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An Overview of M3Rob, a Robotic Platform for Neuromotor and Cognitive Rehabilitation Using Augmented Reality

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Abstract

Stroke is a major cause of disability worldwide and its prevalence has increased in recent decades. Typically, conventional physical therapies for stroke patients can be improved to promote neuroplasticity. Neurofeedback techniques have been proved to enhance not only brain plasticity, but also cognitive functions. However, most rehabilitation approaches do not integrate several types of feedback simultaneously. We hypothesize that the inclusion of neurofeedback in robotic physical therapy and the application of augmented reality should favor brain plasticity in the sensorimotor area, leading to a more successful rehabilitation of paretic limbs. For this reason, we aimed to develop a rehabilitation platform that combines different feedback techniques (haptic robotics, neurofeedback and augmented reality). M3Rob, a robotic platform for hand and wrist neuromotor rehabilitation and cognitive functions recovery, is presented.

1. Introduction

Cerebrovascular accident (CVA) is a major public health problem and is considered the most common cause of permanent disability in adulthood [1]. The sequelae of stroke depend on the region of the brain affected and its extent, including motor and cognitive problems. Mobility problems are the most prevalent, occurring in more than 75% patients with moderate disability. Approximately, 30 % of stroke patients develop dementia within one year of stroke onset [2].

Classical motor rehabilitation methodologies for stroke patients do not target the origin of the problem (brain trauma), which limits the effectiveness of rehabilitation. They focus on repetitive exercises through an exogenous approach, in which the patient is not entirely involved in the lost function recovery. However, previous studies have demonstrated that helping users to learn to control their own brain rhythms through neurofeedback training generates neuroplasticity in the damaged areas, thus leading to an enhancement of the rehabilitation process [3]-[5].

Furthermore, neurofeedback training has been proved not only to enhance neuroplasticity [6], [7], but also enhances certain cognitive functions not directly related to the motor therapy, such as memory, language and visuospatial ability and recognition [8], [9].

Due to the limitations of traditional rehabilitation methods, we consider essential to investigate new strategies that directly address the source of impairment to improve the effectiveness of neuromotor and cognitive stroke rehabilitation, involving the ability of brain networks to restore lost functions and change (i.e., neuroplasticity).

For all the reasons mentioned, the development of a neuro-rehabilitation platform M3Rob (from the Spanish "Mente-Mano-Muñeca Robot"; in English Mind-Hand-Wrist Robot) is proposed. First, the combination of a robotic platform and a brain-computer interface (BCI) system allows stroke patients to perform new therapies that simultaneously address the rehabilitation of neuromotor and cognitive functions. Secondly, the platform is focused on the rehabilitation of the hand and/or wrist due to approximately 60% of patients experience upper limb dysfunction, which is especially prevalent in the hand [10].

Combining these two therapeutic approaches at the same time (neuromotor and cognitive rehabilitation) using augmented reality (AR), the patient would be fully involved in their recovery through constant feedback. Due to this level of feedback (motor, cognitive and AR), users will be aware of their improvement, generating new strategies to restore control of the lost limb and, therefore, favoring neuroplasticity in the affected cortical areas.

Currently, M3Rob is an on-going project. In this document, we detail the most important aspects of the platform, as follows: (i) system overview, (ii) motor, (iii) cognitive and (iv) AR modules

2. System overview

2.1. Background

M3Rob is a continuation of the RobHand project, which was aimed at developing a hand exoskeleton for neurorehabilitation of hand functions through active therapies for people who has suffered a stroke [11]–[13]. RobHand is a hand exoskeleton for performing virtual-based exercises using either passive or EMG-driven control modes.

The evolution of the M3Rob in relation to the RobHand rehabilitation platform integrates the following new aspects: (i) incorporation of wrist module and modification of the hand exoskeleton to make it compatible with the wrist module; incorporation of new sensors (EEG and force), which allows (ii) to introduce neurofeedback providing cognitive rehabilitation and (iii) to develop new strategies based on assist-as-needed paradigms to model a haptic control; (iv) incorporation of AR to the current virtual reality (VR) environment to make the therapy more immersive.

2.2. Description

The M3Rob platform will use the measurement of electromyography (EMG) and electroencephalography (EEG) signals to detect the intentionality of the patient's hand and wrist movements. The EMG will be used to assist in motor rehabilitation, while the EEG through BCI technology will be used as a cognitive rehabilitation tool, aimed at achieving neuroplasticity [3]-[5].in the affected areas and an indirect improvement in general cognitive functions [8], [9].

The monitoring and processing of EMG and EEG will allow the delivery of real-time commands, which will be used to control a modular mechatronic device consisting of a hand exoskeleton and a wrist rehabilitation module, allowing the patient to perform personalized assistive therapies for neuromotor and cognitive rehabilitation, through the use of AR environments oriented towards activities of daily living (ADL).

The mechatronic device will implement haptic control strategies to modulate the physical patient-device interaction, while dynamically adapting online the degree of assistance received by the patient during therapy, by applying the assist-as-needed paradigms. The platform is complemented by a software environment for the local and remote management of therapies, patients, historical data collected online during the execution of therapies, etc.

The M3Rob robotic platform is composed of three main functional modules:

- Motor rehabilitation module. The robotic system, compromising a hand exoskeleton and a wrist module, that provides dynamic assistance to the patient for performing hand-wrist movements during the therapeutic exercises.

- Cognitive rehabilitation module. Monitors and processes the EEG signals of the patient using a BCI system. The BCI system will detect the hand/wrist movement intention while the patient imagines the kinesthetic sensation of performing the movement.

- Augmented reality module. Provides an immersive environment in which a virtual scenario is combined with physical interaction with real elements in order to offer perceptually enriched experiences and enhance the effectiveness of rehabilitation therapies.

3. Motor Rehabilitation Module

The M3Rob rehabilitation platform is modular and can adopt three different configurations to perform hand and/or wrist rehabilitation exercises.

3.1. Configuration for Hand Rehabilitation

The hand exoskeleton assists in flexion/extension movements of the hand fingers using a 4-bar linkage underactuated mechanism for each finger. Each mechanism fixed to a platform is powered by a linear actuator (Actuonix) and has one active rotative degree of freedom (DoF) and one passive rotative DoF for the metacarpophalangeal (MCP) and the proximal interphalangeal (PIP) joints, respectively. The exoskeleton is attached to a forearm support to mitigate the negative effects generated by its weight. The connection is made by means of a spring-loaded interlocking positioning mechanism placed on the back the platform (Figure 1). The RoM of the MCP joint is 70º.

Figure 1. *Hand exoskeleton and forearm support*

3.2. Configuration for Wrist Rehabilitation

The wrist module moves the user's wrist using a mechanism (Figure 2) with three serial revolute active joints (3-DoF RRR). The pronation/supination (PS), flexion/extension (FE) and radial/ulnar deviation (RU) movements of the wrist are assisted by the first, second and third rotational joint, respectively. Each rotational joint is powered by one independent brushed DC motor using cable to transmit the motion. The mechanism has a removable cylindrical handle with a force sensor (Me-Systems). The range of motion of PS, FE and RU joints are 180º, 135º and 110º, respectively.

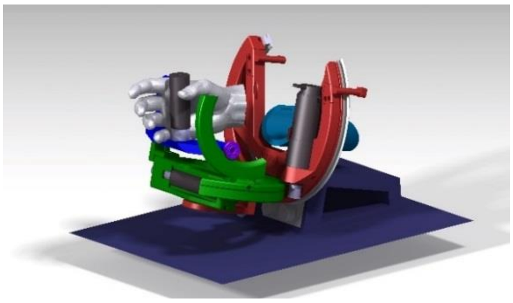

Figure 2. *Wrist rehabilitation module*

3.3. Configuration for Combined Hand and Wrist Rehabilitation

The original hand exoskeleton platform has undergone some modifications to make it compatible with the wrist module, so a linear rail and positioner blocking has been added to connect the hand exoskeleton to the wrist module. In this configuration, the handle is removed (Figure 3).

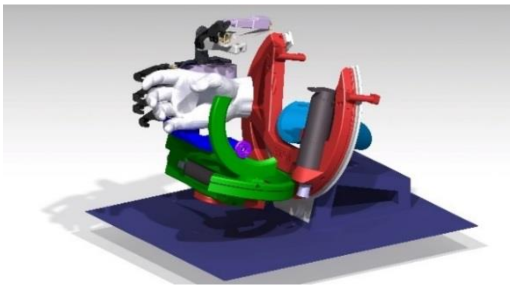

Figure 3. *Hand exoskeleton and wrist rehabilitation module*

4. Cognitive Rehabilitation Module

The most common method for monitoring brain activity is the EEG, given its portability, low cost, and reliability [14]. Since the goal is to improve hand and wrist motor functions, the BCI system should focus on analyzing the cortical area that controls the upper extremities: the sensorimotor region. The EEG signals collected over the sensorimotor cortex may reflect changes in certain frequencies when the user performs or imagines a movement, known as sensorimotor rhythms (SMRs). SMRs are defined as alpha and beta band oscillations that can be generated before, during and after a movement (or even imagined movement) over the sensorimotor cortex [14]. Through neurofeedback training, users can learn to regulate their EEG activity in this region to generate volitional SMRs. Thus, the BCI system can detect the intention to perform a movement even in people with motor impairment, promoting neurological activity in the affected area [4].

One of the most successful strategies to generate contralateral SMRs in both hemispheres is based on the Motor Imagery (MI) of right- and left-hand movements. The effectivity of MI-based BCIs to favor stroke neurorehabilitation has been demonstrated recently [15], not only by improving the movement of paretic hands [4], [16], but also by eliciting changes in functional brain organization due to Hebbian neuroplasticity [5]. Recent studies have also suggested that ipsilateral pre-frontal activity also plays and important role in stroke rehabilitation, although additional investigation is encouraged [16].

The reliability of the MI-based BCIs heavily depends on the user's ability to self-regulate their SMRs, which in turn is closely related the quality of the training and the kinesthetic strategies used to elicit the desired brain activity [3]. One key aspect of MI training is the motivation of the user and the quality of the neurofeedback, which must reflect EEG changes in real-time to allow users to change their mental strategies to provoke them. The simpler feedback would be visual embodied feedback, in which the user is instructed to imagine the kinesthetic remembrance of a random hand movement, while the intensity of the SMRs is indicated in real-time. A deep neural network (i.e., EEGSym [17]) will be used to detect the to detect the probability that the user is imagining the movement of the right or left hand, moving the visual embodied feedback of the Figure 4 accordingly. The quality of this feedback can be improved by involving additional sensory outputs when the SMR is detected, e.g., using neuromuscular electrical stimulation, virtual and augmented reality, or haptic robotics [15].

In M3Rob, visual feedback is provided via a Unity app integrated in MEDUSA© (www.medusabci.com), a novel Python-based software ecosystem to design BCIs and neuroscience experiments in real-time. Screenshots of the cognitive rehabilitation module are shown in Figure 4. The feedback of the first sessions will be always positive to help users learn to modulate their own brain activity on the sensorimotor region. As the sessions increase, the classifier will be updated to progressively show the real feedback.

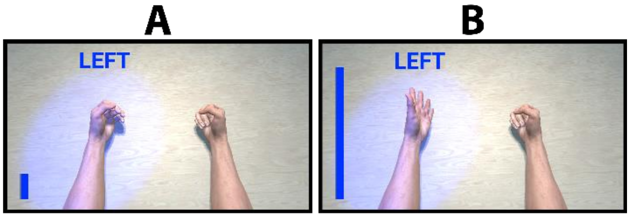

Figure 4. *Visual embodied neurofeedback is provided to reflect the intensity of the motor imagination.*

5. Augmented Reality Module

Gamification has been proved to positively influence different rehabilitation therapies, including those using exoskeletons [18]. This positive influence is directly related to an increase in patients' motivation and engagement, which results in patients performing their exercises in a more sustained fashion. RobHand used VR technologies to facilitate rehabilitation exercises. M3Rob takes this approach further, replacing VR with interoperable AR interfaces. While VR creates a whole virtual environment for the patient, AR extracts and leverages information from the real world, enhancing the properties of existing objects and allowing the creation of new interactive elements which are integrated in the real-world-environment.

Fusing gamification and AR, a set of interactive virtual objects are placed in the real world and visualized through an AR device. These objects and their interactions simulate activities that were previously carried out daily by the patient with additional game-related elements, increasing the motivation of the patient, not only due to the novelty of the therapy, but also due to the transfer from a rehabilitation environment to an enhanced but realistic activity of daily living environment.

In order to develop and easily customize augmented therapies, a set of customizable general-purpose interactive elements is needed. Furthermore, logical protocols and components defining how these elements should be interconnected and how they interact between them is also required. Additionally, it is beneficial to include support for additional hardware, such as controllers or haptic feedback devices. To properly design these components, a close collaboration between software developers and healthcare professionals is needed, ensuring that the virtual elements and the objectives planned within the augmented environments meet the therapeutic requirements for upper limb rehabilitation.

6. Discussion and conclusions

We have presented the M3Rob platform, currently under development, an evolution of the RobHand hand exoskeleton. It will allow patients to undergo therapies for rehabilitation of both neuromotor and cognitive functions damaged by stroke. To the best of our knowledge, this has only been addressed separately. With the proposed platform, the patient will be able to benefit from the combined effects of both therapeutic approaches, which may potentially improve the outcomes of the rehabilitation. Furthermore, the platform adopts three different configurations so that damaged neuromotor functions of the hand and wrist can be rehabilitated individually or simultaneously.

The platform integrates (i) a haptic control for reliable and natural HRI (human-robot interaction) by the modulation of involved forces (ii) assisted-as-needed strategies which not only take into account the exercises performance but also the patient's intention by processing their EMG and EEG signals (iii) the EEG processing will also allow to recover cognitive functions by using neurofeedback (iv) augmented reality so the patient can interact with virtual objects in the real environment.

The brain damage unit of the Benito Menni Hospital Center (Valladolid) is assisting with this project. The unit has defined the clinical protocol for testing M3Rob platform with stroke patients. Furthermore, the protocol has already been submitted to the ethics committee and we are awaiting approval for starting the clinical trial.

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Sesión oral: Neurotecnologías I

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