

Combining virtual reality and a myo-electric limb orthosis to restore active movement after stroke: a pilot study

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ABSTRACT

We introduce a novel rehabilitation technology for upper limb rehabilitation after stroke that combines a virtual reality training paradigm with a myo-electric robotic limb orthosis. Our rehabilitation system is based on clinical guidelines and is designed to recruit specific motor networks to promote neuronal reorganization. The main hypothesis is that the restoration of active movement facilitates the full engagement of motor control networks during motor training. By using a robotic limb orthosis, we are able to restore active arm movement in severely affected stroke patients. In a pilot study, we have successfully deployed and evaluated our system with 3 chronic stroke patients by means of behavioral data and self-report questionnaires. The results show that our system is able to restore up to 60% of the active movement capacity of patients. Further, we show that we can assess the specific contribution of the biceps/triceps movement of the paretic arm to the virtual reality bilateral training task. Questionnaire data show enjoyment and acceptance of the proposed rehabilitation system and its VR training task.

1. INTRODUCTION

Currently, stroke is one of the main causes of adult disability, and by 2030 it is expected to be one of the main contributors to the burden of disease worldwide (WHO 2008). An important goal in the management of stroke patients, in particular in patients with spasticity, involves restoration of normal limb position and ease of passive and active movement execution with the aim of improving functional outcomes such as the ability to carry out activities of daily living (Esquenazi 2004). This is a very demanding task for trained therapists. This is especially problematic in patients with low level of motor control and yet aggravated in the presence of spasticity. In fact, 85% of stroke survivors will present a motor deficit contralateral to the location of the brain lesion (Lai, Studenski et al. 2002). Additionally, 20–40% will also suffer of increased muscle tone or spasticity, what will further limit their level of independence in the activities of daily living (Watkins, Leathley et al. 2002; Sommerfeld, Eek et al. 2004). The large economical and psychological impacts of stroke on our society, in particular on relatives and public health systems, make it necessary to find alternative and novel approaches to address these issues.

Nowadays, it is well understood that recovery after stroke depends on brain mechanisms that allow undamaged brain areas such as contralateral or secondary networks to take over the functions of the damaged areas (Sabatini, Toni et al. 1994; Seitz, Butefisch et al. 2004; Dobkin 2008). In the chronic stage of stroke, neuronal plasticity is the main contributor to true recovery, being dependent on the size, severity, and location of the lesion (Nudo 2007; Murphy and Corbett 2009). Therefore, modern rehabilitation approaches should aim at providing an effective way of driving cortical plasticity and recruiting alternative motor areas to achieve functional brain reorganization, while being accessible to the widest range of patients, in particular to those with worse prognostic. During the intent to perform a motor action, the cortical areas devoted to motor control generate particular activity patterns – reflecting the synchronization and desynchronization of neural activity – known as Sensory Motor Rhythms (SMR) (see Hatsopoulos (2009) for a review). These activity patterns encode motor control signals that can still reach the paretic arm, as long as there are remaining cortico-spinal tracks after the stroke (Butefisch, Kleiser et al. 2006). Control commands effectively

transmitted to the limbs can be assessed by measuring electric potentials at the muscles (electromyogram, EMG). Depending on the brain lesion, the amount of motor control, and therefore of active movement, is compromised. To overcome this limitation, we propose a hybrid Virtual Reality (VR) and robotic approach for the restoration of correct limb pose and active movement. The objective of our hybrid system is to restore motor control of the upper limbs when active movement is compromised but weak EMG responses are still present. Hence, our technology can enable motor impaired patients to exercise movement even when active movement is severely compromised. The restoration of active movement may play a crucial role in mobilizing cortical plasticity, and therefore in accelerating recovery after stroke. First, although passive movement exercising is able to engage motor networks by means of proprio-receptive feedback (Carel, Loubinoux et al. 2000), it has been shown not to be the most effective way of engaging overt execution motor areas (Szameitat, Shen et al. 2012). Second, the activation of motor related networks does not only depend on the action intent, but also on the type of actions and their completion. It has been shown that both the observation and performance of meaningful goal oriented actions can engage additional networks such as the Mirror Neuron System (MNS), which is also known as the action recognition system (Gallese, Fadiga et al. 1996; Kohler, Keysers et al. 2002; Keysers, Kohler et al. 2003). The discovery of the MNS has allowed the emergence of novel stroke rehabilitation approaches based on clear neuroscientific hypothesis on brain recovery mechanisms (Altschuler, Wisdom et al. 1999; Ertelt, Small et al. 2007; Merians, Tunik et al. 2009; Rizzolatti, Fabbri-Destro et al. 2009; Michielsen, Selles et al. 2011). In this project, we propose restoration of active movement as a crucial step to fully engage both the motor control networks and the MNS. Therefore, by restoring active movement and engaging patients in a physical training with meaningful goal oriented actions, our hybrid system is designed to facilitate true recovery by means of cortical plasticity.

Previous myo-electric driven robotic interventions (Hu, Tong et al. 2009) have been shown to lead to improved Fugl-Meyer scores of the upper extremities (Fugl-Meyer, Jaasko et al. 1975) and reduced spasticity as assessed by the modified Ashworth score (Bohannon and Smith 1987). Many control techniques have been explored for myo-electric driven movement assistance such as Fuzzy controllers (Kiguchi, Tanaka et al. 2004) or compliant systems (Tsagarakis and Caldwell 2003; Andreasen, Alien et al. 2005). In this project, we use a unique wearable and portable orthosis with integrated myo-electric measurement capabilities that restores correct limb position (mpower1000, Myomo Inc., Boston, USA). Further, the combination of the myo-electric orthosis approach with a VR training paradigm is appropriate because of the inherent properties of VR systems for motor rehabilitation. VR approaches allow for a combination of features including: low cost; personalization of training; unsupervised training; goal-oriented actions; adaptability to a broad range of patients; quantifiable outcome measures; extended feedback; and motivation thanks to the use of game elements (see Lucca (2009) for a detailed review). Our VR training environment builds on previous work (Bermúdez i Badia and Cameirão 2012) and on training principles that we have shown to accelerate recovery in the acute phase of stroke (Cameirão, Bermúdez i Badia et al. 2011). Thus, our hybrid system exploits state-of-the-art information and communication technologies, a myo-electric robotic approach, and neuroscience based rationale to provide a novel personalized rehabilitation training system that addresses the physical sequels and social impact of stroke. The approach presented here puts special emphasis on patients without or with minimal active movement capabilities and those with spasticity, enabling them to train active movement (Figure 1).

2. METHODS

In our approach, we capitalize on the use VR because it is a particularly enabling technology that can support requirements for an effective training. VR allows creating fully controlled environments that define training tasks specifically designed to target the individual needs of patients. Additionally, intensive movement training can be supported through motivating tasks that use augmented feedback and reward (see Lucca (2009) for review). Besides, our VR based rehabilitation system has been integrated in a game like interaction, capitalizing in motivational factors that are essential for recovery (Maclean, Pound et al. 2000). In addition, VR not only allows for the individualization of training and monitoring by physicians, but also enables patients to play a more active role in their rehabilitation process and be able to self-monitor their own improvements. Nevertheless, the novelty of our approach is the combination of an online adaptation of the level of assistance provided by a robotic limb orthosis with EMG measurement capability during VR training (Figure 1). This technology allows us to restore active movement, compensate for fatigue, and optimize training duration, intensity, repetition, etc.

2.1 Limb Orthosis

The mpower 1000 robotic device (Myomo Inc, Boston, USA) is a portable limb orthosis that is controlled through EMG signals that are measured by an onboard data sampler. 2 EMG channels and 1 actuated joint

are used to restore active movement based on biceps/triceps EMG activation or relaxation (Figure 1, 2–3). The mpower assists its user in the completion of arm movements by means of an embedded electric motor that is activated on the detection of biceps and/or triceps EMG activity. The EMG signals are compared to the baseline EMG activity level of the user and an assistive force – either arm extension or contraction – is executed when EMG changes – muscle contraction or relaxation – are detected. This approach makes therapy accessible to patients with no or weak active moment, but residual EMG activation, as well as to spastic patients with increased muscle tone – with involuntary and permanent EMG activation –, correcting limb position and allowing them to train active relaxation to gain movement control. The mpower connects to the virtual environment via a virtual serial port over Bluetooth, allowing its remote control from within the training environment. This wireless connection provides information on the orthosis settings, arm position, and EMG readings, as well as it allows to remotely adjust the level of motor assistance during training from 0 to 100%.

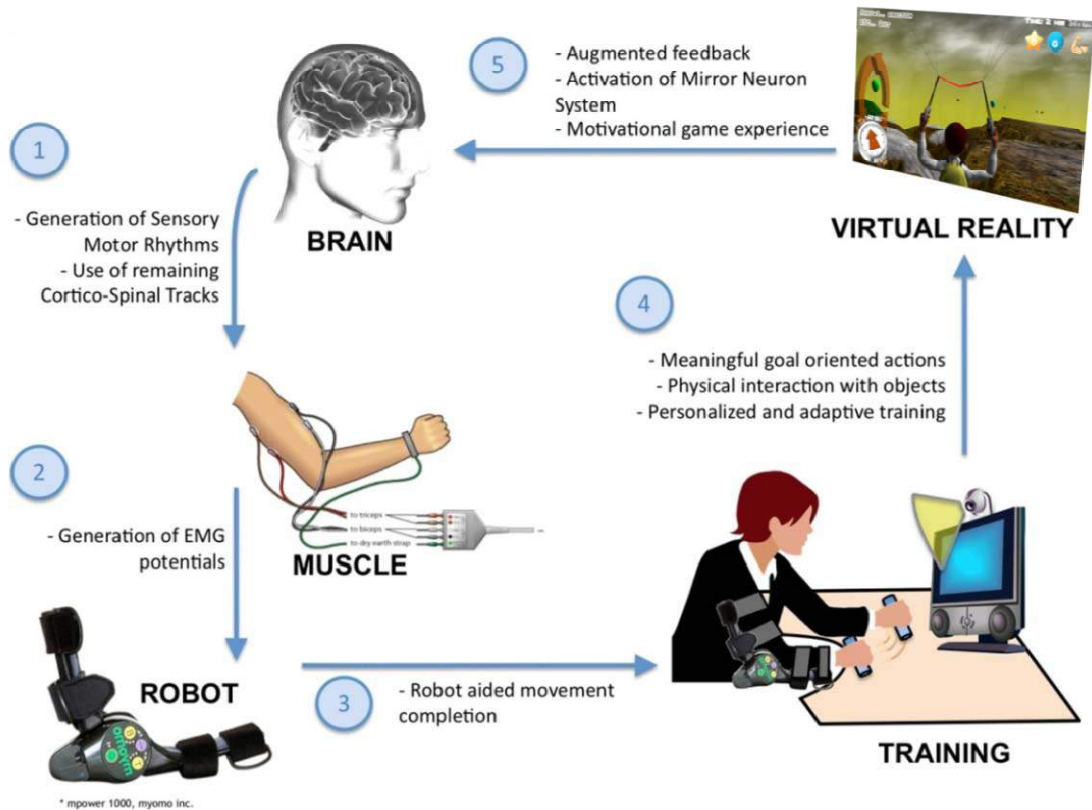


Figure 1. Diagram of the proposed virtual reality and robotic limb orthosis training paradigm showing the role of each technological component (numbered from 1 to 5).

2.2 Tracking

The tracking technology used in this project is the ARToolKit (ARToolworks, Inc., Seattle, USA). The ARToolKit is an augmented reality software toolkit that enables tracking the position (x, y, z) and orientation in space of predefined unique markers by using a webcam as input device. In our system, the ARToolKit was used to track two handles (7 cm diameter × 12 cm high) with unique visual markers. Consequently, users of the proposed system were instructed to grasp and move these handles around a table top in order to interact with the virtual environment (Figure 2, right panel). Thus, an overhead webcam is used to track the position and orientation of the markers, providing the virtual environment with precise information about the position and movement trajectories of the hands of the users during the training sessions.

2.3 Virtual Environment

The virtual environment and training task are based on the Neurorehabilitation Training Toolkit (NNT) (Bermúdez i Badia and Cameirão 2012). The NTT is a virtual training environment developed with the open source game engine Panda3D (www.panda.org) that was designed following neuroscientific and therapeutic guidelines for stroke rehabilitation, such as relevance of training to ADLs, neuronal mechanisms of recovery,

narrative, personalization or individualization, augmented feedback, and engagement (see (Bermúdez i Badia and Cameirão 2012) for a detailed description of the training rationale). In essence, the training task is a game experience consisting of a bimanual coordination task that uses upper limb motor actions as control signals. Bimanual upper limb training tasks have been shown to enhance excitability of cortical motor networks and lead to improved functional outcomes (Stoykov and Stinear ; Byblow, Stinear et al. 2012). The bimanual motor actions are mapped onto the actions of an avatar that controls a glider in the virtual environment, i.e., the physical arm movements of the user are used to control the steering direction of a virtual glider (Figure 2, left panel). Feedback on performance and on-screen information is extensively used to inform the user on the immediate game goals and motor actions to be performed, and as reward. The goal of the game is to gather the largest number possible of collectable items in the virtual environment. Two types of collectable objects are present - easy (balloons) and difficult (stars) – that are accumulated to an on-screen score to provide feedback on performance. In addition, the amount of arm movement measured by the limb orthosis is also provided as a visual score. All tracking and training data are logged as a text file for later analysis.

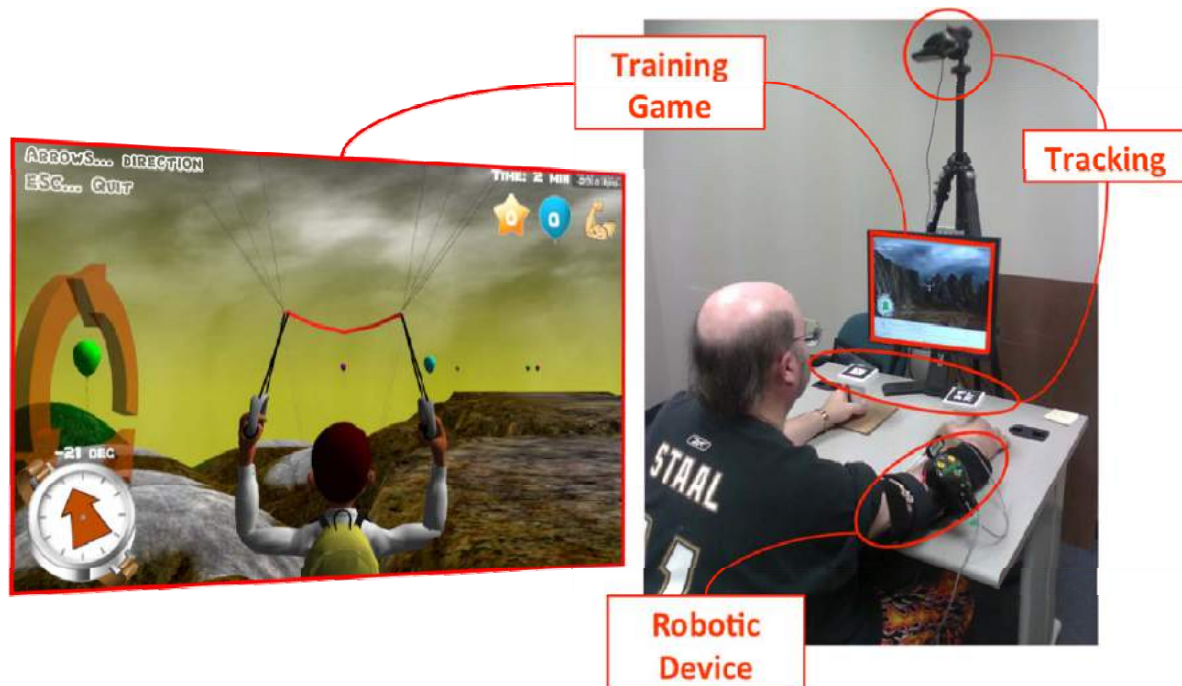


Figure 2. *Prototype of the myo-electric based interactive system for rehabilitation. Left panel: An adaptive training in the form of a game defines the training parameters for a bimanual coordination motor task. The training offers augmented feedback on performance, sustains motivation, and automatically modifies the level of motor assistance offered by the limb orthosis. Right panel: The different components of the system (robotic device, tracking setup, and training game task) while being used by a stroke patient.*

2.4 Pilot Study

The objective of this study was to assess the acceptance and usability of the system, and the impact of the level of assistance of the limb orthosis on task performance and overall arm movement. We evaluated the system with 3 chronic stroke survivors (47–63 years old; > 6 months post-stroke) in a laboratory setting at the University of Pittsburgh (Table 1). All subjects had a very low level of control of their paretic arm but were able to generate voluntary biceps EMG activation and hence drive the robotic orthosis. All subjects used the robotic orthosis in the biceps mode – only controlled by biceps EMG activity – and were asked to use the system for a single training session of approximately 20 minutes. During the training session, the level of assistance of the orthosis was randomly changed between 40 and 90% every time a virtual item was collected. After the training session, subjects were asked to report on their experience by answering a questionnaire about enjoyment, engagement and usability rated using a Likert scale from 1 to 5. All subjects gave their informed consent to participate in this study.

Table 1. *Patients' demographics.*

Age:	47	63	50
Sex:	Male	Male	Male
Stroke type and location:	Hemorrhagic left	Ischemic left	Ischemic right
Handedness:	Right	Right	Right

3. RESULTS

This is a unique system that not only engages users in a game like training experience, but also makes use of a myo-electric capable orthosis to restore active movement. However, the effect of the orthosis assistance in movement restoration and the optimal way of integrating it in an interactive training are difficult to assess. For these reasons, we performed a number of experiments in which we exposed stroke patients to a training session of the combined virtual reality and myo-electric limb orthosis paradigm. Training data were recorded synchronously with tracking data as well as limb orthosis settings. The analysis of the combined data revealed a linear effect of the level of assistance of the limb orthosis in the amount of biceps movement during training as measured by the system in deg/s (Figure 3, left panel). The quantification of this linear relationship will enable us to integrate the virtual reality training and orthosis using statistical techniques to automatically adjust the level of assistance depending on the characteristics of each user, such as for instance the level of motor control, fatigue, or force.

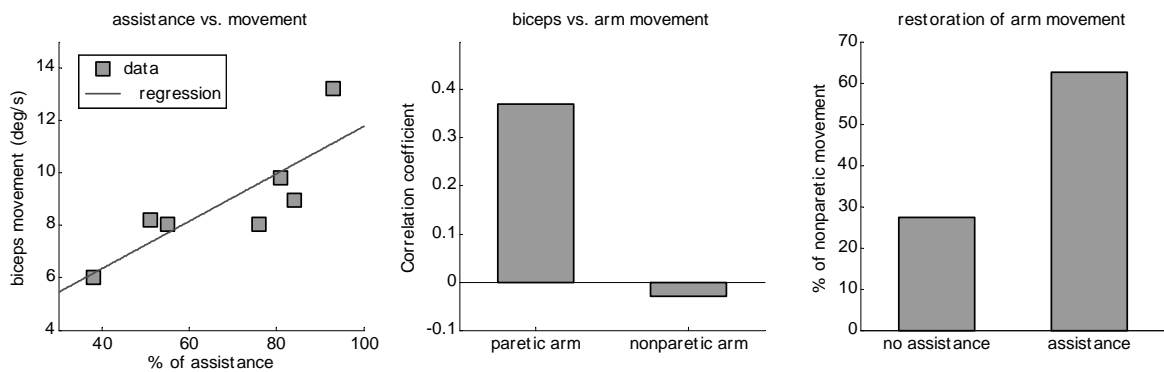


Figure 3. *Effect of the myo-electric limb orthosis during the virtual training task. Left panel: Effect of the level of assistance of the limb orthosis on the amount of biceps movement. Middle panel: Quantification of the contribution of the biceps movement to the overall arm movement, computed as the correlation value of the biceps and arm movements during training. Right panel: Restoration of arm movement. % of arm movement of the paretic arm as compared to the non-paretic arm in presence and absence of robotic assistance. Data from patient 3.*

The integrated system allows us to simultaneously measure both the movement of the arm end effector – tracked by a marker on the handle (Figure 2, right panel) – and the specific movement of the biceps as measured by the orthosis. These data are of extreme value since the particular contribution of the biceps/triceps movement to the overall movement of the arm can now be quantified (Figure 3, middle panel). In our experiment, we could assess that the movement of the limb orthosis showed a low correlation coefficient with that of the end effector (.37) that reveals a low contribution of the elbow joint – and therefore a low biceps/triceps contribution – to the bimanual control task defined in our training. This indicates that possible compensatory movements were used during training. Further, our combined limb orthosis and virtual reality training system allows us to compare differences between paretic and non-paretic arms. This enables monitoring over time the evolution of the patient using the non-paretic arm as reference. Of particular interest is the comparison of the movement capability of the paretic and non-paretic arms when the orthosis assistance is enabled. During our pilot experiment, we have quantified the impact of the active orthosis on the overall movement of the arm in patient 3 and were able to restore the paretic arm movement to about 60% of the non-paretic arm. These results are yet more remarkable when compared to the without assistance condition, in which the overall movement of the paretic arm is below 30% of the non-paretic one (Figure 3, right panel).

Questionnaire data revealed a good acceptance of the system, the most positive aspects being: fun (4.3), entertaining (4), and willingness to use it as regular motor training (4.6). Subjects reported that the system was easy to understand (3.6) but also considered it an uneasy training task (1.6).

4. CONCLUSIONS

Here we presented a novel hybrid system that integrates a VR training and a myo-electric limb orthosis. This system is an extension of the Neurorehabilitation Training Toolkit (NNT) that aims at restoring arm movement in severely affected stroke patients by integrating a portable robotic limb orthosis. In this first pilot experiment, we have successfully deployed and tested our bio-hybrid VR interactive rehabilitation system with 3 chronic stroke patients. The system was evaluated by means of quantitative behavioral data acquired by the system itself and self-report questionnaires. Initial results show that our system is capable of online adjusting the assistance level provided by the orthosis, and that the orthosis assistance has a linear effect on the overall arm movement, being able to restore up to 60% of the active movement capability. Further, our technology allows to separately assess the contribution of the biceps/triceps movement to the overall bilateral training task. This enables to objectively assess and monitor the active contribution of the elbow joint to the movement as well as that of the compensatory actions. Questionnaire data reveal a high level of acceptance of the system and its VR training task. We are currently developing an algorithm to automatically adjust the level of assistance to maximize the outcome of training. In the future, we will assess the long-term impact of these technologies in a randomized controlled trial in the inpatient rehabilitation unit (RHB) of the Hospital of Funchal.

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