Virtual Reality and Hybrid Technology for Neurorehabilitations

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Abstract. Disabilities that follow Cerebrovascular accidents (CVA) and spinal cord injuries (SCI) severely impair motor functions and thereby prevent the affected individuals from full and autonomous participation in daily activities. Several studies have shown that virtual reality (VR) is a technology suitable for rehabilitation therapy due to its inherent ability of simulating real–life tasks while improving patient motivation. In this paper we present our research focuses on the development of a new rehabilitation therapy based on a VR system combined with wearable neurorobotics (NR), motor-neuroprosthetics (MNP) and brain neuro-machine interface (BNMI). This solution, based on hybrid technology aims to overcome the major limitations of the current available therapies. This paper is focused on the Virtual Reality concepts used for the development of the HYPER rehabilitation system.

Keywords: virtual reality, motor-neuroprosthetics, brain neuro-machine interface, neuro-robotics, cerebrovascular accidents, spinal cord injury.

1 Introduction

Cerebrovascular accidents (CVA) and spinal cord injuries (SCI) are the most common causes of paralysis and paresis with reported prevalence of 12,000 cases per million and 800 cases per million, respectively. Disabilities that follow CVA or SCI severely impair motor functions (e.g., standing, walking, reaching and grasping).

Disabilities that follow CVA and SCI are:

1. Tetraplegia refers to the loss of motor and/or sensory function in the cervical segments of the spinal cord (SCI). It results in an impaired function of the arms, trunk, legs and pelvic organs.

2. Paraplegia refers to the loss of motor and/or sensory function in thoracic, lumbar or sacral segments (SCI). Consequently, the arm function is spared, but the trunk, legs and pelvic organs can be affected.

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3. Hemiplegia is paralysis of the side of the body occurring after a CVA. In many cases it comprises weakness of the leg on the affected side, where the drop-foot syndrome often prevents walking.

The main goal of neurorehabilitation is to favor the relearning process of the Central Nervous System (CNS) in the execution of coordinated movements.

The outcome of the neurorehabilitation therapy depends on two main issues [1, 2]:

- the quality and amount of physical activity performed by the patient;
- the active participation of the patient in the rehabilitation process (in other words: motivation).

Physical therapy aims to strengthen the active muscles in several parts of the body. Occupational therapy is specialized in training individuals who have lost muscle strength or coordination to relearn the tasks of daily living, such as eating, dressing, and grooming.

2 Virtual Reality and Rehabilitation

VR environments can provide realistic training for the patient in different scenarios and phases of the rehabilitation. By using VR in conjunction with Human Computer Interfaces (HCI) the training of daily life activities can be much improved in terms of time and quality. This approach permits a realistic and ergonomic training in a safe, interactive and immersive environment.

Examples of interfaces able to interact with VR are mice, joystick, haptic interfaces with force feedback and motion tracking systems.

Repetition is crucial for the re-learning of motor functions and for the training of the cortical activity. This task has to be connected with the sensorial feedback on every single exercise.

Patient motivation is fundamental because active cooperation of the patient is needed to achieve a more functional outcome of the therapy. Motivation can be improved by assigning a serious game format to the therapy. In this way the training activity becomes more attractive and interesting [3, 4]. Moreover, VR shows another advantage: the possibility to be precisely adapted to the patient's therapy and to be specific for each rehabilitation phase. In addition, it represents a precise tool for the assessment of the therapy during each session. The (tracked/saved) data can be used by the rehabilitation specialists for monitoring and managing the therapy [5]. Several researches have shown that, during VR rehabilitation, the movements are very similar to those used in the traditional therapy. Although they appear a bit slower and less accurate, [6, 7] show that they are anyway appropriate for rehabilitation. Finally, [8] have proven good results in executing the movements trained in VR in reality.

Some of the significant studies on the application of robotics for rehabilitation purposes shall be introduced briefly. The Rutgers Arm [9] is one of the first prototypes composed of a PC, a motion tracking system and a low-friction table for the upper extremity rehabilitation. The system has been tested on a chronic stroke subject and has shown improvements in arm motor control and shoulder range of motion (Fugl-Meyer [10] test scores). The same group has developed the Rutgers Ankle for the lower extremity rehabilitation. It is a haptic/robotic platform, which works with six degrees of freedom, driving the patient's feet movements (Fig. 1, left).

Fig. 1. Successful applied examples of technologies for rehabilitation. Up: Rutgers Ankle (on the left) and Lokomat® (on the right). Down: Armeo®.

In [11], the Rutgers Ankle system has been tested. As a result, the group of patients trained with the robotic device coupled with the VR demonstrated greater changes in velocity and distance than the group trained with the robot alone.

Most of the gait rehabilitation systems currently used for therapy are based both on treadmills and body weight support.

The state-of-art in rehabilitation using virtual reality (VR) and robotics is provided by Lokomat® and Armeo® (from Hocoma) for the lower and the upper extremity, respectively (Fig. 1 center and right). These two systems are validated by the medical community and used in several rehabilitation centers [12].

3 Robotic-Based Neurorehabilitation

Rehabilitation and functional substitution of motor functions is still a very active research area. In the last decade, a number robot-assisted rehabilitation systems have been developed in order to support and improve the therapist's action by delivering intensive physical therapy and providing objective measures of the patient's performance [13, 14, 15].

There is no consensus on what are the most adequate robotic-based intervention for rehabilitation of motor disorders [16, 17]. Nevertheless, some key factors for successful robotic-assisted therapy can be identified:

1) *Active role of the patient.* Brain activity plays a fundamental role on the modulation of the neural mechanisms that generate movement [18, 19]. Passive, repetitive training is very likely to be suboptimal, as it leads to the phenomena of "learned helplessness.

2) *Motivation.* Motivation is one of the most important factors in rehabilitation and it is commonly used as a determinant of rehabilitation outcome [20], since it is strongly correlated with the degree of patient's activity. User's motivation can be achieved by means of various different types of feedback and modes of interaction, so influencing the motor re-learning process at different levels [21].

3) *Assist as needed.* In order to imitate the action of the physical therapist in supporting the movement of the limb, the new-generation of robotic systems have been provided with the so called Assist-as-needed (AAN) paradigm [22]. 4) Challenge. Contrary to the assistive techniques, which help the user to reach the task, the challenge-based robotic strategies aim at opposing to the user's intention of movement, using resistance or error-amplification strategies.

5) *Biofeedback.* Biofeedback is a crucial factor for success of the therapy as it informs about the patient's degree of activity and is a key to maintain and encourage the motivation and increasing the active participation of the patient. Currently, biofeedback rehabilitation relies mainly on a single source of information, i.e. force-based feedback. By combining other forms of feedback beside the pure force feedback, such as brain activity (EEG), muscular activity (EMG) and visual information on limb motion, a more accurate and effective outcome might be achieved [23].

6) *Bioinspiration.* Due to the close cooperation between human and robot, it is necessary to know the properties of the human motor system in order to define the design requirements of a rehabilitation device. With the help of a biological model it is possible to predict the system's behavior and optimize the robotic intervention, in terms of adaptability, functionality and energy consumption [24].

Exoskeletal Robots (ERs) are person-oriented robots, operating alongside human limbs to supplement the function of a limb or to replace it completely [25]. MNPs constitute an approach to restoring function by means of artificially controlling human muscles or muscle nerves with Functional Electrical Stimulation (FES).

The integrated application of ERs and MNPs can give appropriate tools for dealing with the above stated key aspects of robotic-based rehabilitation. The hybrid combination of physical and bio-electrical actions on human body can effectively recover the impaired human motor control mechanisms, in both rehabilitation and functional compensation scenarios. The orchestration of ERs, MNPs and latent motor capabilities involves several issues, principally related to the cognitive aspects of human-machine interaction. In a successful scenario, the control signals provided by the patient must be interpreted correctly semantically and temporally by the machine in order to provide the mechanical power and electrical stimulation required to carry out the task [26, 27, and 28].

The main challenge of cognitive human-machine interaction is the development of a multimodal system capable of deciphering user's volitional commands in a robust manner and integrating them with the ER-MNP control systems. This cognitive processes needs a deep understanding of the relation between cognition (the process comprising high level functions carried out by the human brain, including perception, comprehension, construction, planning, self-monitoring) and the motor control. Several signals of different typologies must be analyzed to convey meaningful feed-forward and feedback information. These signals are related to muscular activity (EMG), cerebral activity (EEG), visual and auditory perception, tactile and proprioceptive stimuli.

Brain and Neural to Machine Interfaces (BNMIs) has been recently proposed [29] as an effective multimodal interface to the humans' neural system. BNMIs are gaining momentum as a method to command the exoskeleton-based rehabilitation, since it might constitute new means to improve user-centered strategies for robotic-based training. BNMIs have the potential to improve controllers for movement training by demanding neural control within the involved cortical network, by relying on: (1) passive monitoring, which might assess user's motor intention; (2) information derived from the peripheral nervous system, such as reflex actions that might directly trigger muscle activity; and (3) indirect measures of neural activity (such as EMG).

4 Cerebrovascular Accidents and Spinal Cord Injury Rehabilitation Using Virtual Reality and Hybrid Technology

None of the systems described in paragraph III proposes VR in conjunction with a hybrid and wearable MNP-NR system.

The HYPER project collects different researches in neurorobotics (NR) and motor neuroprosthetics (MNP) both for rehabilitation and functional compensation of motor disorders. The project focuses its activities on new wearable NR-MNP systems that will combine biological and artificial structures in order to overcome the major limitations of the current rehabilitation solutions to Cerebrovascular Accident (CVA) and Spinal Cord Injury (SCI).

The main targets of the HYPER project (Hybrid Neuroprosthetic and Neurorobotic devices for Functional Compensation and Rehabilitation of Motor Disorders) are:

1. to speed up the rehabilitation procedures
2. to improve the outcome of the therapy using new paradigm and technology.

Those results shall be achieved by an integrated use of different means of sensing and actuation. A multimodal Brain Neural Machine Interface (BNMI) is applied to enhance the cognitive interaction and to drive a hybrid NR-MNP system.

Using a multi-channel acquisition approach, the user's outputs (EEG, EMG, kinetic and kinematic information) serve as inputs to the controller of the hybrid platform. The controller, as in the natural human control system, (re)presents a feed-forward component based on predetermined motion and biomechanical models, and a reactive controller that mimics human neuromotor mechanisms and reflexes. In addition to the limb actuation systems (NR/MNP), a virtual reality system generates visual/auditory feedback to increase the user's involvement and immersion, potentiating the cognitive interaction. Both upper and lower parts of the patient body are assisted. The main emphasis is put on restoring daily life activities.

Users' groups have been identified in order to adjust therapy and system components to the various therapy needs. Several scenarios have been developed and elaborated in detail. Each of them includes some or all the components (NP, NR, and VR). The therapy is subdivided in several states from the moment in which the injury happens until the state in which the patient is fully rehabilitated.

In the traditional rehabilitation therapy, different modes of exercises are used:

• Aerobic. Large-muscle activities (eg, walking, treadmill, stationary cycle, combined arm-leg ergometry, arm ergometry, seated stepper).
• Strength. Circuit training, weight machines, free weights, isometric exercise.
• Flexibility. Stretching.

Ranges of movements that are significant in the rehabilitation for CVA or SCI patients have been identified by medical doctors. Any of the daily life functions constitutes a combination of these defined movements.

In the specific, the upper body joints (and related movements) are:

• shoulder (flexion, extension, abduction, adduction, outward medial rotation, inward medial rotation);
• elbow (flexion, extension, pronation, supination);
• wrist (flexion, extension, abduction, adduction)

Similarly, the lower body joints (and related movements) are:

• hip (flexion, extension, abduction, adduction, medial and lateral rotation);
• knee (flexion, extension);
• ankle (plantar flexion, dorsal flexion, inversion and eversion).

For each of them, both degrees and ranges of movement have been specified in order to assess the patient's skills during the rehabilitation process and to parameterize the rehabilitation training based on VR.

During the initial period of our research, patient's movements were tracked by a motion tracking system based on radio frequency. Transmitters were positioned on each joint. This solution offers good tracking performances but it suffers from the use of many cables. Considering the patient's needs it is therefore not an optimal solution. Currently we are using Kinect to provide a marker-less tracking which offer promising preliminary results. The tracking software is based on OpenNI which is a open source library. We are testing the accuracy of such a system comparing with the data provided by the Armeo in the execution of the same arm movements.

The matrices received from the tracker are used for a real-time representation on the screen. The data referring to trajectories are stored in a database for elaboration and therapy assessments.

OpenSceneGraph is used for the 3D rendering since it is an effective open source graphics toolkit. Snapshots of simple VR scenes (reaching, moving and grasping a virtual object) are shown in Fig. 2.

Fig. 2. Up: Snapshots of simple VR scenes: reaching, moving and grasping a virtual object. Down: tracking with Kinect®

The BCI can be intended has a no-muscular communication channel able to send messages and commands from human to an external environment.

An innovative application of this type of devices is to use it in conjunction with a virtual environment for the object manipulation.

Several studies have shown that the use of BCI in the rehabilitation of patient with motor disabilities can provide different potential benefits [30]. Virtual reality can be augmented by an interpretation of the signals coming from different brain area during the execution of motor exercises.

This translation of signals is anyway a very difficult task and it depends on a series of factors (the concentration level is by far one of the most influencing of them).

The conjunction between BCI and realistic virtual reality create a good diagnostic and personalized environment in which it is possible to study the brain signals as answers to external stimuli or to assess the progress of the patient in the rehabilitation therapy.

As first step we have connected a commercial low cost BCI (Epoc® by Emotiv) with an avatar built up on our library for VR environment.

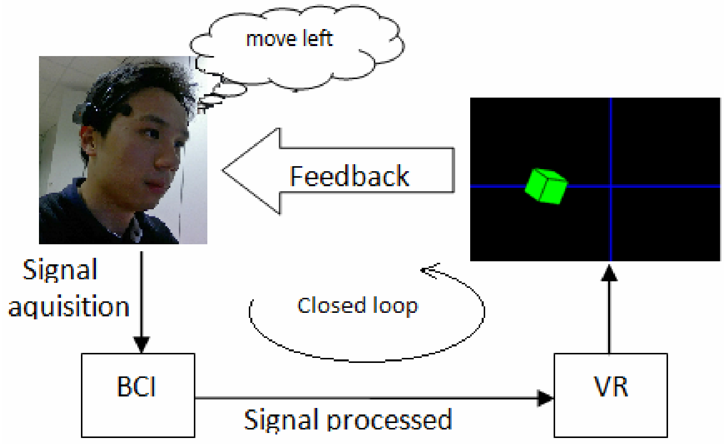

Fig. 3. Closed loop: human-machine interaction trough BCI and VR

The BCI incorporates 14 extensions of electrodes, mostly concentrated around the front of the scalp. The headset is completely wireless and consequently it allows free movements. The headset's electrodes record the resulting brain waves during the concentration, and from them on, the system recognizes that pattern as the specific function. We are using the "Emotiv" cognitive suite to analyze the basic brainwave activities in order to discern the user's conscious intent to perform distinct physical actions on a real or virtual object. It is possible to work with six directional movements (push, pull, left, right, up and down) and six rotations (clockwise, counter-clockwise, left, right, forward and backward). In addition emotional state and facial expressions are augmented the virtual scene. In the near future we will migrate from this basic BCI hardware to a more accurate and professional device ("g.BCIsys" by "G.tec") in order to provide a more precise cognitive analysis.

5 Conclusion

In this paper we have presented the overall architecture and the first development status of an advanced system that combines NR, MNP and VR for rehabilitation and functional compensation. We have focused our attention on the part of the hybrid technology system which concerns about virtual reality enhanced rehabilitation. Preliminary results are promising and we are currently investigating the robustness and accuracy of the tracking system during the execution of the single tasks. Next step will be to provide an advanced and complete scenario of the rehabilitation which will provide a detailed assessment of the patient progresses in rehabilitation.

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