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Multimodal adaptive interfaces for 3D robot-mediated upper limb neuro-rehabilitation: An overview of bio-cooperative systems

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HIGHLIGHTS

- Novel classification of bio-cooperative robotic systems.
- A multimodal 3D robotic platform for upper limb rehabilitation of post stroke patients.
- Mechatronic module for guaranteeing arm-weight support during therapy.

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ABSTRACT

Robot-mediated neuro-rehabilitation has been proved to be an effective therapeutic approach for upper limb motor recovery after stroke, though its actual potential when compared to other conventional approaches has still to be fully demonstrated. Most of the proposed solutions use a planar workspace. One key aspect for influencing motor recovery mechanisms, such as neuroplasticity and the level of motivation and involvement of the patient in the exercise, is the design of patient-tailored protocols and on-line adaptation of the assistance provided by the robotic agent to the patient performance. Also, when abilities for performing activities of daily living shall be targeted, exercises in 3D workspace are highly preferable. This paper wants to provide a complete overview on bio-cooperative systems on neuro-rehabilitation, with a special focus on 3D multimodal adaptive interfaces, by partly in-depth reviewing the literature and partly proposing an illustrative case of how to build such a bio-cooperative based on the authors' current research. It consists of an operational robotic platform for 3D upper limb robot-aided rehabilitation, directly derived from the MAAT system previously developed by the same research group. The system features on-line adaptation of therapy characteristics to specific patient needs and to the measured level of performance, by including the patient in the control loop. The system is composed of a 7-DoF robot arm, an adaptive interaction control system, a motorized arm-weight support system and a module for on-line evaluation of patient performance. Such module records patient biomechanical data through an unobtrusive, wearable sensory system, evaluates patient biomechanical state and updates robot control parameters for modifying level of assistance and task complexity in the 3D workspace. In addition, a multimodal interface provides information needed to control the motorized arm-weight support by means of a dedicated cable–pulley system.

1. Introduction

Rehabilitation robotics is one of the most active research fields in the neuro-rehabilitation panorama. There are several research groups actively working in this field, for the development of new robotic devices, as well as for the application of already existing robots to new challenging scenarios of robot-aided rehabilitation. It has been extensively demonstrated that robotic devices for upper limb treatment may enhance motor recovery and neuro-plasticity due to their ability to supply highly-intensive, repeatable, accurate and patient-tailored movement therapy, while guaranteeing patient safety and unloading therapist workload with respect to traditional methods [1–11]. Additionally, robotic technologies offer the huge advantage of providing the clinicians with

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quantitative and objective measurements about patient's recovery through the sensors embedded into the robots [12,13].

Despite these encouraging findings, however, most of the robotic machines for upper-limb rehabilitation rely on an "if-then" functioning mode, which permits to execute only predefined unidirectional action on human subjects, from the robot to the patient, without actively including the patient in the control loop and participating in the therapy definition [14,15]. Such an approach tends to force the patient to follow predetermined trajectories that usually do not take into account subject features, spontaneous intentions and voluntary efforts [16,17].

Bio-cooperative systems represent the new generation of robotic platforms that promote a bidirectional interaction between the robot and the patient based on multimodal interfaces also arousing interest in the European Commission, who has financed European projects on this topic, such as MIMICS [14] and Echord-MAAT (2009–2013) [15] in the FP7 and AIDE (2015–2018) in Horizon 2020 programme.

Information coming from different sources allows the users to close the loop by providing a continuous feedback on their global status, i.e. their condition, described through user properties, actions, intentions and environmental factors and provided by biomechanical, physiological and psychological measures. The inclusion of physiological and psychological measurements of the patient's state into the control loop, in addition to biomechanical measurements, makes the system "Bio-Cooperative" [14].

Such an approach, trying to adapt dynamically and in real-time robotic assistance to patient's needs, based on continuous multimodal measures of the user's state, is expected to foster patient engagement in robotic therapy more than in previously reported studies in the field [18–23].

The multi-sensory information describing the patient's condition can also be employed to quantitatively assess patient recovery during the therapy.

Moreover, bio-cooperative systems have recently been expanded to include non-invasive Brain Computer Interfaces (BCIs) based on electroencephalography (EEG) and non-cortical interfaces (Electrooculography (EOG) Electromyography (EMG) and eye-tracking) for detecting user movement intentions, and virtual reality environment as well as haptic perception for augmenting sensory feedback for the patient [23].

Robotic technologies for stroke rehabilitation have focused for a long time on simple motor tasks (also called analytical tasks) such as reaching actions, typically restricted to planar workspace, i.e., vertical planes and lateral planes [20], taking into account motor learning principles and biomechanics. In addition, focusing more on separate joints (e.g. proximal or else distal joints alone), rather than distal and proximal together, may have contributed to limit transfer of motor gains to Activities of Daily Living (ADL) [23–25]. Only recently attention has progressed towards more functional tasks, thus developing robotic training oriented to functional upper limb tasks, such as reaching to pick up a drink [26–28]. There is strong evidence that real therapy is effective in improving independence of people with sensory-motor impairment in ADL [6,9,10,25,29–32].

Typical ADL tasks involving upper limb, such as eating, drinking, dressing, and grooming, are normally performed in the 3D space. Furthermore, execution of arm movements within a reasonable workspace during ADL tasks may allow patients to improve functional abilities. In this context robotic devices become assistive robots since they provide help to patients performing daily life activities in 3D space.

In this paper an overview on bio-cooperative systems with multimodal adaptive interfaces for 3D upper-limb neuro-rehabilitation is presented, and an illustrative case of how to build such systems is provided, based on the authors' current research. It is directly derived from the Echord/MAAT system previously developed by the same research group [15,33–35]. It features on-line adaptation of therapy characteristics to specific patient needs and to the measured level of performance, by including the patient in the control loop. The system is conceived to also enable functional tasks of daily living.

The paper is structured as follows. In Section 2 a review of the bio-cooperative systems is reported, by proposing a general scheme of the system and then in-depth analyzing each subsystem. Section 3 presents the platform developed by the authors as a case study of bio-cooperative system for 3D upper limb robotic treatment with special focus on: (i) the adaptive robot control based on real-time monitoring of biomechanical user performance; (ii) a mechatronic module purposely conceived for providing adaptive support to the patient's arm during motor exercises. Discussion and conclusions are finally reported in Sections 4 and 5, respectively.

2. Overview on bio-cooperative control strategies for promoting patient engagement in therapy

A general scheme showing the functioning of a bio-cooperative system is proposed in this section (Fig. 1). It aims at providing a clear picture of all the possible bio-cooperative systems currently available in the literature, which can be obtained from the scheme in Fig. 1 by just eliminating some modules. In particular, with respect to the scheme already presented in [14], it is conceived to also include non-invasive cortical and non-cortical interfaces and context and environmental factors that are soliciting interest in the recent years. Each module will be widely discussed in the following.

As shown in Fig. 1, a central role is given to the patient who is closed in the control loop thanks to a multimodal interface that collects and processes data coming from different sources. The multimodal interface mainly consists of: biomechanical, physiological and psychological measurements for extracting a complete picture of the patient's state during therapy; non-invasive cortical (i.e. EEG) and non-cortical interfaces (EMG, EOG, eye tracking, etc.) for identifying the user's motion intention.

Data fusion and processing algorithms are developed working on the multimodal signals recorded by the acquisition system. Information about patient status and intention are used to update the sensory feedback to the patient (including visual, e.g. virtual reality, audio, and haptic feedback) and the bio-cooperative control in a patient-tailored manner, always guaranteeing safety in human–robot interaction.

2.1. Bio-cooperative control system

One possible categorization of current control algorithms for rehabilitation machines is the following:

- Assistive controller. This is the most widely developed control paradigm [16]. Assistive controllers help participants move their weakened limbs in desired patterns during grasping, or reaching, a strategy similar to "active assist" exercises performed by rehabilitation therapists.
- Challenge-based control. The term "challenge-based" refers to controllers that are in some ways the opposite of assistive controllers because they make movement tasks more difficult or challenging. Examples include controllers that provide resistance to the participant's limb movements during exercise, require specific patterns of force generation, or increase the size of movement errors ("error amplification" strategies) [21].
- Haptic simulation. It refers to the practice of ADL movements in a virtual environment. Haptic simulation offers flexibility, convenience, and safety as advantages compared to practice in a physical environment [26,27].