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WORK-IN-PROGRESS

Grasping Virtual Objects: a Feasibility Study for an Enactive Interface Application in Stroke

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ABSTRACT

Recent studies show that 30% to 66% of patients who suffered a stroke are unable to recover the upper limb functionality and that most patients present motor disability five years after the acute event. Despite a general motor recovery the incapability to reach and grasp objects in the usual environment remains one of the most common disabilities after stroke. At the present time treatments for such impairments have been based on movement repetition of targeted tasks as part of training activities. Clinicians, however, are still looking for the possibility to provide a rehabilitation procedure that could match the natural and intuitive mode of interaction with objects that humans generally have in reaching and grasping in the daily contexts. In the last years the evolution of technologies appears to meet this request, notably with the growing of enactive interfaces. Such interfaces support the perception-action interactions with an environment allowing users to learn how to perform a useful action in a particular context. The expertise gained through the interaction with this multimodal interfaces results, in fact, in the acquisition of intuitive movements that is essentially based on subjective experience and on the perceptual consequences of their motor acts.

The main aim of this work is to investigate the technical and clinical feasibility of using an enactive interface in the rehabilitation of reaching and grasping movements of upper-limb hemiparesis that occurred after stroke. In this study ischemic stroke patients will be requested to perform technology-enhanced grasping task at our rehabilitation center, in addition to usual physical therapy.

Key words: Motor skill – Rehabilitation – Enactive interfaces - Stroke – Reaching and grasping functions

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1. Introduction

Recent studies show that upper limb impairment affects 85% of stroke patients, and that most of stroke patients with initial upper limb impairment still have significant functional problems five years after the acute event (Broeks, Lankhorst, Rumping, & Prevo, 1999). Although intensive therapy for the upper limb after stroke is associated with small but statistically significant improvements in neuromuscular and functional outcomes, scientific results are unclear about the effectiveness of specific upper limb rehabilitation strategies. In the last decades a number of articles have been published on the effect of various rehabilitation methods to improve arm function after stroke are evaluated (Van der Lee, Snels, Beckerman, Lankhorst, Wagenaar & Bouter, 2001; Rodgers et al., 2003; Woldag, Waldman, Heuschkel, & Hummelsheim, 2003). These rehabilitation strategies include a) the increased intensity of physiotherapy, b) a ‘forced use’ of impaired arm, c) the introduction of electrical stimulation and/or electromyographic biofeedback, d) the proposition of repetitive tasks.

Two reviews concerning various types of treatment for the arm in stroke patients concluded that more intensive exercise therapy is beneficial (Duncan, 1997; Richards & Pohl, 1999) and a similar conclusion in favour of more intensive exercise therapy was drawn in two exhaustive meta-analyses, which were not limited to the arm (Langhorne, Wagenaar, & Partridge, 1996; Kwakkel, Wagenaar, Koelman, Lankhorst, & Koetsier, 1997).

Moreover, several studies have been conducted on the role of repeated motor practice for motor learning and recovery. In particular, in a multiple baseline study across individuals it has been shown that the repetitive performance of identical hand and finger movements resulted in a significant increase in hand function compared with conventional physiotherapy (Butefisch, Hummelsheim, Denzler, & Mauritz, 1995).

In spite of the proven effectiveness of physiotherapeutic treatment, functional recovery of the affected upper extremity remains unsatisfactory in most of the cases. A fully recovered arm of a hemiparetic patient will not improve substantially his quality of life if it is not accompanied by recovery in the manipulative abilities of the hand.

In particular, major barriers to arm motor recovery after stroke are coordination deficits and the use of maladaptive movement strategies for reaching and grasping.

2. How are we able to grasp?

Movement strategies, and grasping in particular, have been extensively investigated by several disciplines, including physiatry, kinesiology, neurophysiology and cognitive neuroscience. There is a consensus that grasping an object requires coding of the object's intrinsic properties (size and shape), and the transformation of these properties into a pattern of distal (finger and wrist) movements (Jeannerod, Arbib, Rizzolatti, & Sakatam, 1995). In order to grasp an object the human brain must have the possibility to identify the target object, to evaluate an approximation to it (reaching), and finally to execute the correct movement in order to grasp it. Roughly speaking, human brain must have the possibility to plan an action.

Research on movement has shown that in order to specify a plan of action, the human central nervous system (CNS) must first translate sensory inputs into motor goals - such as the direction, amplitude, and velocity of the intended movement. Then, to perform a movement, it has to convert these desired goals into signals that control the active muscles during the execution of limb trajectory. Specifically, to plan an arm trajectory toward an object, the CNS first has to locate the position of the object with respect to the body and represent the initial position of the arm. To specify the limb's trajectory toward a target, the CNS must locate not only the position of an object with respect to the body but also the initial position of the arm. Information about arm configuration to be used in the programming of the arm's trajectory is provided by the visual and proprioceptive system.

The planning of limbs' movements constitutes an early and separate stage of information processing, in which the formation of arm trajectories the CNS formulates the appropriate command for the desired trajectory on the basis of knowledge about the initial arm position and the target's location. During planning, the brain is mainly concerned with establishing movement kinematics, a sequence of positions that the hand is expected to occupy at different times within the extrapersonal space. Later on, in the execution phase, the dynamics of the musculoskeletal system are controlled in such a way as to enforce the plan of movement within different environmental conditions.

There is evidence that the planning of arm trajectories is specified by the CNS in extrinsic coordinates. The analysis of arm movements has revealed kinematics invariance, suggesting that CNS planning takes place according to the hand's motion in space (Flash & Hogan, 1985). Evidences derived from straight and curved movements indicate that the kinematics invariance could be derived from a single organizing principle based on optimizing endpoint smoothness (Flash & Hogan, 1985). If actions are planned in spatial or extrinsic coordinates, to execute a movement the CNS must convert the desired direction and velocity of the limb into signals that control muscles. The elastic properties of the muscles provide instantaneous correcting forces when a limb is moved away from the intended trajectory by some external perturbation.

Thus, although apparently simple, successful grasping requires to integrate information from various domains devoted to localizing the target in space, analyzing its dimensions, shape and orientation, and selecting the proper hand configuration. Moreover, this complex mechanism appears to be able to operate independently from object semantic identification (Daprati & Sirigu, 2006). Opposition of the thumb is a common feature in most hand-object interaction such grasping, yet placement of the fingers and amplitude of their aperture vary considerably according to the type of hand–object interaction. In particular grasping, characterized by changes in grip aperture, can be distinguished in precision grip - characterized by opposition of the thumb to one or more of the other fingers – and power grip - where the fingers are flexed to form a clamp against the palm (Castiello, 2005).

Two levels of awareness have been identified in representing actions in humans (Jeannerod, 2003). An automatic level relies on unconscious interaction with objects in external world. This level is characterized by a pragmatic processing of the external objects, in which agents are extracting from them those intrinsic and extrinsic properties that are relevant to action. At the failure of automatic level it is possible to substitute a conscious level of action, in which the representation of movements is voluntarily activated and a specific action is intentionally selected from several possible alternative.

Like most of movements directed towards objects, grasping is executed automatically. Once grasping is started, movements are accurately performed leaving only short time for regulations. However, as noted before, object-oriented movements are organized and represented in human mind prior to overt execution. In the action of grasping a cup, for example, the finger position during the reaching phase has to be appropriate for a stable grasp of the specific object. This is possible because of the interplay between the possibility to physically represent the external object and the internal motor planning of the appropriate action to be executed (Paulignan, Frak, Toni, & Jeannerod, 1996).

3. The introduction of technology in rehabilitation

The intrinsic interactive feature of virtual reality (VR) allows the development of effective training environments for the rehabilitation of motor functions (Rose, Attree & Johnson, 1996; Riva 1997; Rizzo & Buckwalter,1997; Morganti, 2004).

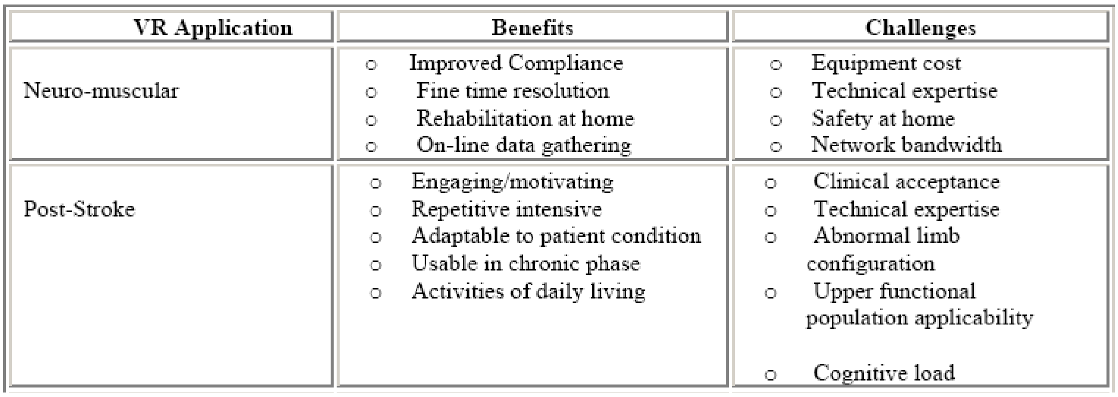
The main innovation of VR is the possibility of providing a new type of human-computer interaction. In fact, all body movements can be potentially used to interact with a virtual environment (VE). Furthermore, the changes of the VE determined by these movements offer new action opportunities. However, VEs should not be considered as equivalent to “natural” environments, but environments that allow the definition of experiences that suite the personal goals of the user.

The raising interest towards the use of interactive simulations, such as VR, in neurological rehabilitation, is justified by several advantages provided by this approach (see Figure 1). First, VR allows the creation of a completely multimodal stimulation, which provides patients with a great sense of involvement in action. Accordingly, VR interfaces developed for rehabilitation application were designed to support a sense of realism for the actions that patients are performing within the simulated worlds.

Furthermore, several studies have shown that knowledge acquired in VR can be transferred in a real environment (Wilson, Foreman, & Tlauka, 1997). These studies emphasize the potential effectiveness of using VR in the treatment of highly social-disabling cognitive dysfunctions, as they suggest that improvements reached in simulated settings may be transferred in patients’ everyday life.

VR training settings enable patients to successfully act within a safety environment. In addition to the reduced performance anxiety, this characteristic can enhance confidence in action execution and foster patient’s motivation, thereby improving his/her autonomy in everyday-like situation. Moreover, acting in a sheltered scenario increases patients awareness of the physical burdens determined by the disease, as well as of the risks associated to the exploration of an unknown environment.

Finally, rehabilitation protocols can take advantage of the patient’s playfulness with the VR experience, thus enhancing his/her motivation and compliance towards therapy.



VR Application	Benefits	Challenges
Neuro-muscular	○ Improved Compliance ○ Fine time resolution ○ Rehabilitation at home ○ On-line data gathering	○ Equipment cost ○ Technical expertise ○ Safety at home ○ Network bandwidth
Post-Stroke	○ Engaging/motivating ○ Repetitive intensive ○ Adaptable to patient condition ○ Usable in chronic phase ○ Activities of daily living	○ Clinical acceptance ○ Technical expertise ○ Abnormal limb configuration ○ Upper functional population applicability ○ Cognitive load

Figure 1: Benefits and challenge of interactive technologies use in rehabilitation (adapted from Morganti, 2004)

In spite of its benefits, the adoption of VR in the field of rehabilitation poses several challenges. First, there is lack of statistical data concerning the efficacy and safety of VR as a rehabilitation tool. Moreover, clinical research is needed to show the cost-effectiveness of using VR in rehabilitation with respect to traditional methods.

Studies on chronic post-stroke patients have shown that VR can improve the performance even long after any conventional therapy has been stopped (Holden & Todorov, 2002). For example, Wilson and colleagues (Wilson, Foreman, & Stanton, 1997) developed a VR tool in order to provide patients with action opportunities which compensated physical burdens determined by their disability. More specifically, the system allows patients to actively construct and execute actions within a simulated environment turning them able to interact with the environment by using sensory channels different from the impaired ones. This approach fostered patients’ autonomy in their everyday environment, and increased their motivation in performing actions. Rose and colleagues (Rose, Attre, Brooks, & Johnson, 1998) have developed a VR system which allows substitution of natural environmental stimulations with artificial stimuli derived from VR simulation. The goal of the experiment was to monitor patient’s reactions to specific categories of stimuli, and to assess patient’s capability of discovering relations among the different kinds of preserved sensory stimulation. This use of VR revealed to be effective in evaluating residual abilities, particularly when clinical symptoms appear to be confused.

Finally, a controlled study assessed the importance of haptic feedback (Broeren, Bjorkdahl, Pascher, & Rydmark, 2002) in VR. A haptic device was used to assess motor coordination in the rehabilitation of upper limb following acute stroke. Patients were requested to perform a coordination task such as reaching, grasping, and moving a haptic device to different positions on the screen. Device coordinates were monitored as well as the target position, time, and trajectories distances. Results showed that, the VR system was able to establish an assessment method for discriminating functional motor skills of upper extremity between healthy individuals and stroke patients. According to the authors of this study, by increasing the complexity of the VR system will be able to lead in motor recovery.

The applications that we have reviewed here encourage the use of VR in rehabilitation. However, to further improve these applications, it is important to create a closer collaboration between technological development and clinical work

Indeed, whit the introduction in rehabilitation of advanced technologies such as immersive VR, the problem of acceptance by both clinicians and neurological patients should be taken into account. These users are often unfamiliar with VR devices such as head mounted display and virtual gloves. Thus, there is a need for developing flexible systems that are easy to install and use, either in an outpatient clinic, or at home.

Among the recent works on advanced technology for rehabilitation an interesting approach comes from the EU-funded project I-Learning (Gaggioli et al., 2004; Gaggioli, Meneghini, Morganti, Alcaniz, & Riva, 2006). The technological tool for upper limb rehabilitation in stroke patients provided in this project consists of a movement tracking system and a custom-designed interactive workbench that the authors define as a virtual reality (VR) mirror. In the I-Learning approach, the VR mirror displays a 3D electronic image of the movement performed by the patient’s healthy limb. This is viewed from an ego-centric perspective that facilitates the generation of kinaesthetic motor imagery by the patient. The treatment has been focused on different motor exercises, such as flexion-extension of the wrist, intra-extra rotation of the forearm and flexion-extension of the elbow. The patient was requested to perform the motor task with the unaffected arm, thus the system records the movement and generates its mirrored 3-dimensional simulation for to guide the patient’s exercise with the affected arm. During the execution of the physical exercise with the paretic arm, the system tracks the movement and measures its deviation from the movement performed with the non paretic arm. Using this measurement, which is done in real time, the system provides the patient with audiovisual feedback describing his performance on the task. At the end of the laboratory training phase, patients are also provided with a portable display device to practice at home. This approach combines action simulation processes, such as imaginative exercises, with VR stimulation. The protocol, by developing egocentric and allocentric upper-limb exercises and supporting them with VR multimodal stimulation and feedbacks, provides patients with the possibility of constructing their own personal image of the motor behaviour that has to be trained and all them to elaborate their own schema and sequences of movements.

In doing that the I-Learning approach introduces a revolutionary vision of VR application that doesn't require immersive technologies, such as HMD, and proposes direct and intuitive possibility of action, based on the patient's experience and on the perceptual responses to motor behaviours. Moreover this peculiar technology solution introduces the possibility of a new approach to VR systems design and development, essentially based on the innovative concept of enactive interfaces.

4. Enaction and enactive interfaces

The concept of enaction appears into cognitive science in 1991 by Varela, Thompson & Rosch with the aim of explaining how mental life relates to bodily activity in a form of embodied action. In their book The Embodied Mind, in fact, these authors suggested a sensorimotor coupling between the organisms and the environment in which they are living that determines recurrent patterns of perception and action that allow knowledge acquisition. Enactive knowledge unfolds through action and it is constructed on motor skills, such as manipulating objects or playing a sport. It is not simply multisensory mediated knowledge, but knowledge stored in the form of motor responses and acquired by the act of "doing". According to the enactive approach, the human mind, is embodied in our organism and it is not reducible to structures inside the head, but it is embedded in the world we are interacting with (Thompson & Varela, 2001). In rejecting the Cartesian mind-body dichotomy (in which there is a "mental" and a "physical" way to acquire knowledge, such as theoretical and procedural learning) the world become inseparable from the subject and humans primary way of relating to things is neither purely cognitive nor sensory, but rather bodily and skilful. Enactive knowledge is more natural than other forms of knowledge acquisition, because it is gained through perception-action interaction in the environment. Moreover, enactive knowledge is inherently multimodal because it requires the coordination of the various senses.

Traditional interaction with the information mediated by a computer is mostly based on symbolic or iconic knowledge. In contrast, enactive interfaces are multimodal interactive systems that coordinate action and perception using ad hoc devices, and allowing the organization and the transmission of this particular type of knowledge.

The basic tenet of enactive interfaces is the role of motor action for storing and acquiring knowledge (like in action-driven interfaces). Such interfaces are able to convey and understand gestures of the user, in order to provide an adequate response in perceptual terms. Enactive interfaces are characterized by a closed loop between the natural gestures of the user (efferent component of the system) and the perceptual activated modalities (afferent component). Thanks to this feature, they can recognize complex gestures.

We know from cognitive research that embodiment can be viewed in two possible ways. On one hand it could be defined as a subjectively lived state in which agents experience their own lives as embodied self. On the other hand embodied agents exist as living and biological organisms (Hanna & Thompson, 2003; Thompson, 2004).

We think that enactive technologies match both these definitions. On the one side, enactive technologies can propose novel training scenarios in which a wide variety of tasks can be easily practiced (embodiment as subjectively lived state). On the other side, if movements practiced in a virtual environment are kinematically similar to movements with physical objects, then the transfer of training to real-world situation might be possible (embodiment as living, biological organism).

The development of such interfaces requires a common vision among different research areas, like neuroscience and human-computer interaction, and more attention to the embodied interactive aspect of human cognition.

In paragraph 6, we provide an example of application of the enactive approach in rehabilitation. Specifically, we describe a protocol in which interactive simulation is used to support grasping task in hemiplegic patients following stroke.

5. The enactive interfaces for rehabilitation

Enactive technologies support a new perspective on rehabilitation that derives from a peculiar vision of motor behavior. This approach is summarized by Merleau-Ponty’s definition of motor intentionality (Merleau-Ponty, 1962). According to this philosopher, intentionality is grounded in the present situation and it is not driven by a pre-existent motor schema.

> In grasping something we direct ourselves toward it and thus our action is intentional. But the action does not refer to the thing by representing its objective and determinate features; it refers to it pragmatically in the light of a contextual motor goal effected by one's body (p.138)

This means that in picking up an object, agent identifies it not by its objective location, but by its egocentric relation to her/his hand. And she/he will grasp the object according to the goal of sipping from it. At the same time, the objects in the environment have "motor meanings", defined by Gibson (1977) as *affordances* that bring forth suitable intentional actions in relation to the motor skills of the subjects. In this way, objects are perceptually situated on the basis of the orientation that they have towards our moving and perceiving bodies. The use of an affordance implies a second reciprocal relationship between perception and action. Perception provides the information for action, and action generates consequences that inform perception. This information may not be only proprioceptive (letting the agent know how its body is performing), but also exteroceptive, and reflects the way the agent has affected the environment in respect to the affordance. The perception of this relationship allows the adaptive control of action, and of the environmental change.

The introduction of this approach in movement rehabilitation (and particularly in the rehabilitation of movement that directly relate humans body with the environment, such as reaching and grasping objects in the world) provides a fresh perspective for developing intervention treatments. Indeed the notion of enactive interfaces, allows the shift of the focus from the rehabilitation of a single motor task to the rehabilitation of global actions. By manipulating the environment, patients become aware of how to perform useful actions and the consequences of those actions. This "pure experiential" approach to rehabilitation requires a highly interactive environment that support agents in a wide experimentation of their action possibilities, while keeping patient safety.

Enactive systems appear to cope with all these needs. First of all they potentially have in input all patient actions, and are can transform these actions in alternative movement possibilities. Furthermore, enactive interfaces provides multimodal stimulation that provide patients with behavioural cues to multiple or alternate sensory ways, thus avoiding at the same time to over-stimulate the perceptual system. This feature supports more accurate knowledge integration and efficient learning. Finally, enactive technologies give the opportunity to localize patients within settings that could be unapproachable, dangerous or stressful for them in the everyday situation.

Despite the growing interest in the use of enactive interfaces for motor retraining, it may be questioned whether reaching and grasping movements in VR environments are performed in a way similar to the movements done in the physical world.

Recently, Viau, Feldman, Mc Fayden, & Levin, (2004) showed how both healthy subjects and individuals with motor impairment used similar movement strategies in a physical and a simulated environment, suggesting that enactive technology is a valuable tool for the study and the retrainment of reaching, grasping and placing movements.

If movements practiced in a virtual environment are kinematically similar to movements with physical objects, then the transfer of training to real-world situation might be possible. Furthermore, enactive technologies can open novel training scenarios in which a wide variety of tasks can be easily practiced. Indeed, recent evidence suggests that neuroplasticity after stroke (and consequently functional recovery), is influenced by the motivation of the patient and the intensity of the training (Kwaddel, Wagenaar, Koelman, Lankhorst, & Koetsier, 1999; Nudo & Milliken, 1996). Finally, the advent of home-based computers and tele-rehabilitation technologies may improve accessibility to training procedure for those patients who are unable to reach rehabilitation facilities.

On the basis of these premises, we are investigating the possibility of using enactive interface rehabilitation of brain-injured patients. In the following paragraph, we describe a rehabilitation protocol based on the use of an enactive interface (a virtual glove), in the rehabilitation of upper-limb hemiplegia following stroke.

6.The use of virtual glove as enactive device for upper limb rehabilitation in stroke

The main aim of this research protocol is to investigate the technical and clinical feasibility of using enactive technologies in the rehabilitation of upper-limb hemiparesis following stroke. Building on the enactive perspective on embodied agentivity described in paragraph 4, we start from the assumption that repetitive motor exercise customized on patient residual abilities could be appropriate for motor recovery of upper limb functionality after stroke. Clinical evidence shows that the neurological impairment after stroke is often associated with cognitive impairment, such as the inability to understand verbal indications, to memorize and correctly use the language for communication. Due to its action-based nature, the introduction of enactive interfaces allows us to overcome this failure in encoding and producing knowledge in a symbolic way. Indeed, the use of enactive interface provides intuitive motor information for the patients on how to perform the task, thereby reducing the necessity of verbal instructions. The mere presentation of the interface to patient supports him in finding the best way to perform the required activity. Moreover an immediate multimodal feedback will be presented to him when the motor task is correctly performed.

6.1 Clinical population

The clinical population will be selected according to two main parameters: *grading* and *staging* of their lesions. By *grading* we mean the severity of the impairment, as assessed with the most used motor function scales, disability scales, and speech/language/mental status scales. By *staging* we mean the time elapsed between the onset of the injury and the beginning of the rehabilitation treatment.

This interface is well-suited for patients who suffered form an ischemic or hemorrhagic stroke in the left hemisphere and to be used during their acute/sub-acute phase of recovery after stroke.

Patients who present the following are excluded from the study:

A severely impaired mental status (according to the *Folstein Mini-Mental State Examination*)

A severe disability (according to the *Modified Ranking Scale*)

Severe orientation/attention impairments

Spatial hemi-inattention and neglect.

6.2 Materials

For the feasibility study on stroke patients, we utilize a virtual glove to grasp objects in a dynamical 3D virtual environment.

The glove is the P5 glove developed for commercial use by Essential Reality. It is a an innovative, glove-like peripheral device, based on proprietary bend sensor and remote tracking technologies, which provides total intuitive interaction with 3D software and virtual environments. The use of the glove allows patients to move through an environment or to pick up objects on the interface. The flexions of all fingers as well as the wrist position are measured through a “base station” tower. The glove has an easy-to use design, with the sensing structure weighing only 128 grams and being placed on the back of the hand. It has 6 degrees of tracking (X, Y, Z, Yaw, Pitch and Roll) to ensure realistic movement. Each finger sensing structure has one resistive bend sensor, which measures the global bending with a 3.0-degree maximum resolution over a range of 0 to 90 degrees. The wrist 3D movement (translations and rotations) is tracked optically using infrared LED mounted on the backhand connector. This allows wrist measurements to be done 60 times every second, while the hand is kept at up to 1.2 meters from the base station.

6.3 Procedures

The exercise that we propose to stroke patients is to reach and grasp target items (e.g., virtual balls) on a graphical 3D surface. Targets appear randomly to patients and they that have grasp and throw them by using the virtual glove. Targets can vary for shape, dimensions, right/left and top/down appearance on the screen, increasing/decreasing velocity and depth. For the preliminary part of the feasibility study, in order to use this enactive interface in a wide range of clinical population, neutrally texturized and coloured 5cm balls are used as target objects. Patients are requested to grasp and throw target objects provided by the interface with a multimodal feedback (visual and auditory). A graphical summary of targets that has been reached or missed by the patient is continuously given to users during the performance.

6.4 Treatment

The treatment consists of 1 daily session, 5 days a week, for 4 consecutive weeks. Each therapeutic session includes 1/2 hour of standard physiotherapy, plus 1/2 hour of computer-facilitated training.

The patient is evaluated 4 times: 1) at the beginning of treatment (baseline assessment); 2) at the end of treatment; 3) three months after the end of the treatment 4) six months after the end of treatment.

The Motricity Index and the Wolf Motor Function Test are measured before and after treatment and during the follow-up. Additionally the quality of movement and the amount of use of the impaired limb is evaluated by using the Motor Activity Log.

The performance in technology-enhanced situations is evaluated through enactive interface response times and sensors data.

At the end of the treatment program, the Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST), for the evaluation of the VR system, is administered to the patients. Patients included in the experimental treatment will be compared with a control group of patients who undergo traditional treatment.

7. Conclusions

In this article, we have provided a scientific rationale for using enactive technology in stroke rehabilitation. Our approach is based on the idea of an embodied cognition in which actions are not just the results of a information processing derived from an external world, as in classical perspective on motor behavior. In embodied cognition, the agents learn how to perform useful actions and what are the consequences which results from their recovered motor ability.

This approach requires a highly interactive environment that allows patients to experiment their action possibilities. The introduction of enactive interfaces that the recovery treatment could be focused on the rehabilitation of a more global notion of agency.

Furthermore, we have reported a specific interface for reaching and grasping objects in a three-dimensional space, specifically suited for upper limb recovery in stroke patients. According to the enactive perspective, the task of picking up an object requires the identification not only of the objective location, but also the egocentric relation of the object to our body. Thus, objects in the environment provide us a readiness to use, defined as *affordance*, bringing forth suitable intentional actions in relation to our motor skills. This implies a second reciprocal relationship between perception and action. Perception provides the information for action, not only in a proprioceptive way, but also in reflecting the way we have changed the environmental context in respect to the *affordance*.

Enactive systems are able to transform these action in different movement possibilities providing multimodal stimulation and action affordances on multiple or alternate sensory ways. This will support more accurate knowledge integration and an efficient learning.

In conclusion, the development of enactive interfaces for rehabilitation might contribute to fill the gap between the neuroscientific study of embodied interactive aspect of human cognition and the clinical practice. This link can highlight new challenges in the treatment of brain-injured patients.

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