The Rehabilitation Gaming System: a Virtual Reality Based System for the Evaluation and Rehabilitation of Motor Deficits

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Abstract— **We have developed a virtual reality based system for the rehabilitation of patients suffering from different neuropathologies such as those brought on by stroke and traumatic brain injury. Our Rehabilitation Gaming System, or RGS, uses a vision based motion capture system with gaming technologies and functionally combines active evaluation, with continuous monitoring and intensive training regimes tuned to the needs of individual patients. Here we assess the validity of the evaluation phase of the RGS by comparing the physical and virtual versions of a diagnostic reaching test with 6 stroke patients. Subsequently we illustrate the ability of our system to provide high resolution information at the level of individual performance.**

I. Introduction

IN the last few years there have been major developments in the application of virtual reality systems to the rehabilitation of a variety of deficits resulting from lesions of the nervous system [1, 2]. One of the main areas is the rehabilitation of stroke patients, in particular with respect to the function of the upper extremities. Stroke represents the major cause of adult disability worldwide, with about 60% of the patients experiencing long term persistent functional disabilities [3, 4]. This leads to high societal costs with respect to the rehabilitation expenses and lost productivity of patients. In addition, the psychological impact on the patient and their social environment must not be underestimated, as many patients regress into depression [5]. After a stroke the recovery of the motor capacity of the hand is of particular interest due to its essential role in the maintenance of instrumental activities of daily living. Conventional rehabilitation programs are based on guided peripheral limb manipulation and occupational therapy. However, the exact impact of this traditional approach on functional recovery is unclear and the optimal regime of physiotherapy is still uncertain. Nevertheless, there is evidence that the quality of recovery depends on the intensity of therapy [6], the repetition of skilled movements [7] that are directed towards the specific motor deficits of the patients [8] and rewarded with performance dependent feedback [9]. Traditional, human therapist dependent therapy can not fulfill these requirements due to the associated expenses. Hence, the need for the deployment of alternative approaches.

Virtual reality based rehabilitation is a method that allows the integration of our understanding of rehabilitation with advanced interactive multi-media technology that can be focused on delivering individualized ‘optimal’ therapy. Several virtual reality systems for upper limb rehabilitation have been developed and tested worldwide following diverse methods and therapy concepts including: systems used to train reaching movements through imitation of a virtual instructor [10, 11] or by means of haptics [12]; to train individual hand and finger properties such as range of motion and strength by means of intense practice of skilled movements [13, 14]; and to train general upper limb movements by mental rehearsal and the imitation of movements of the non-paretic arm [15]. All of these systems are based on a number of implicit or explicit assumptions on how VR based approaches can promote recovery after stroke. Indeed, effort has been made in developing rehabilitation models based on the understanding of the mechanisms of cortical reorganization after stroke [16].

Other advantages of virtual reality systems include the ability to manipulate motivational factors that is believed to have an impact on recovery [17]. In addition, this technology enhances patients’ autonomy during training and decreases the requirement of constant surveillance. Moreover, there is also an enormous potential for monitoring and evaluation that can possibly be coupled with standard clinical evaluation methods, providing complementary data for measuring rehabilitation progress. This represents an important property since these systems enable detecting small variations in performance that will not always be sufficiently detectable to modify scores/levels in the standard clinical scales. Moreover, clinical scales are constructed based on the human observer, while VR and their associated motion capture interfaces provide for more

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intense and high resolution assessment. However, one essential step that must be taken is the calibration of performance and diagnostic measures with respect to standard clinical tests. Here we report on a first step in this direction using RGS.

We have developed a VR based rehabilitation system, or a Rehabilitation Gaming System (RGS) that is specifically designed for the rehabilitation of stroke induced motor deficits. The core concept behind RGS is that the action recognition system provided by the mirror neurons of the pre-motor and parietal cortical areas provide a direct access to the central motor system. The mirror neurons are a recently discovered particular population of neurons that discharge both during goal oriented action execution and observation of the same action when performed by others [18, 19]. We have earlier reported a first prototype of this system [20]. Here we report on a next evolution of the RGS where we combine both evaluation and training in one system. This is an essential step in achieving individualized and autonomous VR based training systems. Here we perform a preliminary assessment of the system based on the evaluation and training of 6 stroke patients. In particular we assess the correlation between physical performance measures and their virtual counterparts. Besides coupling our paradigm with upper limb training therapy, our system has also the potential to be used as an automated tool for diagnostic and monitoring measures during rehabilitation programs.

II. METHODS

A. System Description

The version of RGS used here maps the movements of the user into VR using a custom developed camera based system motion capture system called AnTS (Fig. 1). This solution removes the significant response latencies that precluded ecologically valid interactions in our previous and now outdated system [21]. The motion capture system runs at an update rate of 30 Hz and tracks color patches making use of the Hue Saturation Value (HSV) color space in order to have a better and more sensible color representation. In this color space, the Hue value alone encodes for the color identity. Based on this principle, AnTS tracks color patches that are placed on strategic points of the arms, i.e. elbow and wrist. The position of each of the patches is computed using probabilistic methods that help to solve occlusions and crossing related problems. The joint angles of both arms are computed from the position of the tracked patches by means of a biomechanical model. The median error in the reconstruction of the joint angles is 11 degrees.

The captured joint angles are mapped onto the movements of a virtual avatar embedded within a virtual scenario developed using the Torque Gaming Engine (www.garagegames.com). In addition, RGS uses custom made data gloves to measure finger flexion.

B. Protocol

The first proposed task was developed to train the range of motion of the arm. The subject sits in a chair, facing a computer screen (Fig. 1). Both forearms are placed on a table with hand palms facing downwards, i.e. the table top supports the subject to act against gravity. On the display, the subject can see in a first person view two virtual arms that mimic the motion of their own arms, i.e., the movements performed by the virtual arms correspond to the movements of the real arms.

Fig. 1. The Rehabilitation Gaming System setup. The user wears color patches that are tracked by the motion capture system and these are mapped onto a virtual character. Data gloves provide the finger flexion data. The screen displays a first person view of the gaming scenario in the virtual environment. The dots on the table are the reference points during the evaluation phase of the system.

The patient uses RGS in three phases: In the evaluation phase (1.5 minutes), the patient is asked to touch a sequence of targets marked on the table, at distances from 19 to 42 cm from a resting position, in a specific order (Fig. 1). This is followed by an accommodation period (1 minute) where the patient can make unconstrained movements in order to adjust to the mapping of physical movements to the virtual limbs. In a second phase (1.5 minutes), the patient is asked to perform the same evaluation task in VR. In the last phase, the training phase (10 minutes), the patient sees a landscape where virtual spheres move towards him/her that must be intercepted with the virtual arms. The movements of the virtual arms are directly controlled by the movements of the patient's own arms on the table by means of the motion capture system.

Each time the patient intercepts a sphere, it ricochets back and the patient receives auditory feedback by means of a "positive sound". Over the session points are accumulated for a final score that is continuously displayed to the subject. The difficulty of this interception task is defined by a set of game parameters including: radius of the spheres, movement speed, release time interval and the left/right range of the balls. The task difficulty can be set depending on the capabilities and performance of the subject. In a second gaming level, range of motion training can be coupled with grasping training. This consists in simultaneous interception and grasping of the spheres using data gloves.

The interaction between real and virtual limbs and actions can be controlled and tuned to the properties of the patient and/or the particular training scenario. For instance, different weights can be given to a specific limb in order to amplify the displayed movements.

The data from each session is recorded for subsequent analysis to provide a record of improvement over training sessions. The captured data consists of the joint angles provided by the motion capture system, the coordinates of the virtual arms, event related data (which hand touched a sphere where) and scores.

C. Subjects

6 naive right handed stroke patients with left hemiparesis, mean age of 61 years (range 32-74), Brunnstrom Stage for upper extremity ranging from II to V, Barthel Index from 36 to 72, and Functional Independence Measure (FIM) from 61 to 105, tested our system during single trials (Table 1).

TABLE I
PATIENT INFORMATION

Patient ID	Weeks alter stroke	FIM	Barthel Index	Brunnstrom Stage
1	6	61	36	II
2	4	-	41	IV
3	2	104	62	V
4	8	101	72	IV
5	34	90	64	II
6	2	105	62	-

III. RESULTS

A. Evaluation Phase

In order to give a quantitative measure of the patient's upper limb motor control, we designed a evaluation task to extract the reaching distance and speed of the patient's movement (see Protocol). Therefore, we compared the performance of the paretic and non-paretic arms. We measured the percentage of accomplished movement range and velocity in the given task (Fig. 2).

Considering that the overall goal is to use a virtual reality setup for motor and cognitive recovery, we want to assess the impact and possible limits of this technology when applied to patients with motor and/or cognitive deficits. Therefore, we replicated the evaluation task in our virtual environment using the same criteria mentioned above.

Patient 1 and Patient 2 were excluded from this analysis, as they did not accomplish the complete execution of the real and/or virtual evaluation task within the specified time interval. The results show that our system delivers information that can be used for an automatized quantification of patient's motor capabilities (reaching distance and velocity) (Fig. 2).

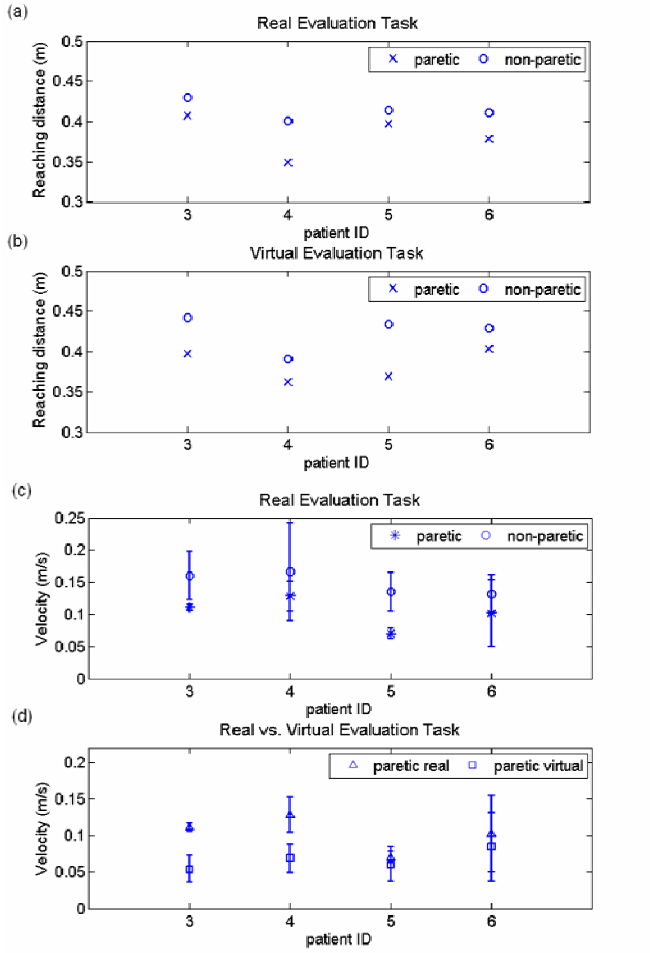

Fig. 2. Reaching distance and velocity of movement across patients during the evaluation phase. (a) Maximum reaching distance of the paretic and non paretic arms during the real evaluation task. (b) Maximum reaching distance of the paretic and non paretic arms during the virtual evaluation task. (c) Velocity of movement for the paretic and non paretic arms during the real evaluation task. (d) Comparison of the velocity of movement of the paretic arm in the real and virtual tasks. Vertical bars indicate the standard deviation.

The reaching distance was computed as the furthest point that the patients reached during the evaluation phase. In all the patients considered for this analysis we observed that there was a systematic asymmetry between paretic and non-paretic arm, and that this asymmetry was preserved when performing the evaluation task in the virtual environment (Fig. 2). Over patients, the mean difference of the reaching distance between paretic and non-paretic arms was of 2.4cm and 3.6cm for the real and virtual task respectively, being not significantly different (Kolmogorov-Smirnoff test, $p = 0.318$). However, although the reaching distance was consistent in the real and in the virtual tasks, we found that there was a general decrease in speed when the patients were performing in the virtual environment (Fig. 2d). Nevertheless, the overall trend of the measure is not affected.

B. *Training Phase*

This phase consists of a virtual reality game designed to train and measure the patient's performance, and assess and promote his/her recovery over time. Moreover, this gives us the opportunity to extract information on more aspects of performance, and over a longer period of time than the evaluation phase (10 minutes), allowing us to further validate the evaluation phase.

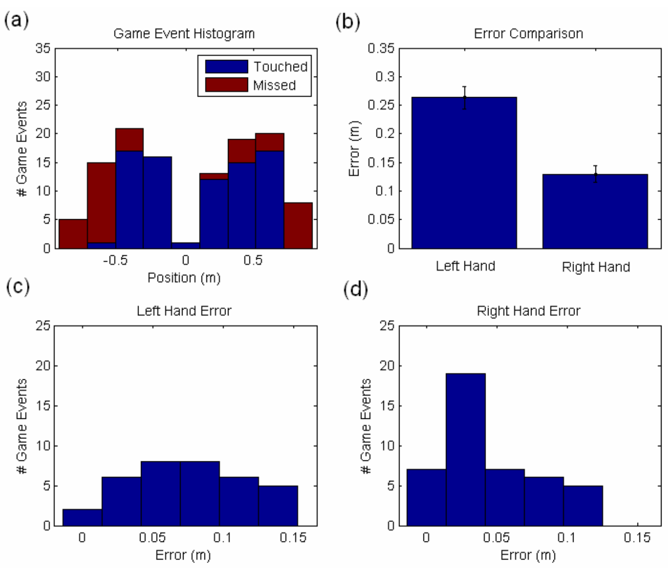

Fig. 3. Game performance analysis of patient 2. (a) Histogram of game events. (b) Error in sphere interception for both arms. The bar denotes the median error, and the error bar the standard deviation. (c) Sphere interception error histogram of the left arm (paretic). (d) Sphere interception error histogram of the right arm.

Within the game we can continuously monitor the coordinates of the virtual arms and related event data. This can be used to the advantage of single patients. We illustrate the analysis of these data with Patient 2 (Fig. 3). Overall game performance is illustrated by a histogram of game events, which represents the number of occurrences of spheres in a certain position on the screen and the corresponding related event, i.e. touched or missed (Fig. 3a). It can be seen that most of the intercepts were performed with the right hand and that many balls are missed at the left hand side (the paretic one), especially closer to the edge. This shows the shorter reaching distance of the paretic arm. Moreover, with our system we can also measure the precision of the intercepts, i.e. how close the hand was to the sphere when touched (Fig. 3b). In the case of Patient 2, we see that the error obtained with the paretic arm duplicates the one of the healthy arm. The imprecision of the motor actions of the paretic arm is shown by a smoother and broader error histogram (Fig. 3*c,d*).

In addition to this analysis we computed again the reaching distance, but using the 10 minutes of data provided by the game. We did not observe significant differences when compared with the physical and virtual evaluation tasks, showing a 9.4% asymmetry (3.9 cm) between the reaching distances of the paretic and non-paretic arms (Kolmogorov-Smirnoff test, $p > 0.3$).

IV. DISCUSSION AND CONCLUSION

Here we presented RGS, a VR based Rehabilitation Gaming System designed for the evaluation and rehabilitation of motor deficits following stroke. Besides developing an automated environment for neurorehabilitation our system is based on the hypothesis that motor execution combined with visual feedback, can trigger the mirror neuron system, and use it as a pathway to promote cortical reorganization. Indeed, it has been observed that action observation seem to have a positive impact on recovery following stroke [22].

Directed towards the needs of the patients, the RGS allows the creation of personalized training scenarios. One requirement for this to happen is to have accurate information on the patients' deficits. Therefore, we have included an evaluation phase in the RGS to have an automatic quantification of the movements of the patient. On the basis of these measures, the parameters of the VR rehabilitation task will be automatically set. However, there are a number of properties of our VR system, such as the Human Computer Interface, the first person view, the realism of the movements, etc, that have to be analyzed in order to understand the limits of the equivalence between real and VR tasks.

To asses these factors, our system was tested by 6 naive stroke patients. The patients were asked to perform an identical evaluation task in both real and VR. The measures extracted from both cases were consistent for all the tested subjects. This points out the equivalence of these real and VR tasks, the evaluation capabilities of our VR system, and the user acceptance of the interface and the system itself. Moreover, the system provided measures of reaching distance and velocity of movement that allowed quantification of the motor deficits of the patients.

In a later phase, the subjects were exposed to a new rehabilitation scenario based on a simple VR game. During the 10 minutes game, a more precise quantification on the patients' performance was obtained, including score, motor action precision, error distribution, etc. This performance measures can be used both for monitoring of the evolution of the patient across sessions, and for providing a biofeedback on the performance of the task.

We believe that our system includes several properties that make it a suitable tool for rehabilitation. Besides the automatic measures and specific training scenarios, the system is versatile and can be easily changed to suit different clinical situations. For instance, we can develop a similar scenario for lower limb rehabilitation by using the legs of the rendered avatar.

To evaluate the efficacy of our system and rehabilitation paradigm, we will soon start a study with patients in the acute phase of stroke, with controls, that will use the system in a regular basis during several weeks.

We envisage the system to include a physiological non-invasive measure system to assess engagement, excitement and stress, and eventually to modify the game parameters accordingly.

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