text{subject } \& \ \|x_H - x_O\| > 10\,\text{cm} \\ 1 & \text{otherwise} \end{cases}\\
&I_{\Delta t}(t) = \begin{cases} \frac{1}{1.875}\left[30\xi^4 - 60\xi^3 + 30\xi^2\right] & 0 \leqslant \xi < 1 \\ 0 & 1 \leqslant \xi \leqslant T/\Delta t \end{cases}
\end{aligned}
\tag{1}
$$

where x_H is the hand position vector; B is a viscosity coefficient (12 Ns/m) acting as damping factor on the hand; K_W is the stiffness (1,000 N/m) of a virtual wall that surrounds the layer of external targets; x_W is the projection of x_H on the wall; $P(t)$ is the time-varying haptic feedback, pulling the hand in the direction of the target x_T; $R(t)$ is a ramp-and-hold function, with a rising time of 0.1 s; $S(x_H)$ is a switch function which is turned off in the first experiment with healthy subjects if the distance of the hand from the origin is >10 cm and is turned on otherwise; $I_{\Delta t}(t)$ is a minimum-jerk impulse, with a unitary peak value, a duration $\Delta t = 0.2$ s and a repetition period $T = 0.5$ s ($\xi = t/\Delta t$ is normalized time for impulse generation); F_A is the bias force in the experiment with patients and is equal to 0 in the other experiment; F_{PEAK} is the peak value of the force impulse train and it is equal to 3 N in the experiment with healthy subjects and to F_A in the experiment with patients.

2.4 Active contribution index

The formulation of this index exploits the fact that the interaction between the robot and the human subjects is characterized by a sequence of short force impulses (duration = 200 ms), separated by a refractory time of 300 ms, which attempt to induce the subject to move actively in the direction of the pull. If the subject does not provide any active focal motor command, i.e. aimed at the target, we may expect the force impulse would determine a small displacement in the direction of the target that would be followed by an almost equivalent backward displacement during the refractory phase, due to muscle stiffness. In this case the overall displacement would be close to zero. On the contrary, if the subject reacts to the impulses with synergistic motor commands we should expect a buildup of coherent overall displacements in the direction of the target.

Figure 3 illustrates the point by summarizing, geometrically, what happens in one period of the impulsive stimulation: t_i is the initial time of a stimulation period and $t_i + T$ is the corresponding final time, which include the impulsive stimulus and refractory times (200 ms + 300 ms); S_i is the integral trajectory of the hand during that time interval and δ_i is the overall displacement[2]; α_i is the angle between the displacement vector and the direction of the force field, i.e. the aiming error.



Notes: t_i is time instant at which a force impulse F is initiated; T is the period of the impulse generation; α_i is the aiming error; δ_i is the displacement of the hand between t_i and t_i+T; S_i is the corresponding hand trajectory

Figure 3. Geometric characterization of the *AC* index

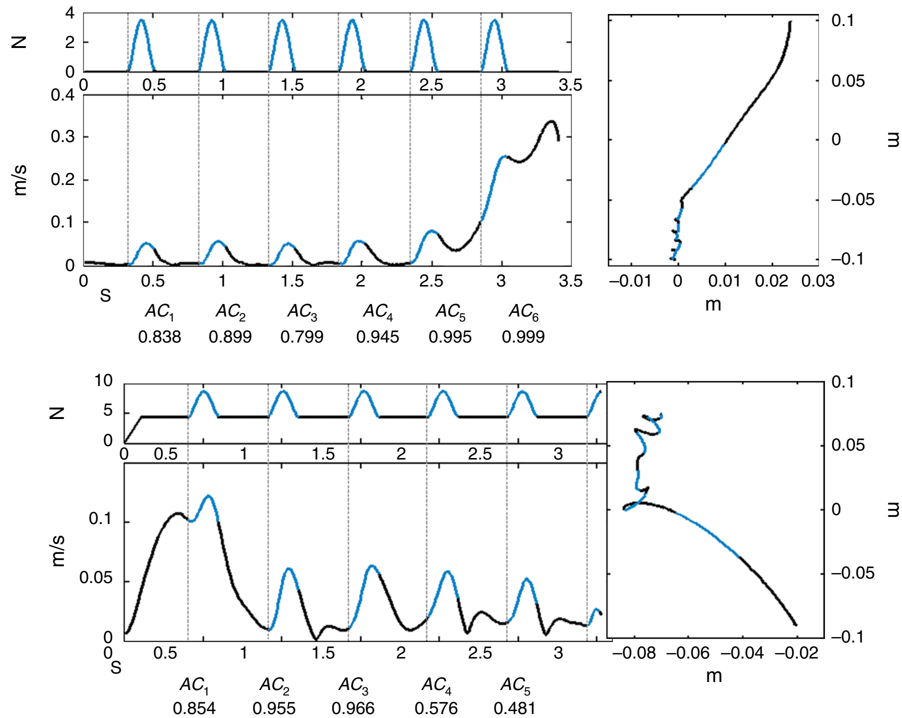
The mathematical formulation of this algorithm is coded by Equation (2):

$$\delta_i = dt\left\|\sum_{j=1}^{N_T}\vec{v}_j\right\|;\ S_i = dt\sum_{j=1}^{N_T}\|\vec{v}_j\|;\ AC_n = \frac{\delta_i}{S_i}$$
$$AC = \frac{\sum_{i=1}^{N_P}\cos\alpha_i AC_i S_i}{\sum_{i=1}^{N_P} S_i} = \frac{\sum_{i=1}^{N_P}\cos\alpha_i\delta_i}{\sum_{i=1}^{N_P} S_i} \tag{2}$$

$\vec{v}$ is the hand velocity vector; $dt = 10$ ms is the sampling time; $N_T = 50$ is the is the number of samples in a given impulse period; N_P is the total number of impulses delivered to the subject. Therefore, AC ranges between 0, corresponding to a purely passive situation in which the average displacement per impulse is null, and one that corresponds to a perfectly straight trajectory aligned with the target. Figure 4 illustrates the computation of the index in the two experiments, namely with a healthy subject (top panel) and stroke patient (bottom panel). In both cases, the blue portions of the curves identify the time intervals in which the force impulses are delivered, whereas the black portions correspond to the refractory period between on impulse and the next one:

- With the healthy subject, the first four impulses (3 N each) displace the hand in the direction of the target by a fraction of a centimeter and are followed by the absence of backward rebounds during the refractory period. The mean speed during the refractory periods is quite small and this pattern is clearly compatible with the subject attempting to estimate the direction of the haptic target before delivering a full-fledged aimed command. After the fifth impulse the distance from the initial position overcomes the 10 cm threshold and the final part of the movement is covered without any haptic feedback, on the basis of the perceived target direction. Please note that the partial AC score grows from one impulse to the next one and is close to one in the final impulse.
- In the case of the stroke subject, the average assistance is larger and active throughout the whole movement, with a bias force of 4.5 N and equal amplitude of the force impulses. After the start of the movement, the bias force is just enough to help the patient to cover about 25 percent of the distance to the target but would be insufficient to reach the target in a "passive" way. The first impulse induces the subject to cover another 25 percent of the distance. The remaining 50 percent requires five more impulses. As expected, such final part of the movement takes more time and is less smooth because in stroke patients there is a well-known resistance to a full extension of the paretic arm. This behavior is reflected by the reduction in the AC index in the last two impulses that also show a slight bouncing back phenomenon. However, the subject does succeed to perform the reaching movement with an average value of the assistive force that, if applied continuously, would have been insufficient to complete the task. This, by itself, is suggestive that pulsed haptic assistance is effective in facilitating the re-emergence of goal-oriented voluntary control in stroke patients.

The data collected in the two experiments were tested for normality (Lilliefors test). In the case of healthy subjects, we carried out a repeated measures ANOVA on the AC index values considering trials and target direction as within variables and



Notes: Each panel holds the profile of haptic assistance (in N), the corresponding speed profile of the hand (in m/s), and the hand trajectory in the workspace (*x*-axis: medio-lateral; *y*-axis: antero-posterior). The blue portions of the profiles identify the phases of pulsed assistance, whereas the black portions correspond to the refractory intervals, between one impulse anche the next one. In the healthy subject the haptic feedback is stopped when the total displacement from the initial position exceeds 10 cm: in the depicted example this required five impulses of 3 N amplitude, after which the movement to the target, achieved with an error smaller than 2 cm, was performed without any feedback. In the patient there is a bias force of 4.5 N which is just enough to help the patient to cover about 25 percent of the distance to the target but would be insufficient to reach the target in a "passive" way; the first impulse induces him to cover another 25 percent and the remaining 50 percent requires five more impulses. Please consider that the force/speed curves are terminated when the target or the virtual wall is reached and generally this occurs with a non-zero speed. For each impulse, the figure reports the corresponding partial score of the *AC* index

Figure 4.
Example of calculation of the *AC* index for healthy subjects (top panel) and stroke patients (bottom panel)

subjects as a random variable. Laterality (right or left hand) was considered as a between-subject effect. We selected a significance threshold of 0.05. To compare the two error measures, we analyzed data from each subject separately and when normality conditions were met, we performed a paired *t*-test with $\alpha = 0.05$ among all the seven target directions separately for the two arms. In the other cases we applied the Wilcoxon matched pair test.

In the case of stroke subjects, since the data were not distributed normally, we performed a ranking test.

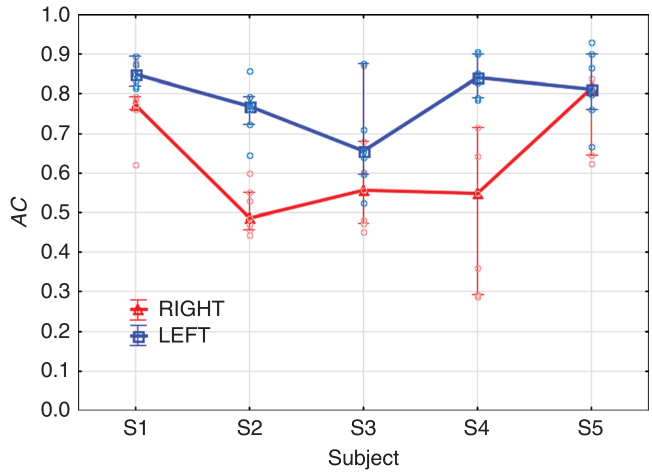
3. Results

3.1 Haptic reaching in healthy subjects

As regards the *AC* index, which expresses the ability of the subjects to sense accurately the force direction and translate that information in a coherent movement, we found rather high values in all cases with a mean value of 0.71. However, we found a statistically significant difference (effect of side, $F = 12.42$, $p = 0.024$) between the right arm (the mean value is $AC_{\text{right}} = 0.63$) and the left arm (the mean value is $AC_{\text{left}} = 0.79$): see Figure 5. If we consider that haptic reaching mainly involves a coordination of the proximal joints of the arm, the difference between the right and left arm is consistent with the general view that the dominant arm of healthy people specializes with precision manipulation tasks involving distal joints whereas the non-dominant arm is specialized for proprioceptive feedback (Goble and Brown, 2007).

The analysis of the aiming accuracy (see Figure 6) shows that indicators of directional error, E and E_{10}, exhibit a number of interesting points. First of all, the aiming error of the non-dominant arm is much smaller than the dominant arm: on average 17.5 deg vs 19.3 deg. This is consistent with the analysis of the *AC* index: in healthy subject the non-dominant arm is generally better in haptic reaching. Moreover, in the case of the non-dominant arm, there is no significant difference between the aiming error at the end of the haptically supported phase and the final error (E_{10} vs E). This means that the directional information on the target acquired in the initial stimulated part, which typically involves four to six impulses, is accurate enough to generate ballistic movements without haptic or visual feedback.

In the case of the dominant arm, the aiming error at the end of the haptically supported phase is significantly greater than the error at the end of the reaching movements ($p < 0.001$ for all subjects): on average, $E_{10} = 38.9$ deg vs $E = 27.1$ deg. This is somehow surprising because during the ballistic part of the reaching movements the subject could not rely on any feedback, except on the knowledge



Notes: Median values and the corresponding interquartile range for the right arm is colored in red and for the left arm is colored in blue

Figure 5.
Mean *AC* index across trials and target directions for the five healthy subjects, all of them right-handed

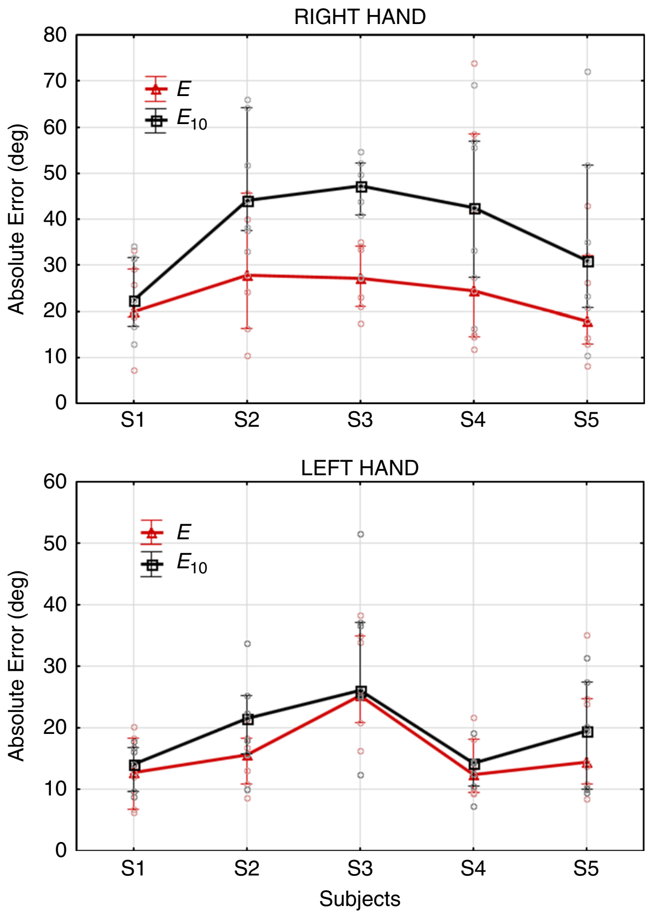


Figure 6. Absolute aiming errors at the end of the movement: E (red circles) and after a displacement of 10 cm from the starting position E_{10} (black circles)

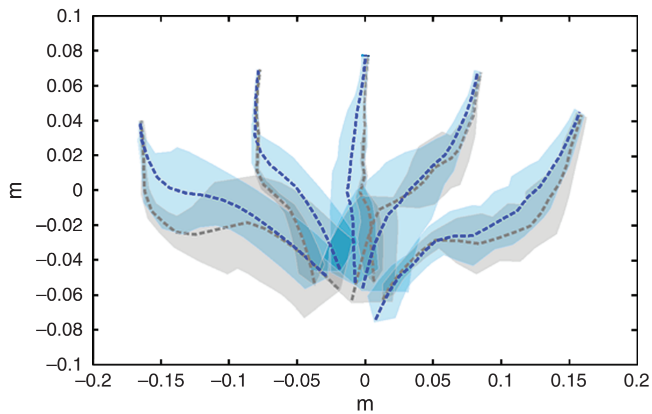
Notes: The errors were averaged across trials and target directions for the five healthy subjects. Median values and the corresponding interquartile range for E is colored in black and for E_{10} in red. Top panel depicts data for the right hand and bottom panel for the left hand

of result, provided by the acoustic signal. We did not analyze directional preferences, which may be determined by biomechanical factors such as arm stiffness properties, because it is outside the purpose of this specific study.

3.2 Haptic assisted reaching in stroke patients

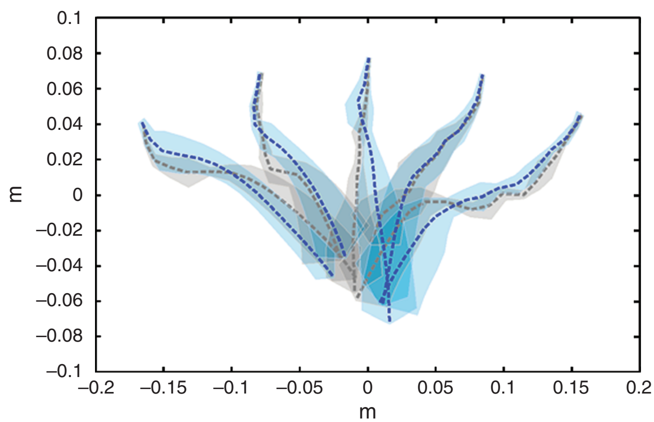
First of all, let us consider the holding force F_A that was evaluated for all the patients at the beginning and at the end of the training sessions: the average values are reported in the last column of Table I. This is the force that the robot must apply to a patient in order to stabilize his arm in different parts of the workspace. F_A ranges between 3.6 N and 9.8 N and, as expected, is higher for more impaired subjects and vice versa: the corresponding FMA score ranges between 55 (the least impaired subject S3) and 21 (the most impaired subject S5). There is also a tendency to decrease the value of the holding force over training, although this is just a qualitative trend indication, given the small size of the population and the limited length of the training process. In any case, such preliminary results are good enough to suggest adopting F_A as a simple parameter for the adaptation of the level of training assistive force to the impairment level of a given patient.

Figure 7 shows for one of the patients (S5) the assisted reaching trajectories to the five different targets in the two experimental conditions, namely with or without visual feedback. In particular, the figure shows the mean trajectories to the different target points (dashed) and the corresponding standard deviation (shaded) in the initial and



Visual feedback
Pulsed assistance

	AC_i	AC_f
T_1	0.592	0.727
T_2	0.693	0.713
T_3	0.718	0.842
T_4	0.788	0.843
T_5	0.074	0.253



No Visual feedback
Pulsed assistance

	AC_i	AC_f
T_1	0.501	0.851
T_2	0.618	0.525
T_3	0.676	0.691
T_4	0.633	0.703
T_5	0.242	0.432

Notes: Top panels correspond to pulsed haptic assistance complemented by visual feedback; the bottom panels refer to pure haptic assistance without visual feedback. In both cases, the graphs show the mean trajectories (dashed, with the corresponding standard deviations, shaded): gray for the first three trials and blue for the final three trials. The tables report the corresponding mean values of the initial and final AC indices (AC_i and AC_f) for the five targets (T_1-T_5)

Figure 7.
Haptic assisted reaching of stroke subject S5

the final three target-sets. The corresponding mean AC index is reported in the two tables, where AC_i stands for the initial trials and AC_f for the final ones.

The figure shows that the smoothness of the reaching movements is clearly improved between the first and the last three target-sets (look at the dashed trajectories, gray vs blue) and this improvement is also reflected by the increase in the associated mean AC value. Last but not least, the data emphasize the fact that visual feedback does not change the overall performance: in contrast, reaching movements assisted by both channels (haptic and visual) are more variable and less smooth than movements that only rely on haptic assistance. This finding, namely that visual feedback is not necessarily beneficial in robot training of stroke patients, is consistent with other studies, for example the evaluation of arm stiffness during robot training (Piovesan *et al.*, 2013): stiffness is consistently higher when vision is present than when it is absent. The figure also shows the evaluated AC indicators for the different movement directions. As expected, the average value of this index is quite smaller than what was found with the healthy subjects and this is obviously consistent with the fact that the reaching movements of the patients are far from being straight, in particular in the final part of the movements.

The overall trend illustrated in Figure 7 for subject S5 was also found for the other stroke subjects. As regards the AC index, Table II reports the distribution among the subjects and the consistent increase between the initial and the final part of the training. Table III provides an overall view of the improvements of all the subjects, as a function of the target position, for the AC indicator and the two performance indicators (V_m and E). In most of the cases there is an improvement greater that 5 percent for at least three of the five targets or movement directions. Moreover, the statistical analysis of such indicators found that they are not distributed normally, suggesting that the performance patterns differ with target location. Thus there is a general trend to

Table II.
AC Index of the stroke subjects: variation between the first and last target sets

	First target set		Last target set	
SUBJ	Mean	SD	Mean	SD
S1	0.622	0.161	0.818	0.042
S2	0.509	0.090	0.542	0.044
S3	0.704	0.120	0.844	0.106
S4	0.732	0.132	0.756	0.144
S5	0.141	0.046	0.664	0.161

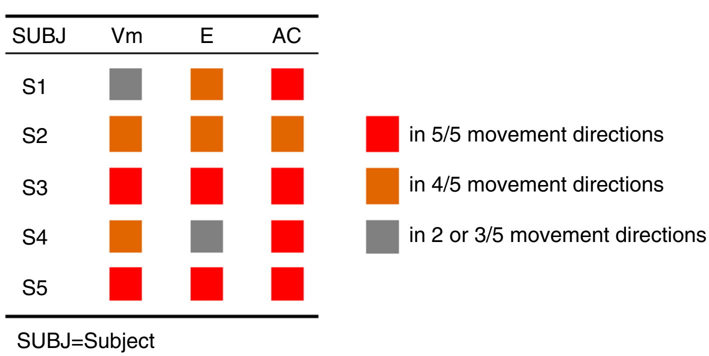


Table III.
Performance improvement between the first and last movement set >5 percent

improvement also in the short time interval between the first and the last target-set, supporting the idea that the new pulsed assistance paradigm is well understood by the patients and allow us to report it as a natural way of human-robot interaction in robot therapy.

4. Discussion

After having demonstrated that pulsed robot assistance has comparable positive effects as continuous assistance on the performance of stroke subjects after a single session of training, while employing a significantly lower average value of assistive force (De Santis *et al.*, 2013), in this paper we showed that pulsed assistance naturally suggests a simple and robust method for evaluating on line the degree of active participation of the patients. This result is linked to other studies in the general area of characterization of haptic dyads already quoted in the introduction, which emphasize the importance of an adaptive modulation of assistance levels (O'Malley *et al.*, 2006; van Asseldonk *et al.*, 2009; Passenberg *et al.*, 2013) and its superiority with respect to constant assistance policies. This style of interaction between the robot and the patient aims at keeping the interaction as far as possible from a paradigm of passive mobilization, in which the robot is the permanent "master" and the patient the permanent "follower"; this resonates well with the observations coming from the analysis of physical collaborative tasks which emphasize the beneficial effect of switching continuously between the two dual behaviors (leader and follower), in such a way to create an implicit bilateral coupling within the dyad (Evrard and Kheddar, 2009). We may think indeed that during the delivery of force impulses the robot is the leader, indicating to the patient in which direction to orient the voluntary control patterns, whereas in the following refractory time, between one impulse and the next one, it is the patient who takes the lead attempting to translate the kinesthetic indication into an effective motor command.

The interaction between the robot and the patient provided by the hand-grasped manipulandum seems appropriate also in view of recent results about the superiority of kinesthetic information over tactile stimuli (Rosati *et al.*, 2014) during skill acquisition. On the other hand, we should take into account, in future developments, the anisotropy in the perception of force direction found by (Barbagli *et al.*, 2006). The experiments on haptic reaching with healthy subjects show that haptic perception is not limited to reactive control mechanisms but allows the subjects to build robust mental representations of spatial targets that are able to drive in a proactive way goal-oriented actions. This also provides a background knowledge for evaluating the performance of patients against a robust reference.

All together the observations above highlight the working hypothesis, on which this paper was built, that it is advantageous to look at protocols of robot rehabilitation in the general context of human-robot interaction in haptic dyads. The results are based on a limited population and thus they are not conclusive but such experiments should be considered as a preliminary, feasibility study and from this point of view we think that the reported evidence is enough to consider the novel *AC* index as a potentially powerful mechanism for the on-line adaptation of robot assistance in robot therapy of stroke patients.

We emphasize the fact that pulsed assistance or pulsed haptic communication is likely to involve quite different physiological mechanisms than the motor illusions induced by vibrations (Goodwin *et al.*, 1972). The kinesthetic effects of vibrations, for example the velocity of the illusory movement evoked by vibration, depend on both the frequency (Roll and Vedel, 1982) and the amplitude (Clark *et al.*, 1979) of mechanical stimulation. In particular, the influence of vibration parameters on movement illusions was investigated by Roll and Vedel (1982) by using the matching procedure, in which subjects track the illusory movements of a restrained, vibrated forearm by moving the non-vibrated contralateral arm. The results show that the optimal vibration frequency of the biceps tendon for evoking illusory extension movements of the elbow is around 70 Hz and the effect is close to null below 10 Hz and thus non-overlap is likely to occur with pulsed assistance.

But what do vibration-induced illusions reveal about proprioception? According to Jones (1986) these illusions demonstrate that the position sense representation of the body and the awareness of limb movement result from the cross-calibration of visual and proprioceptive signals. Moreover, by extending the analysis also to the phantom-limb phenomenon[3] (Bors, 1951) it becomes clear that the perception of limb movement and position are encoded independently and can be dissociated. The pulsed assistance paradigm operates at a much lower frequency, namely well below 10 Hz, and thus is unable to evoke any vibration-induced motor illusion. However, since it involves phasic components in the range of frequencies used by different tactile sensory channels, pulsed assistance is appropriate for providing the patients, as well as the healthy subjects of the control group, critical information for an efficient haptic communication.

On the other hand, one may wonder whether pulsed assistance could have negative effects on performance in spastic subjects, but this does not seem to be the case because also the subjects with rather high values of the ASH score do exhibit improvements in the active contribution index.

The employed frequency of pulsed assistance, namely 2 Hz, was not chosen by chance. Rather, it is suggested by recent theories on intermittent control of a variety of human movements, like upright standing and visuo-manual tracking (Gawthrop *et al.*, 2011; Suzuki *et al.*, 2012). The rationale of such theories is that the risk of instability of actions involving many degrees of freedom, determined by the long delays in the sensorimotor loops, is more easily and more robustly managed by closing the loop intermittently, about two to three times per second. When the loop is closed, appropriate control bursts are delivered. When the loop remains open, the neural controller has the opportunity to observe the intrinsic dynamics of the body-environment system and thus has the chance to identify its evolution in time. Thus intermittent control should not be confused with sampled-data control. Rather, it is characterized by a combination of continuous observation and discontinuous intervention.

In the implementation of pulsed assistance experimented in this study, the activation frequency is fixed (2 Hz). A logical development of the concept is to allow such frequency to adapt, in the sense of triggering the force impulses with appropriate events, detected in the human-robot interaction process.

Notes

1. The sound feedback was intended only for providing knowledge of results rather than a precise evaluation of the aiming error, which could have been provided by means of visual feedback. This was done on purpose in order to induce the subject to focus as much as possible on the haptic component of the task.

2. S_i is computed from the sampled trajectory of the hand by adding the elementary inter-sample displacements from the initial time instant of a force impulse t_i to the final instant of the refractory period $t_i + T$.

3. With healthy subjects haptic reaching with visual feedback was not performed because behavior would be dominated by vision.

References

Barbagli, F., Salisbury, K., Ho, C., Spence, C. and Tan, H.Z. (2006), "Haptic discrimination of force direction and the influence of visual information", *ACM Trans. on Applied Perception*, Vol. 3 No. 2, pp. 125-135.

Bors, E. (1951), "Phantom limbs of patients with spinal cord injury", *Archives of Neurology and Psychiatry*, Vol. 66 No. 5, pp. 610-631.

Casadio, M., Giannoni, P., Morasso, P. and Sanguineti, V. (2009a), "A proof of concept study for the integration of robot therapy with physiotherapy in the treatment of stroke patient", *Clinical Rehabilitation*, Vol. 23 No. 3, pp. 217-228.

Casadio, M., Morasso, P., Sanguineti, V. and Arrichiello, V. (2006), "Braccio di Ferro: a new haptic workstation for neuromotor rehabilitation", *Technol Health Care*, Vol. 14 No. 3, pp. 123-142.

Casadio, M., Morasso, P., Sanguineti, V. and Giannoni, P. (2009b), "Minimally assistive robot training for proprioception enhancement", *Experimental Brain Research*, Vol. 194, No. 2, pp. 219-231.

Clark, F.J., Matthews, P.B.C. and Muir, R.B. (1979), "Effect of the amplitude of muscle vibration on the subjectively experienced illusion of movement", *Journal of Physiology*, Vol. 296, pp. 14P-15P.

Corteville, B., Aertbelien, E., Bruyninckx, H. and De Schutter, J. (2007), "Human-inspired robot assistant for fast point-to-point movements", *Proceedings of the IEEE Conference on Robotics and Automation*, pp. 33639-33644.

De Santis, D., Masia, L., Morasso, P., Squeri, V., Zenzeri, J., Casadio, M., Giannoni, P. and Riva, A. (2013), "Pulsed assistance: a new paradigm of robot training", *Proceedings of IEEE International Conference on Rehabilitation Robotics, Seattle, WA, June 24-26*.

Emken, J.L., Benitez, R., Sideris, A., Bobrow, J.E. and Reinkensmeyer, D.J. (2007), "Motor adaptation as a greedy optimization of error and effort", *J Neurophysiol*, Vol. 97 No. 6, pp. 3997-4006.

Endo, T., Kanno, T., Kobayashi, M. and Kawasaki, H. (2010), "Human perception test of discontinuous force and a trial of skill transfer using a five-fingered haptic interface", *J of Robotics*, Article ID 542360, pp. 1-14.

Evrard, P. and Kheddar, A. (2009), "Homotopy switching model for dyad haptic interaction in physical collaborative tasks", *Proceedings of World Haptics Conference*, pp. 45-50.

Feth, D., Groten, R., Peer, A., Hirche, S. and Buss, M. (2009), "Performance related energy exchange in haptic human-human interaction in a shared virtual object manipulation task", *Proceedings of World Haptics Conference*, pp. 338-343.

Frith, C.D., Blakemore, S. and Wolpert, D. (2000), "Abnormalities in the awareness and control of action", *Philosophical Transactions of the Royal Society*, Vol. 355 No. 1404, pp. 1771-1788.

Gawthrop, P., Loram, I., Lakie, M. and Gollee, H. (2011), "Intermittent control: a computational theory of human control", *Biol Cybern*, Vol. 104 Nos 1/2, pp. 31-51.

Gentry, S. and Murray-Smith, R. (2003), "Haptic dancing: human performance at haptic decoding with a vocabulary", *Proceedings of the IEEE Systems, Man, Cybernetics Conference, Vol. 4*, pp. 3432-3437.

Gibson, J.J. (1966), *The Senses Considered as Perceptual Systems*, Houghton Mifflin, Boston, MA.

Goble, D.J. and Brown, S.H. (2007), "Task-dependent asymmetries in the utilization of proprioceptive feedback for goal-directed movement", *Experimental Brain Research*, Vol. 180 No. 4, pp. 693-704.

Goodwin, G.M., McCloskey, D.I. and Matthews, P.B.C. (1972), "The contribution of muscle afferents to kinaesthesia shown by vibration induced illusions of movement and by the effects of paralysing joint afferents", *Brain*, Vol. 95 No. 4, pp. 705-748.

Hesse, S., Schmidt, H. and Werner, C. (2005), "Machines to support motor rehabilitation after stroke: 10 years of experience in Berlin", *J. of Rehabilitation Research and Development*, Vol. 43 No. 5, pp. 671-678.

Jones, L. (1986), "Perception of force and weight: theory and research", *Psychological Bulletin*, Vol. 100 No. 1, pp. 29-42.

Krebs, H.I. and Hogan, N. (2012), "Robotic therapy: the tipping point", *Am J Phys Med Rehabil*, Vol. 91 No. 11, pp. S290-S297.

McAmis, S. and Reed, K.B. (2013), "Effects of compliant coupling on cooperative and bimanual task performance", *Journal of Rehabilitation Robotics*, Vol. 1 No. 4, pp. 99-108.

Marchal-Crespo, L. and Reinkensmeyer, D.J. (2009), "Review of control strategies for robotic movement training after neurologic injury", *J. of Neuroengineering and Rehabilitation*, Vol. 6 No. 1, pp. 20-35.

Mehrholz, J., Hädrich, A., Platz, T., Kugler, J. and Pohl, M. (2012), "Electromechanical and robot-assisted arm training for improving generic activities of daily living, arm function, and arm muscle strength after stroke", *Cochrane Dat Syst Rev*, Vol. 6, June, p. CD006876.

Nudo, R.J. (2006), "Mechanisms for recovery of motor function following cortical damage", *Current Opinion in Neurobiology*, Vol. 16 No. 6, pp. 638-644.

Nudo, R.J. (2007), "Postinfarct cortical plasticity and behavioral recovery", *Stroke*, Vol. 38 No. 2, pp. 840-845.

Oguz, S.O., Kucukyilmaz, A., Sezgin, T.M. and Basdogan, C. (2010), "Haptic negotiation and role exchange for collaboration in virtual environments", *Proceedings of IEEE Haptics Symposium*, pp. 371-378.

O'Malley, M.K., Gupta, A., Gen, M. and Li, Y. (2006), "Shared control in haptic systems for performance enhancement and training", *ASME J. Dynamic Systems, Measurement and Control*, Vol. 128 No. 1, pp. 75-85.

Pang, X.D., Tan, H.Z. and Durlach, N.I. (1991), "Manual discrimination of force using active finger motion", *Perception & Psychophysics*, Vol. 49 No. 6, pp. 531-540.

Passenberg, C., Glaser, A. and Peer, A. (2013), "Exploring the design space of haptic assistants: the assistance policy module", *IEEE Trans. on Haptics*, Vol. 6 No. 4, pp. 440-452.

Passenberg, C., Peer, A. and Buss, M. (2010), "A survey of environment-, operator-, and task-adapted controllers for teleoperation systems", *Journal of Mechatronics*, Vol. 20 No. 7, pp. 787-801.

Piovesan, D., Morasso, P., Giannoni, P. and Casadio, M. (2013), "Arm stiffness during assisted movement after stroke", *IEEE Trans Neural Syst Rehabil Eng*, Vol. 21 No. 3, pp. 454-465.

Reed, K.B. and Peshkin, M.A. (2008), "Physical collaboration of human-human and human-robot teams", *IEEE Trans on Haptics*, Vol. 1 No. 2, pp. 1-13.

Reed, K.B., Peshkin, M.A., Hartmann, M.J., Colgate, J.E. and Patton, J. (2005), "Kinesthetic interaction", *Proceedings of the 2005 IEEE 9th International Conference on Rehabilitation Robotics, Chicago, IL, June 28-July 1*.

Roll, J.P. and Vedel, J.P. (1982), "Kinaesthetic role of muscle afferents in man, studied by tendon vibration and microneurography", *Experimental Brain Research*, Vol. 47 No. 2, pp. 177-190.

Rosati, G., Oscari, F., Pacchierotti, C. and Prattichizzo, D. (2014), "Effects of kinesthetic and cutaneous stimulation during the learning of a viscous force field", *IEEE Trans on Haptics*, Vol. 7 No. 2, pp. 251-263.

Shaw, R.E., Kadar, E., Sim, M. and Repperger, D.W. (1992), "The intentional spring: a strategy for modeling systems that learn to perform intentional acts", *Journal of Motivational Behavior*, Vol. 24 No. 1, pp. 3-28.

Suzuki, Y., Nomura, T., Casadio, M. and Morasso, P. (2012), "Intermittent control with ankle, hip, and mixed strategies during quiet standing: a theoretical proposal based on a double inverted pendulum model", *J Theorethical Biology*, Vol. 301, pp. 55-79.

van Asseldonk, E.H., Wessels, M., Stienen, A.H., van der Helm, F.C. and van der Kooij, H. (2009), "Influence of haptic guidance in learning a novel visuomotor task", *J. Physiology*, Vol. 103 Nos 3/5, pp. 276-285.

van Beek, F.E., Bergmann Tiest, W.M. and Kappers, A.M.L. (2013), "Anisotropy in the haptic perception of force direction and magnitude", *IEEE Trans. on Haptics*, Vol. 6 No. 4, pp. 399-407.

van der Wel, R.P., Knoblich, G. and Sebanz, N. (2011), "Let the force be with us: dyads exploit haptic coupling for coordination", *J Exp Psychol Hum Percept Perform*, Vol. 37 No. 5, pp. 1420-1431.

van der Wel, R.P., Sebanz, N. and Knoblich, G. (2012), "The sense of agency during skill learning in individuals and dyads", *Consciousness and Cognition*, Vol. 21 No. 3, pp. 1267-1279.

Vergaro, E., Casadio, M., Squeri, V.P., Giannoni, P., Morasso, P. and Sanguineti, V. (2010), "Self-adaptive robot-training of stroke patients for continuous tracking movements", *J of NeuroEngineering and Rehabilitation*, Vol. 7 No. 1, pp. 13-44.

Wegner, D.M., Sparrow, B. and Winerman, L. (2004), "Vicarious agency: experiencing control over the movements of others", *Journal of Personality and Social Psychology*, Vol. 86 No. 6, pp. 838-848.

Wolbrecht, E.T., Chan, V., Reinkensmeyer, D.J. and Bobrow, J.E. (2008), "Optimizing compliant, model-based robotic assistance to promote neurorehabilitation", *IEEE Trans Neural Syst Rehabil Eng*, Vol. 16 No. 3, pp. 286-297.

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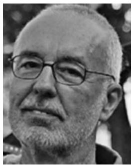

Pietro Morasso, formerly Full Professor of the Anthropomorphic Robotics at the University of Genoa, is now Senior Scientist at the Italian Institute of Technology (Robotics, Brain, and Cognitive Sciences Department). After graduating the University of Genoa in Electronic Engineering in 1968, he was Post-Doc and Research Fellow at the MIT, Boston, USA, in the lab of Prof. Emilio Bizzi. At the University of Genoa he directed the Doctoral School in Robotics and the course of study in Biomedical Engineering. His current interests include, neural control of movement, motor learning, haptic perception, robot therapy, and robot cognition.