Case Report

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

Abstract: We introduce a novel rehabilitation technology for upper limb rehabilitation after stroke that combines a virtual reality (VR) training paradigm with a myoelectric 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 evaluation, we have successfully deployed and assessed our system with three 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 capability of patients. Further, we show that we can assess the specific contribution of the biceps/triceps movement of the paretic arm in a VR bilateral training task. Questionnaire data show enjoyment and acceptance of the developed rehabilitation system and its VR training task.

Keywords: electromyogram (EMG); motor rehabilitation; personalization; robotic orthosis; stroke; virtual reality (VR).

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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 [1]. An important goal in the management of stroke patients, and 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 [2]. This is a very demanding task for trained therapists and 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 [3]. Additionally, 20%–40% will also suffer from increased muscle tone or spasticity, which will further limit their level of independence in the activities of daily living [4, 5]. 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 [6–8]. 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 [9, 10]. 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 the poorest prognostic. During the intent to perform a motor action, cortical areas devoted to motor control generate particular activity patterns – reflecting the synchronization and desynchronization of neural activity – known as Sensory Motor Rhythms [11]. These activity patterns encode motor control signals that can reach the paretic arm as long as there are remaining cortico-spinal tracts after stroke [12]. Control commands effectively transmitted to the limbs can be assessed by measuring electric potentials at the muscles (electromyogram, EMG). Depending on the brain

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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. Our technology is able to detect residual EMG activation and, by means of a robotic orthosis, enable motor-impaired patients to exercise movement even when active movement is severely compromised. There are data that suggest that 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 proprioceptive feedback [13], it has been shown not to be the most effective way of engaging overt execution motor areas [14]. 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 [15–17]. The discovery of the MNS has allowed the emergence of novel stroke rehabilitation approaches based on clear neuroscientific hypotheses on brain recovery mechanisms [18–22]. 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 physical training with meaningful goal-oriented actions, our hybrid VR robotic system is designed to facilitate true recovery by means of cortical plasticity.

Previous myoelectric driven robotic interventions [23] have been shown to lead to improved Fugl-Meyer scores of the upper extremities [24] and reduced spasticity as assessed by the modified Ashworth score [25]. Many control techniques have been explored for myoelectric driven movement assistance such as fuzzy controllers [26] or compliant systems [27, 28]. In this project, we use a unique wearable and portable orthosis with integrated myoelectric measurement capabilities that restore correct limb position (mPower1000, Myomo Inc., Cambridge, MA, USA). Further, we believe the combination of the myoelectric orthosis approach with a VR training paradigm is appropriate because of the inherent properties of VR systems for motor rehabilitation. The 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 [29]. Our VR training environment builds on previous work [30, 31], on training principles that we have shown to be effective in the chronic phase of stroke [32], and on accelerating recovery in the acute phase of stroke [33]. Thus, our hybrid system exploits a state-of-the-art information and communication technologies, a myoelectric robotic approach, and a 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 (see Figure 1).

Methods

In our approach, we take advantage of the use of VR because it 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 [29]. VR allows not only for the individualization of training and monitoring by physicians, but also enables patients to play a more active role in their rehabilitation process and self-monitor their own improvements. Besides, our VR-based rehabilitation system has been integrated into a game-like interaction, capitalizing in motivational factors that are essential for recovery [34]. Nevertheless, the main novelty of our approach is the combination of an online adaptation during VR training of the level of assistance provided by a robotic limb orthosis with EMG measurement capability (Figure 1). This technology is designed to restore active movement, compensate for fatigue, and optimize training duration, intensity and repetition.

Limb orthosis

The mPower 1000 robotic device (Myomo Inc., Cambridge, MA, USA) is a portable limb orthosis that is controlled through EMG signals that are measured by an on-board data sampler. Two EMG channels and one actuated joint are used to restore active movement based on biceps/triceps EMG activation or relaxation (see Figure 1, points 2 and 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 is executed (either arm extension or contraction) when EMG changes (muscle contraction or relaxation) are detected. This approach makes therapy accessible to patients with residual EMG activation or involuntary and permanent EMG activation, correcting limb position and allowing them to train active contraction/relaxation to gain movement control. The mPower connects to the virtual environment through 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

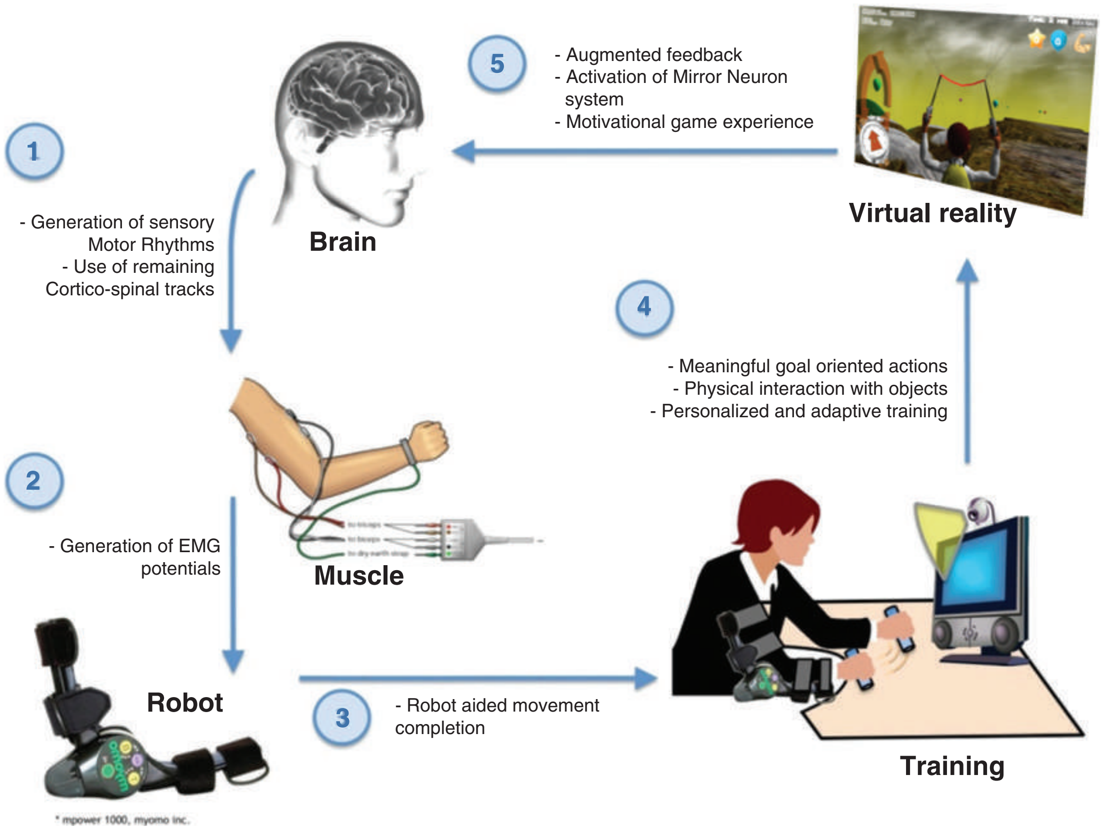

Figure 1 Diagram of the developed virtual reality and robotic limb orthosis training paradigm showing the role of each technological component (numbered from 1 to 5).

position, and EMG readings, and it allows remote adjustment of the level of motor assistance during training from 0% to 100%.

Tracking

The tracking technology used in this project is the ARToolKit (ARToolworks, Inc., Seattle, WA, 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 an input device. In our system, the ARToolKit was used to track two handles (7 cm diameter×12 cm high) tagged with unique visual markers. 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 user's hands during training. Users of the system are instructed to grasp and move these handles around a table top in order to interact with the virtual environment (see Figure 2, right panel).

Virtual environment

The virtual environment and training task are based on the Neurorehabilitation Training Toolkit (NTT), which is freely accessible at http://neurorehabilitation.m-iti.org/NTT. 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 [30] for a detailed description of the training rational). 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 was selected because it has been shown to enhance excitability of cortical motor networks and lead to improved functional outcomes [35, 36]. 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 (see 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, as well as a reward mechanism is used. The goal of the game is to gather the largest possible number 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.

Pilot evaluation

The objective of this pilot study was to assess the acceptance and usability of the system, as well as the impact of the level of assistance of the limb orthosis on task performance and overall arm movement.

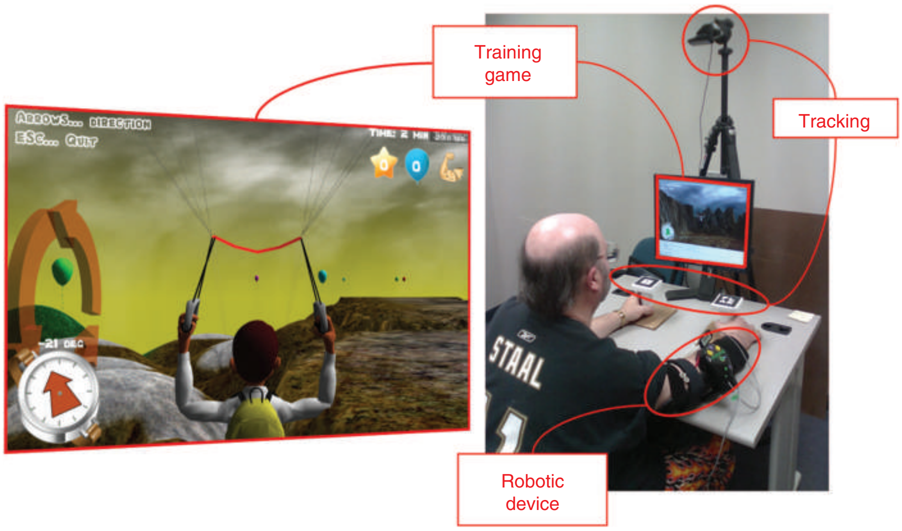

Figure 2 Prototype of the myoelectric-based interactive system for rehabilitation.
Left panel: an adaptive training in the form of a game defines the training parameters for a bimanual coordination motor task. The training offers augmented feedback on performance, sustains motivation, and automatically 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.

We evaluated the system with 3 chronic stroke survivors (47–63 years old; >6 months poststroke) in a laboratory setting at the University of Pittsburgh (see Table 1). All subjects had a very low level of control of their paretic arm but were able to generate voluntary EMG activation, and hence able to drive the robotic orthosis. All subjects used the robotic orthosis in biceps mode (only controlled by biceps EMG activity) and used the system for a single training session of approximately 20 min. 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.

Results

This is a unique system that not only engages users in a game-like VR training experience, but also makes use of a myoelectric-capable orthosis to restore active movement. However, the effectiveness of the orthosis assistance in movement restoration and how to optimally integrate it in an interactive training experience need to be studied before any longitudinal deployment. For these reasons, we performed a number of experiments in which we exposed three stroke survivors to single training sessions of the combined VR and myoelectric limb orthosis paradigm. The integrated system allows us to simultaneously measure both the movement of the arm end effector (tracked by a marker on the handle) and the specific movement of the biceps as measured by the orthosis (see Figure 2, right panel). Training data were recorded synchronously with tracking data as well as the limb orthosis settings.

Table 1 Patients' demographics.

Age, years	47	63	50
Sex	Male	Male	Male
Stroke type	Hemorrhagic	Ischemic	Ischemic
Stroke location	Left	Left	Right
Handedness	Right	Right	Right

The analysis of the multimodal data revealed a linear effect of the level of assistance of the limb orthosis with the amount of biceps movement as measured by the system in deg/s (see Figure 3, left panel). The existence of this linear relationship between the level of assistance and movement execution is an important feature of the system because it will enable us to integrate, into the VR training environment itself, straight forward statistical modeling techniques to automatically adjust the level of assistance depending on the characteristics of each user. This will allow us to improve the level of motor control or compensate for fatigue or loss of force during training. Moreover, the system provides us with additional valuable data, allowing us to quantify the particular contribution of the biceps/triceps movement to overall movement (Figure 3, middle panel). In our experiment we could assess that the movement of the elbow joint (measured by the limb

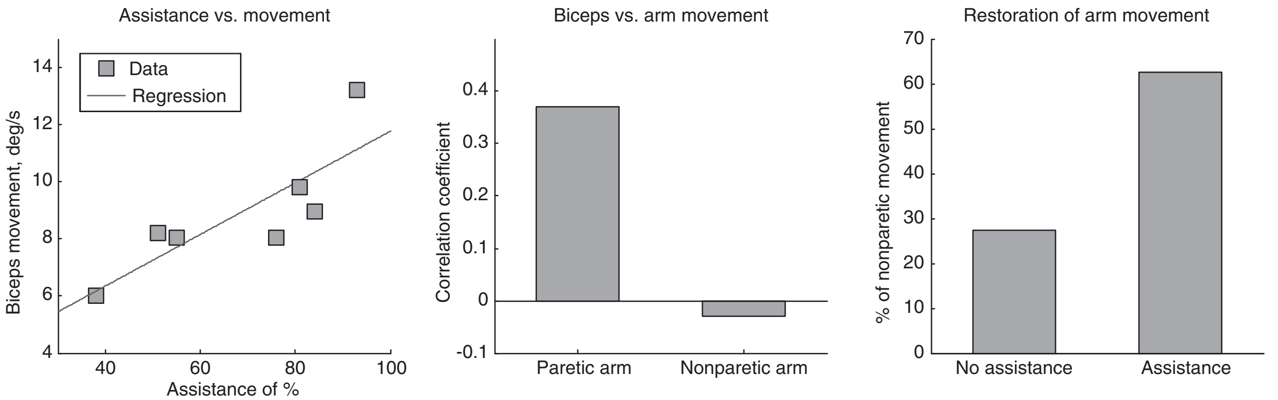

Figure 3 Effect of the myoelectric limb orthosis during the virtual training task.
Left panel: effect of the level of assistance of the limb orthosis on the amount of biceps movement. Middle panel: quantification of the contribution of the biceps movement to the overall arm movement, computed as the correlation value of the biceps and arm movements during training. Right panel: restoration of arm movement. Percentage of arm movement of the paretic arm as compared to the nonparetic arm in presence and absence of robotic assistance. Example data from patient 3.

orthosis) showed a low correlation coefficient with that of the end effector (r=0.37). This 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 correlation indicates that possible compensatory strategies were used during training. Further, our VR training system allows us to assess and compare differences between paretic and nonparetic arms. This enables us to monitor recovery over time using the nonparetic arm as reference. Of particular interest is the comparison of movement capability of the paretic and nonparetic 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 and we verified that the myoelectric orthosis was able to restore the paretic arm movement to about 60% of the nonparetic arm in patient 3. These results are yet more remarkable when compared to the absence of assistance, in which case the overall movement of the paretic arm was below 30% of that of the nonparetic one (see 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 as a challenging training task [1.6].

Discussion

Here we presented a novel hybrid system that integrates VR training and a myoelectric limb orthosis. This system is an extension of the NTT that aims at restoring arm movement in severely affected stroke patients by integrating an EMG-driven portable robotic limb orthosis. This system is specifically designed to be used by patients without or with minimal active movement capabilities, i.e., those with the poorest prognostic, enabling them to train active movement. The robotic orthosis is combined with a gaming training environment that is based on clinical guidelines and designed to recruit the MNS and to promote neuronal reorganization. By using a robotic limb orthosis, we are able to restore active arm movement in severely affected stroke patients. We hypothesize that the restoration of active movement facilitates the full engagement of motor control networks during motor training.

In this first pilot experiment, we have successfully deployed and tested our biohybrid VR-interactive rehabilitation system with three 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 level of assistance has a linear effect on the overall arm movement. We showed that the myoelectric orthosis is able to restore up to 60% of the active movement capability. Although encouraging, these results require further investigation to better understand how the level of assistance relates to improvements in motor control and also to the overall recovery process of the paretic arm in a longitudinal intervention. Another of the strengths of the presented approach is that our technology allows assessing the individual contribution of the biceps/triceps movement to the overall bilateral training task. We have shown that we can objectively assess and monitor the active contribution of the elbow joint to overall arm movement as well as detect and quantify the presence of compensatory strategies. Questionnaire data reveal a high level of acceptance of the system and its VR training task, although it was found to be challenging. This is an expectable result because in this experimental protocol patients with no or very low active movement were exposed to varying levels of orthosis assistance, including low levels of assistance. This effect will be minimized in the future by using an algorithmic solution to automatically adjust the level of assistance to each patient, thus maximizing the outcome of training. The long-term impact of these technologies will be assessed in a randomized controlled trial in the inpatient rehabilitation unit of the Hospital of Funchal.

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