Assessment and Treatment of the Upper Limb by Means of Virtual Reality in Post-Stroke Patients

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Abstract. The disability deriving from stroke impacts heavily on the economic and social aspects of western countries because stroke survivors commonly experience various degrees of autonomy reduction in the activities of daily living. Recent developments in neuroscience, neurophysiology and computational science have led to innovative theories about the brain mechanisms of the motor system. Thereafter, innovative, scientifically based therapeutic strategies have initially arisen in the rehabilitation field. Promising results from the application of a virtual reality based technique for arm rehabilitation are reported.

Keywords. Stroke, Rehabilitation, Motor Learning and Control, Augmented Feedback, Virtual Reality

Introduction

Stroke is a leading cause of death and disability for men and women of all ages, classes, and ethnic origins worldwide. Several epidemiological surveys were conducted on cerebro-vascular disease, especially in the United States, where 500,000 new strokes occur each year causing 100,000 deaths and leaving residual disability for 300,000 survivors. Moreover, approximately 3 million Americans have survived a stroke with some degree of residual disability [1, 3].

Within 2 weeks after stroke, hemiparesis is present in 70-85% of patients and a percentage, between 40 to 75%, is completely dependent in their activities of daily living [4]. There is a lack of epidemiological data for European countries, although in the United Kingdom the Oxfordshire Community Stroke Project (1983) reported an annual incidence of 500 new cases in a 250,000 people community, with a peak in people older than 75 years [5]. In a recent study conducted in Norway, a total annual incidence of 2.21 strokes per 1000 people was reported. This rate is congruent with other European countries showing that there are no regional variations within Western Europe [6].

The estimates of the total cost of stroke are very variable in relation to the difficulty of calculating the indirect cost resulting from disability and mortality. A 1993 estimate placed the total annual cost of stroke at $30 billion in the United States, of which $17 billion are direct costs (hospital, physician, rehabilitation, equipment) and $13 billion are indirect costs (lost productivity) [7].

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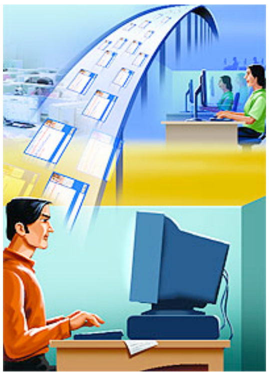

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The main cost of stroke survivors is related to their residual motor disabilities that interfere with personal, social and/or productive activities. Surprisingly, there are few therapeutic approaches to restore lost functions. Nowadays the available rehabilitative therapies are currently working to develop treatments that are closely related to motor learning principles.

Recently the development of tools for quantitative analysis of motor deficits gave the opportunity to increment the amount of data in clinical practice to better study human motor behavior with consequent important practical implications. First of all, it will be possible to infer the anatomical structures that modulate the different elements of motor control. Furthermore, it may help to better characterize motor deficits and, as a consequence, to plan individually modified therapeutic approaches. Finally, the quantitative analysis of movement may allow to monitor pharmacological therapies (i.e drugs interacting with the central neurotransmitters levels) that could modify the human motor behavior [8, 9].

1. Rationale

1.1 Neurophysiology of motor learning

Research on the physiological underpinnings of movement dynamics has traditionally focused most extensively on the primary motor cortex (M1) pointing out that neurons in M1 are modulated by external dynamic perturbations. Some investigators [10] indicate that several premotor areas feed M1 which then projects to the spinal cord. These areas are intensely interconnected with each other, with a parallel contribution to the control of movement [11].

Other work on primates demonstrated that several cortical cells in motor and pre-motor areas responded selectively to kinematic variations during motor adaptation tasks. These cells, clearly identified in the monkey SMA, are involved in the process of kinematics-to-dynamics transformation, hence in new motor task learning [11]. Doya et al. [11, 12] proposed other correlations between the motor learning problem and circuitry at the cortical level, suggesting that different brain areas are involved in three different kinds of learning mechanisms: supervised learning, reinforcement learning and unsupervised learning.

The cerebellum is supposed to be involved in real-time fine tuning of movement by means of its feed-forward structure based on massive synaptic convergence of granule cell axons (parallel fibers) onto Purkinje cells, which send inhibitory connections to deep cerebellar nuclei and to inferior olive. The circuit of the cerebellum is capable of implementing the supervised learning paradigm which consists of error driven learning behaviors. Reinforcement learning is based on the multiple inhibitory pathways of the basal ganglia that permit the reward predicting activity of dopamine neurons and change of behavior in the course of goal directed task learning. The extremely complex anatomical features of the cortex suggest that information coding is established by an unsupervised learning paradigm in which the activity is determined by the Hebbian-rule of synaptic updating. In this paradigm the environment provides input but gives neither desired targets nor any measure of reward or punishment [11, 12].

Recent neurophysiologic studies demonstrated that some natural complex systems have discrete combinatory architecture that utilizes finite numbers of primary elements to create larger structures, such as motor primitives in spinal cord [13]. Poggio and Bizzi [14] hypothesized a hierarchical architecture where the motor cortex is endowed with functional modular structures that change their directional tuning during adaptation, visuo-motor learning, exposure to mechanical load and reorganization after lesions, i.e. the circuit of interneurons as central pattern generators, unit burst generators, and spinal motor primitives contributing to motor learning. In the latter case the force fields stored as synaptic weights in spinal cord may be viewed as representing motor field primitives from which, through linear superimposition, a vast number of movements can be fashioned by impulses conveyed by supraspinal and reflex pathways [14]. Computational analysis [15] verifies that this proposed mechanism is capable of learning and controlling a wide repertoire of motor behaviors. This hypothesis suggests that the cortical lesion induced by a stroke could modify the hierarchical architecture with negative influences on learning and controlling new motor behaviors.

1.2 Neurophysiopathology of stroke lesion

From the physiopathologic perspective, much evidence demonstrated that the location of the stroke lesion is related to upper limb motor deficit severity. Specifically it is argued that patients with cortical stroke have a better motor outcome than patients with subcortical stroke. Furthermore, patients with mixed cortical plus subcortical stroke tended to improve more than patients with pure subcortical stroke despite the expected larger size of mixed lesions. Although subcortical strokes are normally smaller than cortical strokes, they are more likely to involve primary (from M1) and secondary motor pathways (from SMA and premotor area, PMA). The descending fibers from primary and secondary motor areas converge in the internal capsule maintaining their somatotopic distribution. Consequently, even small subcortical lesions produce devastating motor effects. The probability of upper limb motor recovery after stroke is hence linked strictly with the anatomical lesion: 75% for patients with lesions restricted to the cortex (MI, PMA, SMA); 38.5% for those with subcortical or mixed cortical plus subcortical lesions not affecting the posterior limb of the internal capsule (PLIC); and 3.6% for those with involvement of the PLIC plus adjacent corona radiata, basal ganglia or thalamus [16].

1.3 Computational approach to the upper limb rehabilitation.

The computational approach to the motor system is a powerful analysis, in the field of neuroscience, which offers the opportunity to unify the experimental data in a theoretical framework. In the computational perspective, the motor behavior is intended as the manifestation of an engineering system, whose basic task is to manage the relationships between motor commands and sensory feedback. This management is necessary for two reasons:

1. it ensures that our movements achieve their goals;
2. it enables us to learn by experience to make more accurate and effective movements.

Recently, Han et al. developed a computational model for bilateral hand use in arm reaching movements to study the interactions between adaptive decision making and motor learning after motor cortex lesion [17]. This model combines a biologically plausible neural model of the motor cortex with a non-neural model of reward-based decision making and physical therapy intervention. The model demonstrated that in the damaged cortex, during therapy, the supervised learning rules ensured that underrepresented directions of movement were “repopulated”, thereby decreasing average reaching errors.

The authors suggested that after stroke, if no therapy is given, plasticity due to unsupervised learning may become maladaptive, thereby augmenting the stroke’s negative effect. They also indicated that there is a threshold for the amount of therapy based on three types of learning mechanisms (unsupervised, supervised and reinforcement) required for the recovery process; below this threshold motor retraining is “in vain”. In other words, there is an absent or exiguous use of the arm exhibiting the “learned non-use” phenomenon. In the absence of supervised or reinforcement learning, subsequent motor performance worsens with any amount of rehabilitation trials. On the contrary, if unsupervised learning is not present, motor performance improves with any amount of rehabilitation trials in the late period.

1.4 Virtual reality as an emerging therapy

Virtual Reality (VR) is an innovative technology consisting of a computer based environment that represents a 3-D artificial world. VR has been already applied in many fields of human activity. New computer platforms permit human-machine interactions in real time, therefore the possibility of using VR in medicine has arisen. The present level of technical advances in the computer interface allows the development of VR systems as therapeutic tools in some neurological and psychiatric pathology. For example, stroke survivors may undergo rehabilitative therapeutic procedures with different VR systems [18, 19]. The use of a VR-based system coupled to a motion tracking tool allows us to study the kinematics of arm movement in the restorative process after stroke. Furthermore, the possibility of modifying the artificial environment, where the patients could interact, may exploit some of the mechanisms of motor learning.

We know from physiological studies that humans perform a large variety of constrained and unconstrained movement in a smooth and graceful way because the CNS enables us to rapidly solve complex computational problems. One hypothesis is that the CNS needs little information in order to adapt movements to the changing of the external requirements, providing that it already contains preprogrammed algorithms for function [20]. These algorithms produce regularities in biological movements that are not in any way implied by the motor task. Accordingly with this view, a given movement can be characterized by variant and invariant elements. For instance, the variant part of a reaching movement is the distance of the targets (corresponding to the amplitude of the movement). The invariant part consists of straight paths with a bell-shaped speed profile in all movements [21, 22].

In our laboratory, we experimented with a VR based setting for the assessment and treatment of arm motor deficit in patients after stroke. We compared a VR based (reinforced feedback in virtual environment, RFVE) and traditional physical therapy technique (conventional therapy, CT) in the treatment of arm motor impairments in post-stroke patients. The studied population met the following inclusion criteria: a single ischemic stroke in the region of the middle cerebral artery at least six months before the study (proven by means of CT scan or MRI); conventional physical therapy treatment received in the early period after stroke; mild to intermediate motor impairments of the arm assessed as a Fugl-Meyer Upper Extremity score (F-M UE) between 20 and 60, at baseline [23]. Clinical history or evidence of memory impairments, neglect, and apraxia or aphasia interfering with verbal comprehension were all considered exclusion criteria.

The experimental intervention was the RFVE treatment and the control procedure consisted of conventional physical therapy treatment. Both therapies were oriented towards upper extremity motor rehabilitation. In the first one, the subject was requested to perform different kinds of motor tasks while the movement of the entire biomechanical arm system's end-effector was simultaneously represented in a virtual scenario by means of motion-tracking equipment. The equipment included a computer workstation connected to a 3D motion-tracking system (Polhemus 3Space FasTrak, Vermont, U.S.A) and a high-resolution LCD projector which displayed the virtual scenarios on a large wall screen. The electromagnetic 3D motion-tracking sensor was positioned on a manipulable object (rubber ball, polystyrene cube etc.) held by the subject, or, alternatively, was attached to a glove worn by the patient in cases of severe grasping deficits. The physical therapist could create numerous virtual motor tasks for the arm through the use of flexible software, developed at the Massachusetts Institute of Technology (Cambridge, MA, U.S.), which processes the motion data coming from the end-effector receiver. The therapist selected the characteristics and the complexity of the motor tasks in order to suit each patient's arm deficit. In the virtual scenario, the therapist determined the starting position and the characteristics of the target, such as target orientation, for each task or the addition of other virtual objects to increase the task's complexity. A simple reaching movement could accomplish some tasks, while others required more complicated movements, such as putting the envelope in the mailbox, hitting the nail, or pouring the glass in the carafe. The subject moves the real envelope, hammer, or glass and sees on the screen the trajectory of the corresponding virtual object toward the virtual mailbox, nail, or carafe.

During the RFVE therapy, patients were asked to perform motor tasks according to constraints specified beforehand by the therapist. Subjects were given information about their arm movements during the performance of motor skills (knowledge of performance, KP) by the movement of the end-effector's virtual representation. The therapist's movement and trajectory could also be displayed in the background of the virtual scene in order to facilitate the subject's perception and adjustment to motion errors (learning by imitation) [24]. Moreover, knowledge of the results (KR) regarding motor task correctness was supplied to patients in the form of standardized scores and by displaying arm trajectory morphology on the screen. Initially, the above mentioned KP and KR were provided at a frequency of more than 90% and were gradually decreased as performance improved.

In the CT group the subjects were asked to perform specific exercises for the upper limb with a strategy of progressive complexity. First, the patients were requested to control isolated motions without postural control, with physical therapist support if necessary, then postural control was included and, finally, complex motion with postural control was practiced. For example, patients were asked to touch different targets arranged upon a horizontal plane in front of them; to manipulate different objects; to follow trajectories displayed on a plane; to recognize different arm positions.

The physical therapists chose the exercises in relation to functional assessments and patient needs.

The aim of this study was to compare the RFVE and CT approaches towards the treatment of arm motor impairments in post-stroke patients. We hypothesized that a rehabilitation technique based on motor learning rules, specifically the kinematic information about arm movements in a virtual environment, could significantly improve the motor outcome scores better than CT therapy. Before and after the treatment, the degree of motor impairment and independence in daily living activities were evaluated in both groups with the F-M UE score and the Functional Independence Measure scale (FIM) [25]. At the same evaluation times, for all of the patients, we determined the mean duration (MD) in sec, mean linear velocity (MLV) in cm/sec, and the number of sub-movements (SM) in 36 motor trials organized into four tasks.

The patients' starting position was the same in all of the trials. The different orientation of the target (horizontal, vertical and diagonal on the subject's frontal plane) determined the complexity of the movement in terms of involving the activation of different muscles. The patients were randomly assigned into the 2 groups and both groups underwent the therapy for 1 hour treatment sessions daily, 5 days a week for 4 weeks.

Analyzing clinical (F-M UE and FIM) variables, we found, in both groups, a statistical significance within the groups for the F-M UE (p-values<0.00, p-values<0.016, respectively) and for the FIM (p-values<0.00, p-values<0.009, respectively) scales. The robust regression analysis revealed that the F-M UE values after the treatment were systematically higher in the RFVE patients than in the CT subjects (β =-4.26, p-value<0.005). We observed the same result also for the FIM values after the treatment (β =-4.59, p-value<0.02). The kinematic (MD, MLV, SM) parameters changed significantly after the treatment only in the experimental group (p-value = 0.01, 0.00 and 0.02 respectively), in contrast to those of the control subjects (p-value = 0.18, 0.11 and 0.15 respectively). Finally none of patients who underwent the RFVE therapy complained of any discomforts due to interaction with the virtual world, such as cybersickness, altered eye-motor coordination or postural disequilibrium, thereby demonstrating that this VR-application is safe for neurological patients.

Our results confirm that late therapy may improve motor performance as suggested in others studies using different rehabilitation techniques [26, 27]. The kinematic results were coherent with the RFVE rationale based on the amplification of kinematic feedback to promote motor recovery; furthermore the improvement in motor performance occurred concurrently with kinematic variation. In our opinion, the higher results achieved with RFVE treatment were connected with the rationale of the VR based technique which exploits the motor learning mechanisms.

2. Conclusion

In our VR setting, patients were given information about their arm movements during the performance of motor skills (KP) that consisted of the representation of their end-effector, and "virtual teacher" movement which showed the actual kinematics of the hand path in order to practice "learning by imitation". The teacher, as other relevant feedback, realizes an ideal environment to implement new predictors or to modify disrupted forward models. These mechanisms are developed by means of amplification of the actual state. On the other side, new or better controllers can be developed by means of different sensorimotor context presented in every scenario, as by the utilization of graphic models that reproduce the visual objects' appearance, giving coherent contextual information. Furthermore, instructions imparted by the therapist during the experimental procedure and the virtual representation of the correct movement contributed to providing information about motor performance, thereby exploiting so-called “supervised learning”. Moreover, the object’s trajectories displayed on-screen allowed patients to evaluate the accuracy of their movement (KR), thereby promoting the identification of successful motor strategies through the “trial and error” paradigm. A second kind of KR provided to patients was a reward delivered when the task performance score surpassed a pre-established threshold. These two phenomena contributed to generating the basis for the “reinforcement learning” mechanism.

In our experience, the synergistic activity of supervised, reinforcement and learning by imitation facilitates faster development of the kinematic internal models essential for motor learning. The opportunity for supplying patients with a measurement of motor performance generated an auto-competitive stimulus for progressively improving the correctness of arm trajectories session by session. The above aspect, combined with the novelty and the originality of the VR-based therapy, motivated the patients to enthusiastically participate in the rehabilitation sessions.

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