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

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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

Table 1
Identified hybrid system for grasping function.

System	Application	Robotic device	FES device	Drawback
NESS HandMaster [20,21].	Finger flexion/extension.	Forearm-Hand plastic orthosis. Passive Device.	5 channels (EDC, EPB, FDS, FPL and thenar). Open loop. Button triggered.	Passive robotic device. Preprogramed FES parameters. Limited functional response to FES during grasping. Non-associative assistance.
HANDS [22].	Fingers extension.	Wrist hand splint. Passive device.	1 channel (EDC). Closed loop: EMG-based. EMG triggered.	Passive robotic device. Limited to user with normal EMG activity. Limited functional response to FES during grasping.
Wrist training [23–25].	Wrist flexion/extension.	Two parallels bars. Active device. Controlled by voluntary EMG.	2 channels (FDC and EDC). Closed loop: EMG-based. EMG triggered.	Limited to user with normal EMG activity. Limited functional response to FES during grasping. No fingers assistance.

Meaning of abbreviation and acronyms: *HANDS*: Hybrid assistive neuromuscular dynamic stimulation; *EMG*: Electromyography; *EDC*: Extensor digitorum communis; *EPB*: Extensor pollicis brevis; *FDS*: Flexor digitorum superficialis; *FPL*: Flexor pollicis longus.

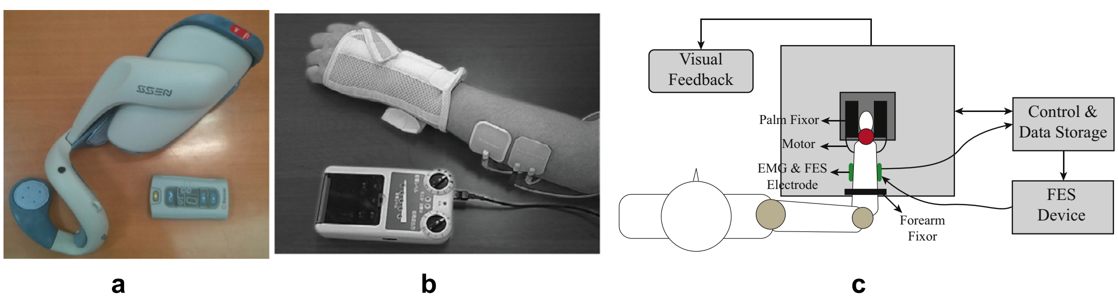

Fig. 1. Hybrid robotic systems for grasping rehabilitation. (a) Newest version of the NESS HandMaster device [20,21] (b) Hybrid assistive neuromuscular dynamic stimulation (HANDS) (figure adapted from [22]); (c) Experimental setup for wrist flexion/extension training (figure adapted from [23]).

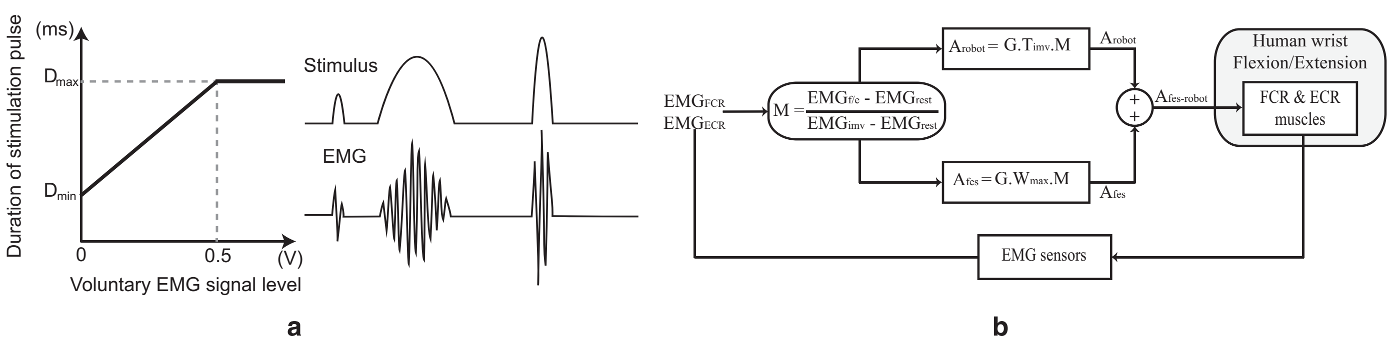

Fig. 2. Implemented robot and FES control algorithm for grasping movement. (a) EMG-based FES control strategy for hand opening and closing [22]. D_{min} and D_{max} define the minimum and maximum stimulation pulse width. (b) Cooperative control strategy by Hu et al. for wrist flexion/extension [23–25]. A_{robot}, A_{fes} represent the torque and FES assistance respectively; G and K are the constants gains used to adjust the magnitude of the assistance torque and FES; T_{imv} is the maximal value of the torque during isometric maximum extension (T_{imve}) and flexion (T_{imvf}); $W_{max,FCR/ECR}$ is the maximum stimulation impulse width applied on the FCR or ECR muscles; $EMG_{flex/ext}$ is the EMG of agonist muscle; EMG_{rest} is the average of EMG level of the muscle; EMG_{imv} is the maximal EMG amplitude of the muscle.

error) was obtained when FES and robot provided equal contribution (50% FES and 50% robot) [24].

3.1.2. Hybrid robotic rehabilitation systems for reaching

We identified four main hybrid systems for the rehabilitation and assistance of reaching functions (Table 2). All of them, in contrast with grasping devices, focus their action on proximal joints, i.e. shoulder and elbow.

Barker et al. [28] combined the robotic system called Sensorimotor Active Rehabilitation Training (SMART), with FES. The SMART device consists of a manipulator mounted on a linear track that allows elbow frontal flexion/extension movements (see Fig. 3a). This mechanical system reduces the difficulty of carrying arm extension movements by limiting the allowed degree of freedoms and minimizing the resistance to the movement. The movement assistance was triggered by voluntary EMG activation and was driven by FES applied to the triceps muscle. A predefined stimulation pattern was used, consisting of one second of ascending ramp, 5 to 10 s of constant stimulation and one second of descending ramp.

Wu et al. [29] implemented the bilateral arm training (BAT) approach, shown in Fig. 3b. It was designed to emphasize frontal symmetrical bilateral movements to coordinate the use of both arms during repetitive movement. Two passive manipulators, placed over linear tracks delimited in the horizontal plane, were combined with FES. Like the SMART device, the parallels bars

Table 2
Identified hybrid systems for reaching function.

System	Application	Robotic device	FES device	Drawback
SMART + FES [28].	Elbow extension in horizontal plane.	Horizontal guide platform. Passive device, variable mechanical load.	1 channel (TR). Open loop. EMG triggered.	Constrained movement. Passive robotic device. Preprogramed FES parameters.
BAT system [29].	Elbow extension in horizontal plane.	Horizontal guide platform. Passive device.	1 channel (TR). Open loop. Triggered by error position.	Constrained movement. Passive robotic device. Preprogramed FES parameters.
Planar end-effector device + FES [30].	Elbow extension in horizontal plane.	5-link planar arm manipulator. Actuated device. Impedance controller.	1 channel (TR). Closed loop: FB+FF. Button triggered.	Constrained movement. Non-associative assistance.
SAIL system [31,32].	Shoulder flexion and elbow extension in 3D.	ARMEO® exoskeleton. Passive device.	2 channels (AD and TR). Closed loop: FB+FF. Button triggered.	Limited FES-Robot interaction. Non-associative assistance.

Meaning of abbreviation and acronyms: *SMART*: Sensorimotor active rehabilitation training; *BAT*: Bilateral arm training; *SAIL*: Stimulation assistance through iterative learning; *FES*: Functional electrical stimulation; *TR*: Triceps muscle; *BI*: Biceps muscle; *AD*: Anterior deltoid muscle; *FB*: Feedback controller; *FF*: Feedforward controller; *BMI*: Brain-machine interface.

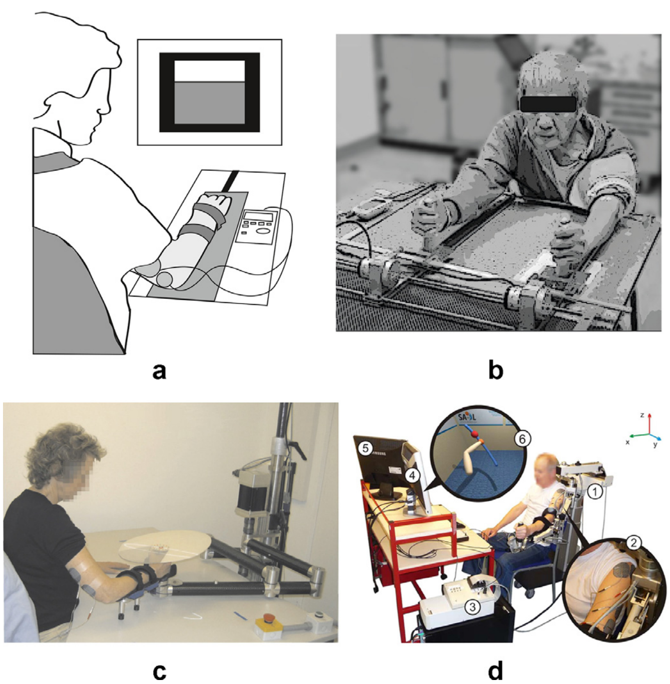

Fig. 3. Hybrid robotic rehabilitation system for reaching movements. (a) SMART device combined with FES (figure adapated from [28]). (b) BAT training based on two parallel bar and FES (figure adapted from [29]). (c) Planar end-effector workstation combined with FES [30,33]. (d) Unconstrained 3D workstation based on ArmeoSpring exoskeleton [31].

supported the arm's weight and constrained the workspace. Additionally, the manipulator position was used to trigger the FES on/off events. The FES was turned on when the affected arm was falling behind the unaffected arm during the extension movement. The electrical stimulation was applied to triceps muscle with preprogramed stimulation parameters.

Hughes et al. presented an actuated planar end-effector device combined with FES applied to the triceps muscle [30,33,34]. In this case, the hand of the patients was strapped to the end of a five-link robotic arm. Subjects had to follow elliptical shaped trajectories at a constant velocity. These trajectories were projected on a plexiglass disc located over the user's forearm and hand (Fig. 3c). To ensure safe interaction between the robot and human subjects, a second-order dynamic equation was also used to implement an impedance control [33]. The FES assistance was driven to assist elbow extension movements, using a closed-loop control scheme composed of a linearized feedback controller and a learning feedforward loop [34]. To this aim, a full FES-based human arm model was developed (see [34,35] for further details). This detailed model was used to implement the linearized controller in a simple PID arrangement. The learning feedforward loop was used to adjust the stimulation level to produce an improved performance on successive attempts. For this purpose, they implemented the linear iterative learning control algorithm (ILC). This algorithm facilitated precise tracking over the reference trajectory by adapting the required FES assistance accordingly. This combined control strategy is shown in Fig. 4a. By implementing this control architecture, the authors tried to fully exploit the association between the users motor capabilities and the level of assistance required to help them achieve such movement.

The studies mentioned so far did not consider unconstrained scenarios, i.e. including higher degrees of freedom or complex functional tasks. The 3-dimension rehabilitation system called SAIL (Stimulation Assistance through Iterative Learning) falls in this category [31,32]. The general system, shown in Fig. 3d, combined the passive upper limb exoskeleton ArmeoSpring® with a two-channel FES system. The ArmeoSpring® was used to ensure safety and facilitate the execution of reaching movements by suppressing the effect of gravitational forces. The FES system was applied to the anterior deltoid and triceps muscle to assist the arm extension in the 3D space. Subjects were asked to perform reaching exercises that consisted in following a reference point displayed on a screen. The reference point travelled along a fixed trajectory at various speeds. Authors implemented a similar control scheme for the previously mentioned planar task [34]. The system was assumed as two single-input, single-output (SISO) configuration, and under this scenario the control and movement of the forearm and upper arm could be considered independently [36]. This simplification allowed the implementation of the control scheme shown in Fig. 4b, based on a PID feedback controller with a feedforward loop consisting of a phase-lead ILC algorithm. The ILC modifies the control input using the tracking error information from previous trials in order to improve performance.

Further development regarding the control architecture was made using the same rehabilitation scenario, in which an input–output linearizing controller with ILC [37] and a Newton-method based ILC controller [38] were developed. However, due to the limited time available during clinical trials, and considering the time-demanding procedure required for musculoskeletal model identification, these strategies were only evaluated on healthy subjects.

3.1.3. Hybrid robotic systems for reaching and grasping

The execution of ADLs requires a coordinated sequence of movements involving proximal and distal joints. For this reason, recent approaches prioritized the assistance of both reach-

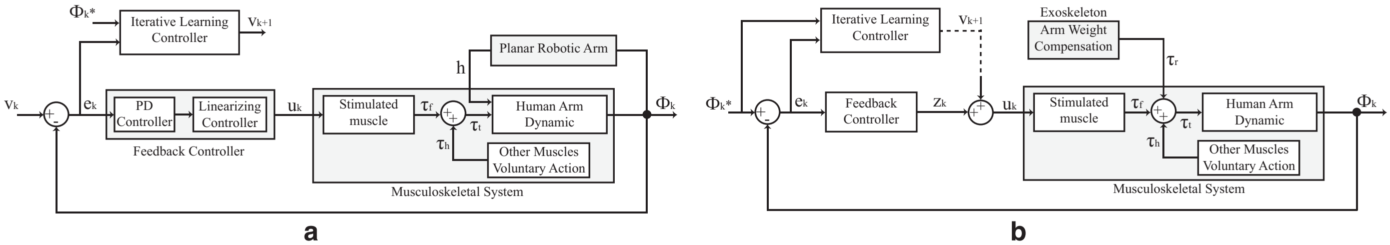

Fig. 4. FES control strategies implemented in hybrid robotic therapies for reaching movements. (a) Control scheme representation implemented in the planar end-effector workstation [30]. Φ^*_k is the reference trajectory and Φ_k is the measured joint angle at time k; V_{k+1} represents the feedforward update signal for application on next trial; e_k is the error at time; μ_k is the actuation signal; τ_f, τ_h, τ_t are the torque generated due to stimulated muscle, contribution of others muscles and the sum of both respectively; h is the torque provided by the planar robotic device. (b) Block diagram of control strategy for 3D rehabilitation system [31]. Φ^*_k is the reference trajectory and Φ_k is the measured joint angles at time k; V_{k+1} represents the feedforward update signal for application on next trial; e_k is the error at time; z_k is the actuation signal for the feedback controller; μ_k is total ($V_k + z_k$) the actuation signal; τ_f, τ_h, τ_t are the torque generated due to stimulated muscles, contribution of others muscles and the sum of both respectively; τ_r is the torque provided by the exoskeleton to support the arm against gravity.

Table 3
Identified hybrid systems for rehabilitation of reaching and grasping functions.

System	Application	Robotic device	FES device	Drawback
Robotic device + FES [39].	Reaching support and hand opening.	Reaching: Robot (Demcon, Enschede, The Netherlands); Active device. Grasping: none.	Reaching: none. Grasping: 9 channels (3 EDC, 3 FDS, and 3 thumb); MPC controller; Button triggered;	Dissociated functional assistance. Passive robotic device. Preprogramed FES parameters Non-associative assistance.
GO SAIL [40].	Shoulder flexion, elbow and wrist extension, 3D space.	Reaching: SaeboMAS robot; Passive device. Grasping: none.	Reaching: 2 Channels (AD, TR). Closed loop: FB+ FF. Grasping: 1 channel (EDC); Closed loop: FB+FF; Button triggered;	Passive robotic device. Limited functional response to FES during grasping. Non-associative assistance.
GO SAIL 2 [41].	Shoulder flexion, elbow, wrist and fingers extension, 3D space.	Reaching: SaeboMAS robot; Passive device. Grasping: none.	Reaching: 2 channels (AD, TR); Closed loop: FB+FF. Grasping: array of 24 channels (EDC); Closed loop: FB + FF; Button triggered.	Passive robotic device. Non-associative assistance.

Meaning of abbreviation and acronyms: *SAIL*: Stimulation assistance through iterative learning; *FES*: Functional electrical stimulation; *EDC*: Extensor digitorum communis; *FDS*: Flexor digitorum superficialis; *TR*: Triceps muscle; *AD*: Anterior deltoid muscle; *FB*: Feedback controller; *FF*: Feedforward controller; *MPC*: Model predictive control.

ing and grasping functions within the same rehabilitation system (Table 3). Westerveld et al. [39] presented a feasibility study of a custom-built 3D end-effector robotic device combined with FES. The robotic device compensated the arm weight against gravity and provided active reaching guidance with damper-based drivetrains [42]. This device guided the arm toward the references position using previously recorded paths, while FES was used to facilitate grasp and release of objects. A total of nine stimulation channels were used, three targeted at the thumb muscles (abductor pollicis longus, opponens pollicis and flexor pollicis brevis), three placed at the flexor digitorum superficialis and others three located over the extensor digitorum communis muscles. A VisualEyez motion capture system was used to track the position of the hand and fingers. The model predictive control algorithm, based on a second-order linear dynamic polynomial model, was used to set the stimulation intensity (pulse amplitude) during grasping [43].

As an extension of the SAIL system, the GO-SAIL system proposed by Meadmore et al. [40] was focused on training reaching and grasping functions through the execution of goal-oriented movements using real objects (see Fig. 5a). The user's arm was assisted during the execution of five different tasks (closing a drawer, pressing a light switch, stabilizing an object, pressing a button and lifting to reposition an object) that spanned the 3D workspace. In order to facilitate the execution of these functional tasks, the ArmeoSpring exoskeleton was substituted by a mobile arm support, called SaeboMAS. This device was used only when it was needed to support the arm against gravity. Thus, the user's affected arm was strapped to the mobile arm while the FES was applied to three muscles groups: anterior deltoid, triceps and wrist and fingers extensor (the wrist and finger extensor was additionally stimulated with respect to the SAIL system). The GO-SAIL used a control strategy similar to the one implemented in the SAIL system, in which the ILC algorithm adjust the stimulation intensity in the current attempt at the task based on the errors of previous movements.

Recently, Kutlu et al. [41] introduced some improvements to the GO-SAIL system to allow a better control of finger movements during the execution of the proposed ADL tasks. The main improvements consisted in incorporating a new sensing mechanism that measures the arm joint angles, and an electrode array (24 channels in a 6×4 configuration) on the forearm to enhance control of the hand and wrist. In this case, an additional term was added to the control scheme implemented for the GO-SAIL system for grasping support. It was assumed that the movements of the arm segments (shoulder and elbow) are decoupled from the hand. Thus, two separated controllers were combined as shown in Fig. 5b. A proportional-derivative controller was implemented in the feedback loop to control the arm movements, whereas a proportional gain was considered for controlling the hand. For the feedforward loop, an ILC algorithm was implemented in a phase-lead configuration to update the control parameter.

3.2. Clinical evaluation

In this section, we present a brief overview of the clinical evaluations carried out with several of the reviewed hybrid robotic systems. Table 4 presents a summary of the main features of these studies.

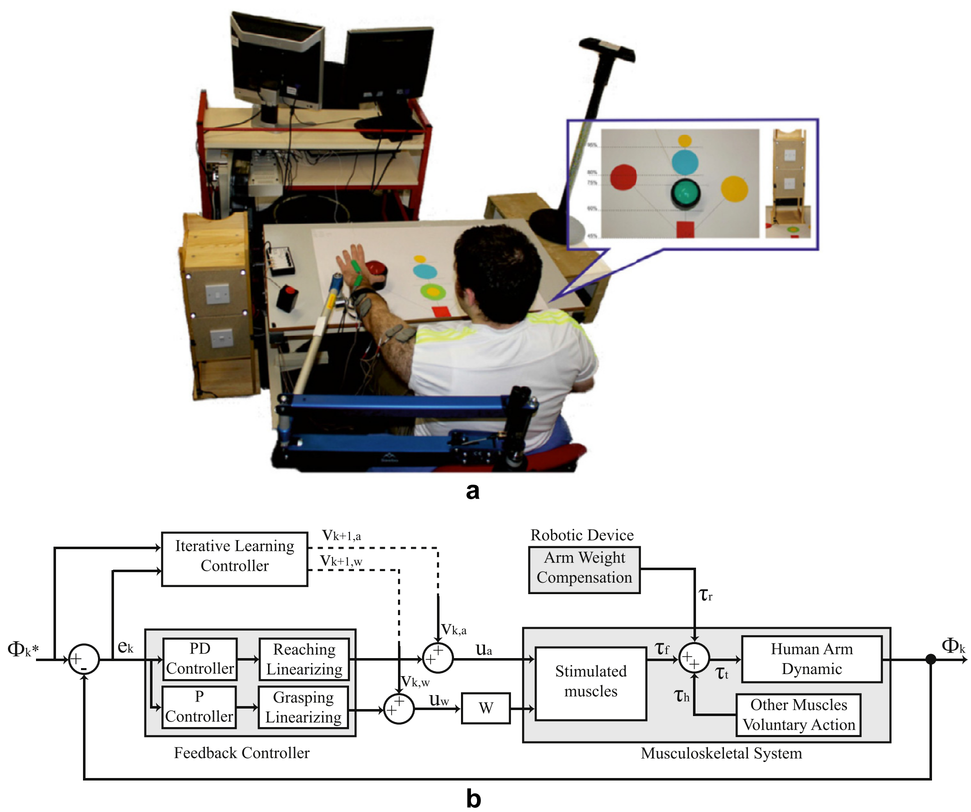

Fig. 5. (a) Hybrid robotic system design for combined reaching and grasping rehabilitation [40]. (b) The implemented FES control scheme by Kutlu et al. [41]. Φ^*_k is the reference trajectory and Φ_k is the measured joint angles at time k; $V_{k+1,a}$ and $V_{k+1,w}$ represent the feedforward update signal for application on next trial at the shoulder and elbow, and, wrist and fingers respectively; e_k is the error at time; u_a and u_w are the actuation signal for shoulder and elbow, and, wrist and fingers respectively; τ_f, τ_h, τ_t are the torque generated due to stimulated muscles, contribution of others muscles and the sum of both respectively; τ_r is the torque provided by the robotic device.

Table 4
Clinical assessment of the reviewed hybrid robotic systems.

System	Patients	Control group	Outcomes scales
		Grasping	
NESS HandMaster [20,21].	77 chronic strokes [20]. 22 sub-acute strokes [21].	None [20]. Group1: NESS users; Group 2; Conventional therapy [21].	Clinical: JT, B&B, NHPT, MAS, PPI [20]. Clinical: PROM, MAS, B&B, JT [21].
HANDS [22].	20 chronic stroke.	None.	Clinical: UEUS, SIAS, MAS. Pressure force during handwriting. Neurophysiological: CI, H-Reflex, and MEP.
Wrist Training [23–25].	5 chronic Stroke [23]. 5 chronic Stroke [24]. 26 chronic stroke [25].	None [23]. None [24]. Group1: EMG-driven Hybrid system; Group2: EMG-driven of robotic device [25].	Clinical: FMA, MAS, ARAT. Neurophysiological: CI.
		Reaching	
SMART + FES [28].	33 chronic stroke.	Group1: EMG-driven Hybrid system; Group 2: robot alone; Group 3: no intervention.	Clinical: motor assessment scale, MAS.Isometric force. ROM.
BAT system [29].	23 chronic stroke.	Group 1: Hybrid system. Group 2: Robot alone.	Clinical: FMA, MAL.
Planar end-effector device + FES [30].	5 chronic stroke.	None.	Clinical: FMA, ARAT. Task performance. Isometric force.
SAIL system [31,32].	5 chronic stroke.	None.	Clinical: FMA ARAT. Task performance.
		Reaching and grasping.	
Robotic device + FES [39].	5 chronic stroke.	None.	–
GO SAIL [40].	5 chronic stroke.	None.	Clinical: FMA, ARAT. Task performance
GO SAIL 2 [41].	4 chronic stroke.	None.	Clinical: FMA, ARAT. Task performance

Meaning of abbreviation and acronyms: *FES*: Functional electrical stimulation; *HANDS*: Hybrid assistive neuromuscular dynamic stimulation; *SMART*: Sensorimotor active rehabilitation training; *BAT*: Bilateral arm training; *SAIL*: Stimulation assistance through iterative learning; *JT*: Jebsen–Taylor; *B&B*: Box & Block; *NHPT*: Nine-holes peg test; *PPI*: Perceived pain intensity; *ROM*: Range of movement; *UEUS*: Upper extremity utility score; *SIAS*: Stroke impairment assessment set; *FMA*: Fugl–Meyer assessment; *MAS*: Modified Ashworth score; *ARAT*: Action research arm test; *FIM*: Functional independence measure; *MAL*: Motor activity log; *CI*: Co-contraction index; *MEP*: Motor evoked potential.

3.2.1. Clinical outcomes of hybrid system for grasping rehabilitation

The NESS HandMaster was evaluated in two separate studies. Related papers reported trials with a high quantity of chronic (n = 77) [20] and sub-acute (n = 22) [21] stroke patients.

Alon et al. [20] evaluated the NESS HandMaster with 77 chronic stroke patients. They reported a significant improvement in the Jebsen–Taylor, Box & Block and Nine-Peg Test scores. Also, the results showed a significant reduction in the perceived pain intensity after therapy. While the modified Ashworth scale (MAS) at the shoulder, elbow, wrist and fingers was not significantly reduced.

Ring and Rosenthal [21] defined two types of sub-acute stroke patients to evaluated the NESS HandMaster. Type I was composed by those patients with no active voluntary motion at the fingers and wrist (n = 10). Type II was composed of patients with partial active voluntary range of motion (n = 12). Patients were also assigned to the control group (conventional therapy) and the treated group (NESS Hand Master users). Considering the MAS, a significant improvement was found on type I treated group for shoulder and fingers (P = 0.05 and P = 0.04), and in the type II treated group for the shoulder (P = 0.03), wrist (P = 0.04), fingers (P = 0.01), and thumb (P = 0.04). The evaluated range of motion of the arm joints showed a greater improvement in proximal upper limb in the type I treated group. However the difference did not reach a level of statistical significance. The type II treated group showed greater level of improvements, with significant level for shoulder flexion (P = 0.03), wrist extension (P = 0.02) and wrist flexion (P = 0.04). The functional tests (Box & Block and the Jebsen–Taylor) presented significant improvement in both types of the treated group.

In the case of the HANDS system, its effects were evaluated in 20 chronic stroke patients [22]. Results revealed significant improvements (P < 0.01) in two of the four evaluation points (drinking with a glass and turning over a page) of the upper extremity utility score (UEUS). The finger test as well as the knee–mouth test of the stroke impairment assessment test (SIAS) also improved significantly (P < 0.001 and P = 0.02). The MAS were reduced significantly at the elbow wrist and finger extensors (P < 0.001), and the pen pressure capability increased significantly (P = 0.008). The H-Reflex showed significant changes of reciprocal inhibition at all three intervals after intervention (0, 20 and 100 ms), while the co-contraction index measured with EMG and the motor evoked potential elicited by transcranial magnetic stimulation improved, but not significantly. The clinical outcome measures and computer-aided ratings were assessed in 15 of the 20 patients three months after the end of the intervention. The evaluation showed a significant effect in comparison with the pretreatment assessment of time in the “drinking with a glass” task and the “turning over a page” task in the UEUS, the SIAS finger score, the MAS (elbow, wrist, finger) score, the pen pressure, and the grip strength (P < 0.05). When comparing the post-treatment values with those at the 3-month follow up, a significant difference was found in the “drinking with a glass” task and the grip strength (P < 0.05).

With their wrist training system, Hu et al. [25] carried out a single-blinded randomized controlled trial with 26 chronic stroke patients to evaluate the effectiveness of the wrist training platform. Recruited patients were divided into two different groups, in which fifteen of them received EMG-driven robot therapy (control group), and the rest (n = 11) EMG-driven FES robot rehabilitation (experimental group). The clinical evaluations showed significant improvements in the Fugl–Meyer assessment (FMA) shoulder/elbow, a significant decrease in the MAS elbow/wrist for both groups after the training, and these improvements were sustained after 3 months (P < 0.05). The experimental group achieved higher scores (better outcomes) in the post and 3-month follow-up evaluation. The FMA wrist/hand and the action research arm test (ARAT) significantly improved only in the experimental group (P < 0.05) and this increase compared with the baseline remained till 3 months later. The EDC and FCR pair co-contraction index (CI) was significantly decreased for the experimental group (P < 0.05); and after session 10, most CI values of experimental group were significantly lower than those of the control group (P < 0.05). These findings show the potential of the hybrid approach to conduct both clinical and neurophysiological improvements.

3.2.2. Clinical outcomes of hybrid system for reaching rehabilitation

With the SMART+FES system, Barker et al. carried out a single blinded randomized clinical trial with 33 chronic stroke subjects [28]. The subjects were allocated in one of three groups: SMART Arm with stimulation triggered by volitional EMG activation (SMART + FES), SMART Arm alone (SMART), and home program without alternative treatment (control). The authors reported that both SMART and SMART + FES groups demonstrated a significant improvement in all outcome measures after 4 weeks (post training) and at 12 weeks (2-month follow-up), while the control group showed no change. The difference in the amount of improvement exhibited by the SMART and SMART + FES groups was not statistically significant. However, these groups presented higher degree of improvements when compared with the control group. These findings are opposite to those found during the wrist training [25], where major improvements were reported in the FES + robot group. The authors justified the previous remark mentioning that the repetitive nature of the therapy was principally responsible for the observed changes in the evaluations.

The BAT system was assessed with 23 chronic stroke patients [29]. The patients were divided into two groups: training with BAT and FES (experimental), and BAT without FES (control). The results revealed no differences in the inter- and intra-groups for the FMA and the MAS. The ARAT presented significant improvements after training in both groups and one-month follow-up the evaluation was only significantly in the experimental group.

Hughes et al. [30] presented a preliminary evaluation of a planar end-effector device combined with FES, with five chronic stroke patients. The results indicated improvements in the tracking ability of patients when performing unassisted reaching task (without FES). They also report an improvement in the generated force under isometric conditions measured with the end-effector robot. Clinical assessment showed a reduction in upper limb impairment using the FMA score ($P \leq 0.05$), while the ARAT did no show significant changes.

A preliminary clinical evaluation of the SAIL system was performed with five chronic stroke subjects [31]. The execution of unassisted reaching task (without FES) showed that the tracking accuracy improved over the course of the intervention for both shoulder and elbow. The clinical scales revealed significant improvements in the FMA (P = 0.001), while no changes were found for the ARAT. These results were consistent with the ones obtained when training the reaching with the planar end-effector device and FES [34]. The authors reported that with the SAIL system the FMA scores obtained were greater (mean difference of 9.3 vs. 2.5) [31]. Authors suggested that one possible reason for the difference in results is that the SAIL intervention trained two muscles in 3D space, whereas the planar end-effector device and FES trained only triceps in 2D space.

3.2.3. Clinical outcomes of hybrid system for reaching and grasping rehabilitation

The system presented by Westerveld et al. [39] was validated in a single session with two stroke patients. As this single session was focused on verifying the system integration and safety issues, no conclusion was made with respect to rehabilitation outcomes. However, authors reported a success rate of complete grasp, move and release tasks with different objects ranged from 33% to 87% in healthy subjects. In severe chronic stroke subjects especially the hand opening had a low success rate (<25%) and no complete movements could be made.

Meadmore et al. [40] presented the evaluation of the GO SAIL system with five chronic stroke subjects. Based on previous results obtained with the SAIL system for reaching rehabilitation (see Section 3.2.2), the authors hypothesized that the incorporation of assistance for the wrist and finger extensor (besides the shoulder and elbow) will reduce the motor impairment (assessed by the FMA) and it would also yield to significant improvement in the ARAT scale. The results validated their hypothesis since both the ARAT ($P = 0.005$) and the FMA ($P = 0.036$) scales improved significantly. Also, the performance of unassisted movement (without FES) improved significantly. Nevertheless, the authors pointed out that there is still a need for a fine control of finger movements that allows greater abilities for execution of ADL.

The study presented by Kutlu et al. [41] addressed the issues mentioned in the GO SAIL system. The improvements introduced (explained in Section 3.1.3) were assessed with four chronic stroke individuals. Again, this study demonstrates improvement in movement accuracy during reaching and grasping task. However, contrary to expectations the results did not show any statistically significant improvements for ARAT and FMA scales.

4. Discussion

The ten different systems reported in this review represent, to the best of our knowledge, the state of the art of the combined use of robotic and FES devices for upper limb rehabilitation after stroke.

4.1. Improving technical aspects: hybrid approach challenges

Hybrid robotic systems combine two technologies (FES and robotic devices) into one platform, complementing each other, to overcome the performance of each independent approach. For this purpose, it is necessary to establish what is the role of each technology within each platform and how it will improve the overall result of rehabilitation.

The most used hybrid robotic systems combined an end-effector and an FES device. The end-effector robots have been mostly employed to support the arm's weight and to delimit the workspace while the FES was used to drive the movement of the arm during the task execution. The main advantage of this approach is the simplicity of the setup (usually 1 DoF) that facilitated the implementation of the control algorithms. However, two main drawbacks arise when considering these devices. First, the amount of assistance during movement is limited since the mechanical forces are not applied directly to specific joints and the movement is mainly driven by FES. Second, the range of motion of this type of robotic devices is limited. Therefore, only a limited set of rehabilitation exercises can be carried out, hindering tasks generalization, which is an important factor for promoting motor recovery after stroke [44].

Among the reviewed studies, only the SAIL system presented by Meadmore et al. [31] considered the use of a passive exoskeleton in combination with FES. Passive exoskeletons have the advantage of fully supporting the whole arm against gravity at the joint level over end-effector devices. Also, they may provide a larger range of motion in the 3D space. This provides more freedom to apply FES and focuses it only on driving the arm movements, this way reducing the stimulation intensity and the muscle fatigue onset. However, this setup is limited by mechanical constraints and requires a robust and reliable FES system to drive the movements successfully.

A full hybrid robotic system (from the actuation perspective) is the one that provides support by combining an exoskeleton with active actuators and FES. Several systems following this approach have been reported for lower limb and gait rehabilitation [19]. Despite the broad diffusion of powered upper limb exoskeletons in recent years [45], the combination of these devices with FES has not been reported for the upper limb rehabilitation. This combination could improve the performance of current hybrid robotic systems significantly since the arm movement does not only depend on the FES capacity. For example, the low success rate reported in [39], due to the inability of driving the movement with FES, could be significantly improved if additional mechanical assistance is provided at the joint level. Furthermore, this combination could allow the development of novel interventions, such as targeting specific muscles groups with FES, while supporting the rest of the arm movement with the exoskeleton. However, the main challenge for full hybrid robotic systems is the development an optimally shared control between the FES, the exoskeleton and the patient movement capacity to promote and potentiate the effects of therapy.

Therefore, a robust FES controller plays a crucial role in the successful deployment of hybrid robotic systems. The performance of FES systems depends on the control strategy, the number of stimulation channels and the correct electrode placement. The control strategy should be able to compensate the non-linear and time-varying response of the musculoskeletal system due to the non-physiological motor unit recruitment.

Simple FES control strategies (e.g. open-loop and linear feedback controllers, i.e. PID) are often inadequate for controlling the execution of motor tasks, mainly caused by the high muscle response variability [10,36]. Also, when using a model-based feedback controller the modeling of the musculoskeletal system is a major factor to carry out the tasks successfully. For instance, Westerveld et al. [39] used a model predictive control algorithm based on a second order model, and got a success rate of less than 20% for opening the hand. The disorders to the central nervous system caused after Stroke (e.g. spasticity) could affect significantly the quality of the EMG signals, which limits the applicability of the EMG-based controllers.

Alternatively, the implemented learning feedforward loop considered in [30,31,40,41] represents an interesting approach, since it exploits the repetitive nature of robot-aided rehabilitation to learn from the errors of previous attempts. This learning capability provides a way to compensate and adapt to the physiological changes of patients (e.g. muscle response variation due to muscle fatigue or spasticity).

A good control of grasping motion is necessary for promoting the patients' motivation and engagement during therapy since the inability to perform the tasks could yield users in feeling frustrated. For grasping tasks, the number of stimulation channels influences the precise control of the hand and fingers movements considerably. Due to the high density of muscles at the forearm, the use of few stimulation channels typically results in a reduced motor functional response and this problem is more noticeable when surface electrodes are used [9]. It has been demonstrated that the use of multi-pad electrodes (e.g. a matrix of electrodes) improved the precision of controlled movement significantly [46]. Yet, this approach has been only considered by Kutlu et al. [41].

4.2. Rehabilitation outcomes

Published systematic reviews reported that after robot-based therapy, stroke patients presented a reduction in motor impairment but did not improve in functional abilities [47,48]. It has been suggested that upper limb rehabilitation is location specific [40,49]. Thus, reaching rehabilitation will only improve motor impairment in the proximal joints (shoulder and elbow) while grasping training will have a repercussion only in the wrist and fingers. In line with this evidence, the hybrid robotic systems for reaching [30,31] showed improvements in the motor impairments (measured by FMA) but not in functional improvements (measured by the ARAT scale). However, when the assistance was provided to the hand and wrist together with the proximal joints [40], it resulted in significant improvement in the FMA and ARAT scores. This evidence suggests that the whole upper limb must be considered in rehabilitation to achieve a better reduction in motor impairment and functional changes.

Under a clinical perspective, performing a direct comparison between studies becomes a challenging task due to the lack of standard evaluation metrics or procedures across studies. This issue was pointed out by Huang and Krakauer [14] for post-stroke rehabilitation therapies. Also, the relatively small number of studies and their methodology, as well as the small number of subject that were tested, makes it difficult to reach a generalize conclusion. Only four studies considered the inclusion of a control group for the evaluation of the hybrid robotic systems [21,25,28,29], and these control groups were different in all cases. The inclusion of a control group for demonstrating the effectiveness of a hybrid rehabilitation system is important. However, it is difficult to implement in practice due to the high number of patients that will be required during the experiments. In fact, since two therapies are being implemented jointly (robot and FES), at least three groups of patients would be necessary to check whether the hybrid robotic system results in significant improvements with respect to robotic and FES separately.

However, the significant improvements achieved in most of the reported studies support the hypothesis of the benefits of using combined robotic devices with FES for upper limb rehabilitation after stroke.

4.3. Improving the human-machine interaction: associating assistance with voluntary effort

Associating the assistance onset with the user's movement intention in a timed manner has been shown to be an important factor for promoting neuromuscular recovery [50,51]. Recent studies have demonstrated that the application of peripheral assistance precisely synchronized with the user's motor intent induce long-term potentiation in the corticospinal pathway in healthy [51,52] and stroke patients [53].

In this regard, only a few of the reviewed hybrid systems have addressed the associative paradigm by using voluntary EMG activation to trigger the system assistance [22,25,28]. However, the optimal stimulus timing may be degraded by the intrinsic delay between cortical and peripheral activity [50]. Also, the quality of the EMG could be affected as a result of the level of impairment, which has a direct impact on the timing and reliability of the intention detection systems.

EEG-based brain-computer interface could be used as an alternative to the EMG intention detection for hybrid robotic systems. The advantage of these interfaces is that the synchronization between motor intent and motor execution can be realized without much delay. However, these interfaces have shown low reliability, mainly caused by the presence of noise and artifacts in the acquired signals [54]. Nevertheless, this is an interesting avenue that could be exploited to promote neuroplasticity and potentiate the rehabilitation effects of hybrid robotic systems.

5. Conclusions

This paper has presented an overview of studies in which the combined use of robotic devices with FES was reported for rehabilitation of upper limb motor function after stroke. Hybrid robotic systems are an emerging approach aimed at combining two different but complementary methods. The main goal under this hybrid perspective is to enhance current rehabilitation capabilities of each individual technique.

Still many challenges remain to be investigated. The inclusion of exoskeleton devices with active actuator will enable a more natural movement in an unconstrained environment, with the capability of implementing more complex and sophisticated rehabilitation paradigms. Estimation and management of muscle fatigue elicited due FES must be conducted to mitigate its adverse effects. The different clinical scales used to evaluate the rehabilitation effect of the hybrid therapies hinder the comparison between systems. Yet, it is suggested that future systems should comprise reaching and grasping training in order to enhance motor impairment and functional abilities.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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