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Hybrid robotic systems for upper limb rehabilitation after stroke: A review

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ABSTRACT

In recent years the combined use of functional electrical stimulation (FES) and robotic devices, called hybrid robotic rehabilitation systems, has emerged as a promising approach for rehabilitation of lower and upper limb motor functions. This paper presents a review of the state of the art of current hybrid robotic solutions for upper limb rehabilitation after stroke. For this aim, studies have been selected through a search using web databases: IEEE-Xplore, Scopus and PubMed. A total of 10 different hybrid robotic systems were identified, and they are presented in this paper. Selected systems are critically compared considering their technological components and aspects that form part of the hybrid robotic solution, the proposed control strategies that have been implemented, as well as the current technological challenges in this topic. Additionally, we will present and discuss the corresponding evidences on the effectiveness of these hybrid robotic therapies. The review also discusses the future trends in this field.

1. Introduction

According to the World Health Organization, 15 million people suffer a stroke worldwide each year [1]. Recent estimates envisage that this number will increase by 3.4 million people by the year 2030 [2]. One of the most relevant body functions affected after stroke is the capability to control voluntary movements [3], that hinders the execution of activities of daily living (ADL). This motor impairment presents an important impact on the quality of life of stroke survivors.

The main focus of stroke rehabilitation is the recovery of the affected neuromuscular functions and the achievement of independent body control. However, after completing standard rehabilitation, approximately 50–60% of stroke patients still experience some degree of motor impairment [4]. In particular, stroke patients with unilateral upper arm paralysis rarely regain arm and hand functions to the point of effective use in ADLs [5].

This evidence highlights the need for better ways to improve the current rehabilitation interventions aimed at recovering arm function. For this purpose, the inclusion of alternative rehabilitation therapies, such as functional electrical stimulation (FES) and robots, has been increasing over the last decade. FES-based therapy uses low power electrical pulses to generate muscles contraction and produce joint movements. It has been reported that the use of FES could result in higher benefits with respect to conventional therapy for upper limb functions after stroke [6,7]. Besides promoting motor improvements, it has been shown that FES could also induce changes in cortical excitability and stimulates cortical reorganization [8,9]. However, this technique imposes some challenges that limit its widespread use for upper limb rehabilitation. The high complexity and non-linearity of the musculoskeletal system preclude the accurate and reliable control of movements [10–12]. Also, the non-physiological recruitment of motor unit causes high metabolic costs, yielding a fast and sudden occurrence of muscle fatigue [13], which in turn prevents a favorable evolution of the therapy.

Robotic rehabilitation has been introduced as a promising tool that automates intensive rehabilitation paradigms, i.e. allowing higher dosage, intensity, and longer exposure to the treatment [14,15]. Additionally, they provide reliable kinematic and kinetic measurements, which can be used to quantify the patient’s evolution. Furthermore, this technology can be used in

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combination with other technologies, such as virtual reality environment, to increase patients' compliance with the treatment. Nevertheless, robot-assisted therapies are susceptible to the slacking effect, where patients take a passive attitude and let the robot drive the movements without performing any effort, resulting in no functional improvements [16,17]. The assisted-as-needed (AAN) control strategy represents the most common method used to tackle this issue. Under this approach robots provide assistance only when the users are not able to execute the movements by their own capabilities [17]. Despite the development of sophisticated control algorithms aimed at improving rehabilitation outcomes, the use of robotic exoskeleton is still controversial due to the lack of strong evidence demonstrating a superior capability to restore motor function compared to conventional therapy [18].

The combined use of FES and robotic technologies has been proposed as a solution to overcome their individual limitations and increase the robustness, safety and effectiveness of the rehabilitation interventions. This combined approach has been named Hybrid Robotic Rehabilitation Systems. According to Del-Ama et al. [19] hybrid systems can be defined as *"those systems that rehabilitate or compensate motor functions through the combined action of muscle activation with FES and mechanical/electromechanical forces supplied to joints"*. Key technological aspects concerning this approach for lower limbs have been previously identified and discussed (see [19] for further details). Nonetheless, a critical review focused on the application of this technology to upper limb rehabilitation is still missing in the literature.

Our main objective with this review is to describe the current hybrid robotic approaches, including their rehabilitation targets and the control/intervention strategies, and also their potential benefits for rehabilitation of the upper extremity. To this aim, we will discuss the most important works submitted in the literature on this topic. We will address the analysis from a technological (e.g. type of devices, multimodal actuation, usability) and a clinical perspective. We will also discuss the main challenge for the consolidation of this approach in rehabilitation practice.

2. Methodology

Literature in this topic was identified based on searches on the following web databases: the Institute of Electrical and Electronics Engineering (IEEE Xplore), PubMed and Scopus databases. The search was carried out without a time limit. To reject those studies focused on the lower limb, the term '*upper limb*' followed by the logical conjunction '*and*' were combined with the following keywords*: Hybrid Exoskeleton, Functional electrical stimulation, Robots and Exoskeleton*.

Additionally, relevant referenced literature from the selected publications was also considered in the survey. Selected studies were independently reviewed and the following inclusion criteria were applied:

- All papers must fit into the definition of the hybrid robotic system, i.e. present a combined use of robotic devices (passive or active actuation) and FES.
- The technology must be focused on upper limb rehabilitation.
- Studies should consider at least one of the following outcome measures: kinematic data, EMG signals, force measure, clinical scales and functional evaluation in stroke patients.
- The paper should be written in English.

Studies in which robotic therapy and FES were used separately, or in which the techniques were not used as therapy, were excluded from this review. Also, hybrid robotic systems assessed in pathologies different from stroke were ignored.

3. Results

A total of 14 selected papers were included in this review, which correspond to 10 different hybrid robotic systems. These systems were classified into three different groups: systems that focus only on grasping ($n = 3$), systems that focus only in reaching ($n = 4$), and systems that combine reaching and grasping ($n = 3$).

3.1. Technical overview of hybrid systems

3.1.1. Hybrid robotic rehabilitation systems for grasping

Table 1 shows a summary of the hybrid robotic rehabilitation systems that have been used for grasping. The NESS hand Master system represents the first reported hybrid robotic system [20]. This system was designed to train grasping functions. It consists of a five-channels electrical stimulator embedded in a passive wrist orthosis (see Fig. 1a). The system assists the hand opening and closing by mean of electrodes placed over the extensor muscles, extensor digitorum communis (EDC), extensor pollicis brevis, flexor muscles, flexor digitorum superficialis (FDC), flexor pollicis longus and the thenar muscles group for thumb movement. The electrical pulses are conducted through an open-loop strategy with constant preset stimulation values (pulse amplitude, pulse width and frequency). The passive orthosis does not contribute to joint movements, but supports the wrist joint to facilitate grasping and to smoothen the muscle response to the FES. This orthosis is wired to a control unit used to configure manually the FES parameters and to trigger the electrical assistance by pressing a button.

A similar solution, called hybrid assistive neuromuscular dynamic stimulation (HANDS), was presented by Fujiwara et al. [22]. In this study, the authors integrate a wrist hand splint with a single channel electrical stimulation for fingers extension assistance [22]. In this case, stimulation was given solely to the EDC muscle, whereas the splint contributed to inhibition of flexors over activated muscles, and therefore the applied electrical stimulation enhanced agonist muscles recruitment responses. Although this system relies on a single stimulation channel, its main advantage is that the stimulation intensity could be set using a pulse width modulation technique proportional to the recorded volitional electromyography (EMG) from the targeted muscle [26,27]. Fig. 2a depicts the controller rule implemented in this system, where D_{min} corresponds to the minimum pulse width duration that facilitates voluntary contraction, and D_{max} is the threshold pulse duration equivalent to the highest endurable intensity during maximum voluntary contraction. The voluntary EMG signal was calculated by taking the raw EMG signal after 20 ms of the electrical stimulus, thus both artifact and M-wave were discarded.

Hu et al. [23–25] presented a FES-robot system for wrist flexion/extension rehabilitation, in which both assistive parts are driven by voluntary EMG signals detected from flexor carpi radialis (FCR) and extensor carpi radialis (ECR) muscles. The robotic system is based on an actuated end-effector device, composed of two small parallel bars delimited in the horizontal plane (see Fig. 1c). Stroke patients were seated with their affected arm mounted on the system to track a cursor displayed on the screen by moving their wrist at different angular velocities. The total support was given by the contribution of the robot (A_{robot}) and FES (A_{fes}) assistance. The controlled assistance shown in Fig. 2b followed a proportional relation between the EMG amplitude, the maximum torque value during isometric contraction (T_{imv} for robot assistance) or maximum stimulation pulse width (W_{max} for FES assistance), and the constant assistance factor (G), used to adjust the support level (ranged from 0 to 1). Although the assistance factor allows setting different actuation level individually to each system, it was demonstrated that better performance (less tracking