Upper-limb exoskeletons for stroke rehabilitation

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Abstract. Upper-limb exoskeletons provide high-intensity, repetitive, task-specific, interactive and individualized training, making effective use of neuroplasticity for functional recovery in neurological patients. Most exoskeletons have robot axes aligned with the anatomical axes of the subject and provide direct control of individual joints. Recently, novel mechanical structures and actuation mechanisms have been proposed, but still result in bulky and heavy exoskeletons, limiting their applicability into clinical practice. Technological efforts are needed to promote light and wearable exoskeletons that implement active-assistive controllers, providing "assisted-as-needed" rehabilitation therapy, towards patient's motivation and self-esteem. An overview of upper-limb exoskeletons, including mechanical design and control algorithms, will be provided. Special focus will be put on the current evidence about the efficacy of wearable robotic technologies on motor recovery and about other therapies that can be combined with exoskeletons to improve their therapeutic effects.

Keywords: Exoskeleton, Upper-limb, Rehabilitation, Stroke, Functional Electrical Stimulation, Virtual Reality, Randomized Controlled Trial

1 Introduction

About 80% of stroke survivors suffer from upper-limb paresis [15], which strongly affects their capability to perform activities of daily life (ADL), decreasing their independence and quality of life. Neuroplasticity is the basic mechanism underlying improvements in functional outcomes after stroke. Rehabilitative interventions should make effective use of neuroplasticity for functional recovery, proposing high-intensity, repetitive, task-specific, interactive and individualized training [13]. Technology-supported rehabilitation is emerging as a solution to support therapists in providing such training for a long duration, allowing the participants to progress in task difficulty and to achieve the desired movement, so as to increase their motivation [5]. In the last thirty years, several robotic devices for upper-limb rehabilitation have become commercially available [2]. Therapeutic robots can be divided into two categories: end-effector devices (e.g. InMotion Arm Robot, known as MIT-Manus [12]) and exoskeleton-type devices (e.g. Armeo Power, Hocoma [20]). End-effector devices hold the patients hand or forearm at one point and generate mechanical forces at the interface to move the arm. They are easy to setup but they suffer from limited control of the proximal joints, which could result in abnormal postures. Conversely, exoskeleton-type devices are characterized by robot axes aligned with the anatomical axes of the subject and provide direct control of individual joints, which can minimize abnormal posture or movement and provides a better control of the arm motion [16]. These advantages are paid by a more complex design of mechanical structure and control algorithms. This contribution focuses on arm exoskeletons for stroke rehabilitation dealing with mechanical and control design, current evidence about their efficacy, alone or in combination with other therapies, up to potential areas for future research.

2 Mechanical design and actuation

Upper limbs anatomical structure is very complex and flexible, permitting the human arm to perform a wide range of movements leveraging on 9 Degrees of Freedom (DOFs). A successfully designed upper-limb exoskeleton operates alongside the human arm smoothly supporting its natural kinematics. In literature, arm exoskeletons mainly provide support at the shoulder and at the elbow, only few of them are provided handles to support the motion of wrist and hand [16]. Regardless the number of supported DOFs, the design of upper-limb exoskeletons suggests that robot axes aligned with anatomical axes of the human arm improve robot's wearability and safety. However, since the instantaneous center of rotation of the shoulder changes during motion and since an incorrect axis alignment leads to undesirable interaction forces and uncomfortable postures, additional actuated or passive DOFs have been added to adjust and self-compensate misalignments [11,27,20].

Regarding the actuation mechanisms, three main technologies can be identified: pneumatic, hydraulic and electric actuators. Pneumatic and hydraulic actuators provide higher power to weight ratio with respect to electric motors, but their efficiency strongly depends on pressure losses due to friction or to fluid leaks. Pneumatic and hydraulic, due to their nature, are inherently safe and compliant, thus suitable for applications involving human-robot interaction. These actuators have been widely tested in exoskeletons in the past years, however due to their power consumption, low efficiency and limited control bandwidth, they did not find great consensus [10]. On the other side, due to their ability to produce large amount of torque, their commercial availability and their intrinsic precision in controlling motion, current solutions mainly implement stiff joints actuated by electric motors. Nowadays, the interest in compliant control for human-robot interaction has led to the development of new approaches that involve the use of electric motors in series with elastic elements, the so-called series elastic actuators (SEAs) [26]. SEAs were initially developed to improve force control accuracy, meeting interest in the rehabilitation field given provided advantages in terms of safety, tolerance to mechanical shocks and indirect torque

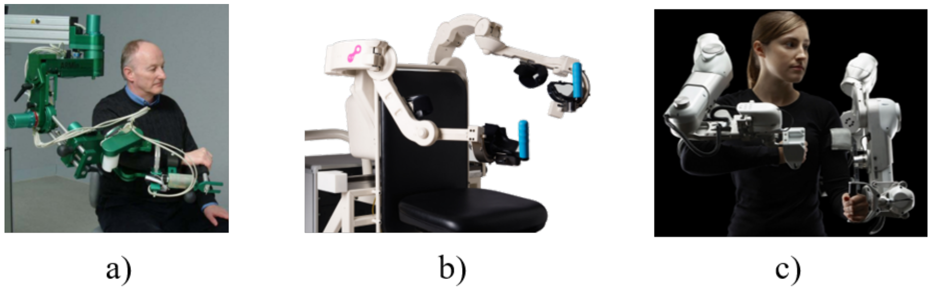

Fig. 1. Upper-limb exoskeletons. a) ARMin III [20] b) AleX [22] c) Harmony [11]

measurements [11]. Motors can be both co-located with respect to the axis of rotation of the physiological joints, which leads to a simpler control strategy, but worsens the encumbrance and portability of the system; or positioned behind the exoskeleton, leveraging on the cable-driven approaches, which use wires and pulleys to transmit the power to the actuated joints [22]. With the current solutions, however, it is clear that such complex mechanical design has led to powerful, bulky and heavy exoskeletons (Figure 1). This drawback strongly limits their applicability into clinical practice and still requires technological efforts to promote light and wearable exoskeletons for robot-assisted rehabilitation therapy.

3 Control algorithms

According to Proietti et al. robot-assisted rehabilitation for upper-limb motor recovery has led to promising results, however most publications do not deal with control aspects [23]. Most exoskeletons are controlled in passive or active-assistive mode [2]. In passive mode, the robot performs the movement regardless of subject's response to therapy. However, repetitive passive motion of the arm has come out with limited effects on neuroplasticity. Conversely, more complex control strategies based on subject's involvement could lead to better results, at least after the first stages of the rehabilitation process when intensive, repetitive and task-oriented training are the key-features for an effective recovery. This is the case of active-assistive mode, where, after the patient has recovered a sufficient amount of motor control, the controller assists the arm motion in a human-like way, exploiting any residual ability of the patient and letting the user drive the movement, improving patient motivation and self-esteem [23]. Many approaches have been proposed to implement assisted-as-needed strategies, but the most widespread rely on admittance control or impedance control, where the controller shapes the dynamical relation between position and force, as a compromise between tracking the position of the end-effector and controlling the effort imposed by the robotic arm [4]. More advanced controllers take advantage from friction and gravity compensation techniques to counterbalance the weight and the inertia of the exoskeleton during free-space motion. Other controllers involve the use of surface EMG signals to estimate muscle activation and provide EMG-modulated forces, towards patient's active involvement during exercises [16].

4 Effects of exoskeletons on upper-limb motor recovery

The effects of robotic devices on rehabilitative outcomes after stroke have been strongly investigated through randomized controlled trials (RCT) and, in the latest years, through systematic reviews and meta-analysis [29,19,28]. Robotic training can be used in addition to usual care to help both therapists and patients in the management of the paralyzed upper-limb and to achieve better rehabilitation outcomes [29]. A recent Cochrane review, including 34 trials (1160 participants), demonstrated that stroke patients who receive electromechanical and robot-assisted arm and hand training after stroke might improve their ADL, arm and hand function and strength [19]. Meta-analyses of 38 trials (1206 participants) showed significant but small improvements in motor control and muscle strength of the paretic arm and a negative effect on muscle tone when robotic training is compared to usual care [28]. Similar results were achieved also in [3], where a comparison between conventional therapy and robot-assisted rehabilitation showed that the latter is more effective in improving upper-limb motor function recovery, especially in chronic stroke patients. It is important to underline that these positive effects on the recovery of arm functions have been mainly achieved using end-effector robotic devices, while there is still a lack of evidence regarding exoskeletons, recently investigated by two systematic reviews [28,3]. They both concluded that so far there is no evidence about the superiority of exoskeleton-assisted training with respect to usual care; however, the effects of exoskeletons have been insufficiently investigated and final conclusion cannot be drawn. Finally, few studies compared different training modalities, but available data indicated that active-assistive mode, stressing the patient's active contribution, led most consistently to improvements in arm function [2].

5 Combination between exoskeletons and other therapies

Several therapeutic approaches have been combined with upper-limb exoskeletons, making robotic based-interventions more functional and task-oriented. In this contribution, we focus on the use of FES and VR in combination with exoskeletons.

5.1 Functional Electrical Stimulation

FES has been strongly used to enhance functional recovery of the paretic arm in stroke survivors [8]. When FES is combined with the patient's residual voluntary effort [1], cortical plasticity seems to be enhanced, having therefore the potential to improve the therapeutic effects of FES [6]. The combined action of robot-assisted therapy supporting elbow and wrist motion and EMG-triggered FES has shown positive effects on muscle coordination in subacute [24] and chronic stroke survivors [25]. FES has been combined also with passive anti-gravity exoskeletons, e.g. ArmeoSpring (Hocoma) [18] or with custom-built passive exoskeleton [21]. In a recent RCT [9], 68 stroke patients were randomized in an experimental group, training with a passive anti-gravity exoskeleton combined with an arm EMG-triggered neuroprosthesis in addition to conventional therapy, and a control group performing only conventional therapy of equal dose. Preliminary results showed the superiority of the training with the hybrid robotic system, supporting the use of exoskeleton devices combined with FES.

5.2 Virtual Reality

VR is an interactive and individualized treatment modality, which can provide sensorimotor training in enriched environments, so as to maximize patients engagement [17]. Several systematic reviews have shown the superiority of VR training with respect to usual care in improving motor function and ADL independence, mainly when VR is exploited to increase the time spent in therapy [14]. Several groups have combined VR with multi-joint upper-limb exoskeletons in order to prevent the slacking effect which may characterize robotic rehabilitation when assistance is too supportive [7]. These pilot studies showed promising results in terms of functional improvement and increments of active and passive ranges of motion. In [7], the level of difficulty for the exercise was adjusted by a performance-dependent adaptation algorithm; which may facilitate motor learning by progressively challenging the subject in accordance with the individual capacity. However, more extensive RCTs are needed to demonstrate the superiority of VR combined with upper-limb exoskeletons with respect to VR and robotic rehabilitation alone, as well as to usual care

6 Perspectives and challenges

Overall, exoskeleton-type devices have entered the clinical practice of arm stroke rehabilitation. Robotic devices enable several-to-one therapy paradigms, allowing high-dosage and high-intensity treatments, which are recognized as the major positive elements for the recovery process. However, the superiority of exoskeleton-assisted training with respect to usual care is still a matter of challenge. To fill this gap, well-design RCTs should be conducted and should include cost-effectiveness analysis to evaluate the economical sustainability of these technological solutions. A crucial aspect of exoskeleton design is the human-robot interaction, which should let the human take the lead role, guaranteeing at the same time that the robot closely observe the human and decide when to provide corrective actions. Integration of biological signals, such as EMG, is mandatory to achieve this interaction. Despite many significant advances, effective strategies, which can realize minimal assistance paradigms, are still under investigation. Rehabilitation exoskeletons can also be integrated with multiplayer games, which are recently emerged as a promising approach to increase patients motivation. In order to favor the transfer of motor gains to ADL, it is important to integrate distal and proximal arm training; indeed, so far, exoskeleton devices have been focused mainly on the proximal joints but to make robotic training more functional it is mandatory the integration of robotic hand modules. Finally, the development of home-based rehabilitation systems is the ultimate goal for achieving high intensity in post-stroke therapy. Home-based exoskeletons would assure a safe, intensive, and controlled training with limited supervision, under a remote control of a human therapist.

Conflict of interest declaration

The Authors declare that there is no conflict of interest regarding the publication of this contribution.

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