Istraživanja i projektovanja za privredu
ISSN 1451-4117
DOI:10.5937/jaes0-44644
www.engineeringscience.rs

Journal of Applied Engineering Science
Vol. 22, No. 1, 2024
Review Paper
Paper number: 22(2024)1, 1167, 55-68

LITERATURE REVIEW: USER INTERFACE OF SYSTEM FUNCTIONAL ELECTRICAL STIMULATION (FES) AND ARM ROBOTIC REHABILITATION

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Interface technology development for human-robot interaction (HRI) in rehabilitation systems has increased in recent years. HRI can effectively achieve specific motor goals desired in rehabilitation, such as combining human intentions and actions with robotic devices to perform the desired stroke rehabilitation movements. Rehabilitation devices are starting to be directed towards using devices that integrate functional electrical stimulation (FES) with robotic arms because they have succeeded in providing promising interventions to restore arm function by intensively activating the muscles of post-stroke patients. However, FES requires a high level of accuracy to position the limbs for the functional tasks given because excessive electrical stimulation can cause fatigue in the patient, so it is necessary to provide electrical stimulation with an amplitude that suits the patient's needs. Unfortunately, most studies have a constant voltage amplitude and do not consider the voltage that matches the patient's muscle needs; this treatment can cause fatigue in the patient. Robotic devices as rehabilitation aids have the potential to support external power and adapt electrical stimulation needs to the voltage amplitude applied to the FES. Integrating FES with a robotic arm support system into one hybrid neuroprosthesis is attractive because the mechanical device can complement muscle action and increase rehabilitation's repeatability and accuracy rate. The integration of FES and robotic arms is a promising approach in the future. This article reviews the state of the art regarding motor rehabilitation using functional electrical stimulation (FES) devices and robotic arms for the upper limbs of post-stroke patients. A narrative review was done through a literature search using the IEEE-Xplore, Scopus, and PubMed databases. Nine different rehabilitation system articles were identified. The selected systems were compared critically by considering the design and actuators, components, technological aspects, and technological challenges that could be developed in the future. This article also examines the development of HRI and emerging research trends in HRI-based rehabilitation.

Keywords: interaksi manusia-robot, arm robot rehabilitasi, FES

1 INTRODUCTION

According to the World Health Organization (WHO), stroke sufferers have increased to 15 million people every year. This number is estimated to increase by 3.4 million people in 2030. One of the body functions affected by stroke is the motor function of the upper limbs [1]. The decrease in motor skills reduces quality of life and hinders carrying out life activities. The drop that occurs is influenced by residue in the muscles of the upper limbs [2]. Post-stroke rehabilitation is the main focus in restoring neuromuscular function and restoring independence to stroke sufferers [3]. This paradigm causes the development of post-stroke rehabilitation of the upper limbs to continue to develop.

The development of post-stroke rehabilitation has been heavily influenced by research examining the field of engineering rehabilitation. The results are carried out with the Human-robot interface (HRI), which combines intention with action between humans and robots and allows humans to interact safely with robotic systems [4]. HRI can effectively achieve specific motor goals desired in rehabilitation, such as combining human intentions and actions with mechanical devices to perform hand grasping movements, reach for objects, or walk; these devices can be practical stroke rehabilitation tools [5]. Rehabilitation devices are starting to be directed using functional electrical stimulation (FES) devices integrated with robots because they have been intensively successful in encouraging plasticity and residual recovery in post-stroke patients [6]. FES was first introduced in 1967 by the Ljubljana Rehabilitation Engineering Center (REC), which stimulated the peroneal nerve by implanting it in hemiplegic patients [7]. FES-based rehabilitation provides low-power electrical stimulation capable of producing muscle contractions and joint movement [8]. It has been reported that using FES can benefit more than conventional therapy used for post-stroke rehabilitation [9]; [10]. Apart from improving motor repair, it has been studied that FES can also cause changes in cortical excitability and stimulate cortical reorganization [11]. Research on FES as upper limb rehabilitation during early development focuses on the influence of the magnitude of electrical stimulation input (pulse amplitude, pulse width, and frequency) to command coordinated movements through the elbow, wrist, and hand. However, in its development, the use of FES has had several challenges; excessive use has resulted in fatigue in post-stroke patients [12], [13].

Recently, a rehabilitation robot arm integrated with FES as wrist rehabilitation carried out by a research group showed more promising rehabilitation effectiveness in motor recovery of upper limbs [14]; [15]. Repair via a robotic arm was introduced as a good tool with an intensive rehabilitation automation system that allows higher doses, intensity, and more prolonged exposure to treatment [16]. A rehabilitation robotic arm provides reliable kinematic and kinetic measurements that can be used to measure patient progress [17]. However, pure robot-assisted rehabilitation is susceptible to the slacking effect, where the patient adopts a passive stance and allows the robot to move the upper limbs without making any effort, resulting in no functional improvement [18]. A rehabilitation robot arm integrated with FES has the potential to produce a device with greater strength and more precise control due to the force exerted by the actuator [19]. The actuator assistance from the rehabilitation robot arm makes it possible to provide external power. It can delay muscle fatigue due to electrical stimulation with the force given by the robot arm to post-stroke patients [20].

FES integrated rehabilitation robot arm enables the development of new rehabilitation interventions. FES and arm robot rehabilitation are possible solutions to overcome the limitations of each Technology so that they can increase the durability, safety, and effectiveness of rehabilitation interventions. The FES technology approach integrated with the rehabilitation robot arm can target specific muscle groups in patients stimulated through the FES device with movement support through the outer frame of the rehabilitation robot arm. In this article, we will conduct a literature review regarding Technology that integrates FES and arm robot rehabilitation, with the primary aim being to describe various literature that examines Technology that combines FES and arm robot rehabilitation, including rehabilitation targets and rehabilitation strategies carried out, as well as potential and the benefits of Technology for use as upper limb rehabilitation for post-stroke patients. The various literature approaches were carried out by analyzing from the point of view of the use of FES device technology and robotic arms used for upper limb rehabilitation in post-stroke patients, such as the voltage and frequency of stimulation given, the use of channels, the control system used and the active or passive actuators on the robotic arm. This article also discusses clinical trial perspectives on the use of FES devices and rehabilitation robotic arms.

2 PROPOSED METHOD

The method used in this article is a literature review to synthesize the use of FES technology and arm robot rehabilitation for upper limbs for post-stroke sufferers. The search used a narrative study conducted on the Scopus, IEEE Xplore, and Pub-Med databases. There is no limit on the publication date. There are no exceptions for articles, both conference articles and journal articles. We completed the search in October 2022. The search query was already defined, so the resulting studies had the following characteristics:

a) All articles must comply with the definition of a control system that integrates FES devices and rehabilitation robot arms.
b) Technology focused on rehabilitation of upper limbs.
c) The studies considered at least one of the outcome measures, including kinematic data, EMG signals, strength measures, clinical scales, and functional evaluation in post-stroke patients.

A search using keywords related to FES integrated control systems and arm robot rehabilitation resulted in 279 articles: 121 papers from Scopus, 32 from IEEE Xplore, and 126 from PubMed. We screened studies using three main steps to eliminate documents unrelated to the focus of this review. The methodology is described according to the prism flow diagram in Figure 1.

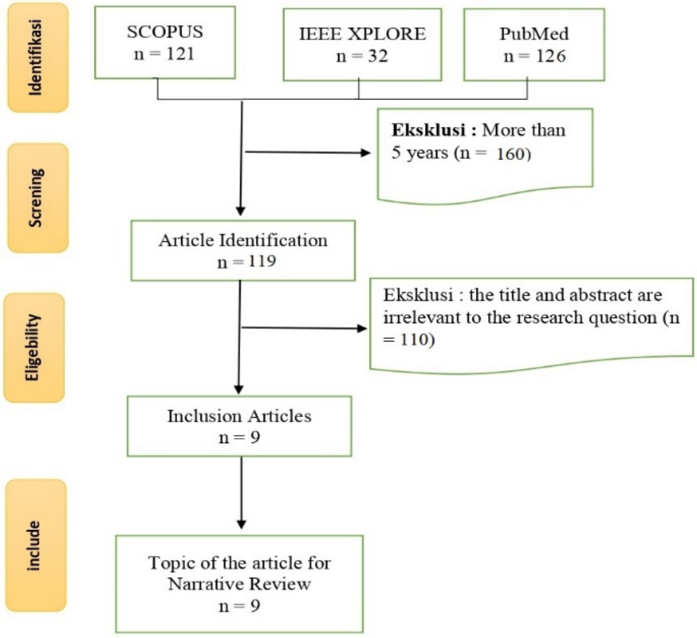


Fig. 1. Prism Flow Diagram

Mapping and developing research trends can be done using bibliometric analysis. Figure 2 shows that data related to the studied research themes grows and develops rapidly yearly.

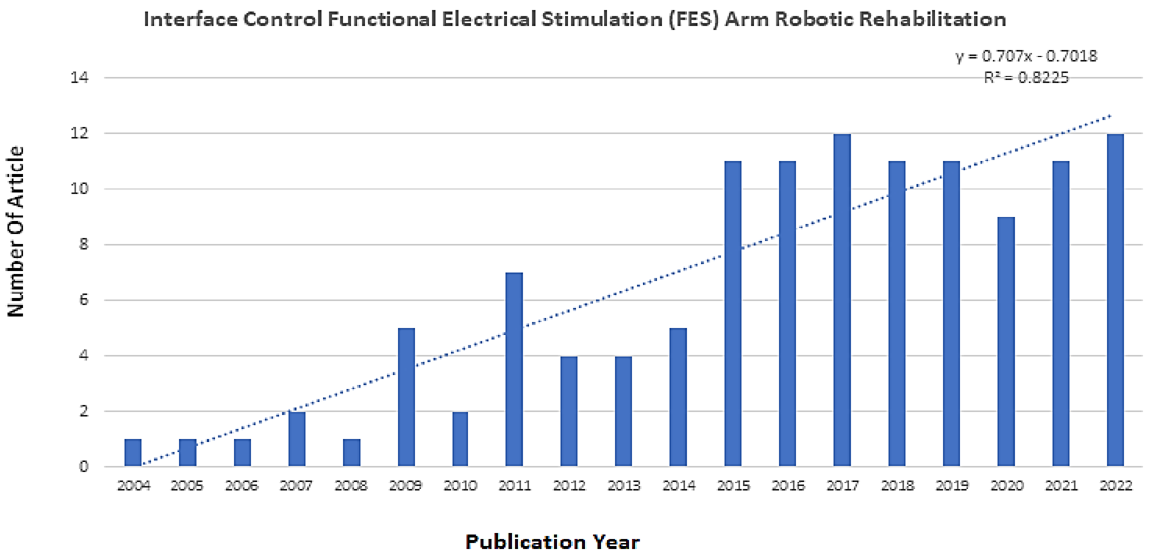


Fig. 2. Trends in research on FES interface control and upper limb rehabilitation robot arms

The selection of articles conforms to predetermined criteria, then presented in a logical and systematic order so that they can be used as a reference for future research by quantitatively analyzing the characteristics of articles in the research area that discuss the use of FES technology and robotic arm rehabilitation in the upper limbs. The development of research trends published periodically every year, with the search criteria used, shows that research interest in discussing the use of FES technology and arm robot rehabilitation in upper limbs from 2004-2022 has increased, with the highest number of publications in 2017 and 2022.

3 RESULTS

3.1 Study of FES Integration Technology with Rehabilitation Robot Arm

The control system on the FES device and the rehabilitation robot arm have been introduced as promising technologies to support intensive rehabilitation, allowing more extended training [17]. The control system on the FES device and the rehabilitation robot arm has the potential to offer great benefits for the rehabilitation of post-stroke patients by providing electrical stimulation to specific muscle groups, which is supported by the movement of the exoskeleton of the rehabilitation robot arm, enabling plasticity and recovery of post-stroke patient residue [21]. Based on predetermined criteria, nine selected articles were identified. Then, the articles were classified into three groups: use of active actuation exoskeletons with DC motors (n = 4) and use of active actuation exoskeletons with pneumatics (n = 2). use of passive actuation exoskeletons (n =3). The criteria obtained from 9 articles were then analyzed based on usage.

3.2 Integration of FES and robot arm with DC motor actuator (Active)

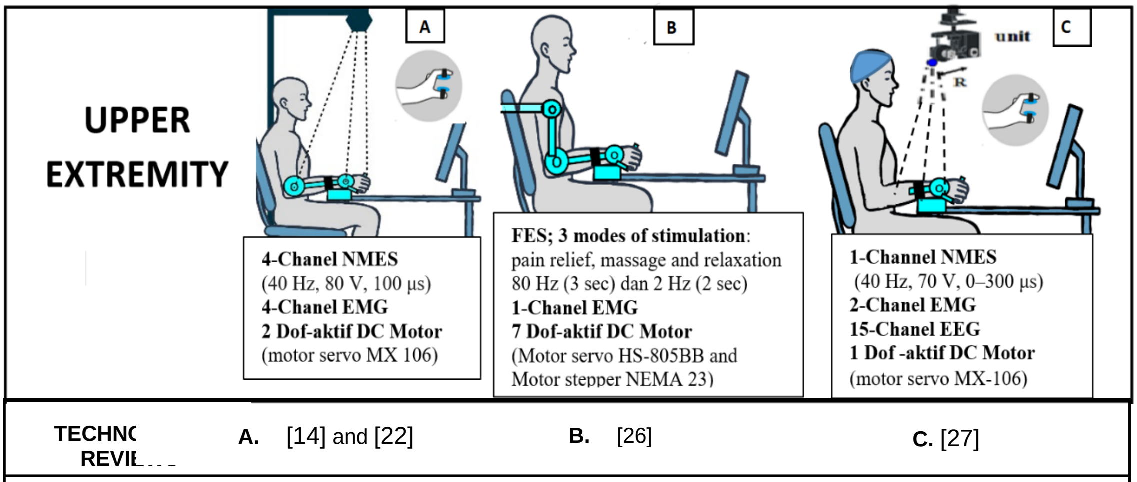
FES integrated with a rehabilitation robotic arm allows perfecting accuracy to achieve kinematics and reduce muscle fatigue so that muscle stimulation can be carried out intensively and repeatedly for post-stroke patient rehabilitation [14]; [22]. In general, the active actuator model with a DC motor is used as a component to convert electromechanical energy because of its ability to regulate the speed and torque required for the rehabilitation robot arm [23]; [24]. FES integrated with a rehabilitation robot arm needs to consider the control system used in the technology to determine the dynamics of technological development applied to post-stroke patients. The control system will influence the device's performance and the therapeutic scenarios developed [25]. The use of control systems for various types and sizes of electric motors or servo motors that are commercially available needs to be considered, so it is essential to discuss the kind of robot, actuator, support movements, degree of freedom (DoF), robot device because considering the type of motor affects the weight. The motor torque must be adjusted to the needs of the rehabilitation robot arm to ensure patient safety and comfort when using the robot arm to assist the patient with joint movement [26]. Apart from that, it is essential to discuss the magnitude of the voltage and frequency of stimulation in FES because it influences the level of muscle fatigue due to electrical stimulation, which stimulates cortical reorganization in the patient's muscles [11]; [20]. Table 1 explains several studies that discuss the integration of FES with rehabilitation robot arms using active actuators with DC motors.

Table 1. Integration of FES and arm robot rehabilitation using active actuators with DC motors

Reference	Type Of Robot	Actuation	Supported Movements	DoF	Robot device	Electrical Stimulation Device
Qian et al. [14] and Rong et al. [22]	NMES + Robot	DC Motor (motor servo MX 106)	Elbow (EF) Wrist (EF)	2-Active	Mechanical design of two elbow and wrist orthotic limb extensions Controlled by voluntary EMG 4 channels	NMES 4 channels (80V, 40 Hz, 100 µs) and NMES 4 channels (80V, 40 Hz, 0-200 µs) Controlled by voluntary EMG 4 channels
Bouteraa et al. [26]	Exoskeleton + ES	DC Motor 1. Motor servo HS-805BB 2. Motor stepper NEMA 23	Shoulder (internal rotation) Elbow (EF, PS) Wrist (EF)	7-Active	The mechanical design consists of three segments: Shoulders, forearms and wrists Manual control system preset mode and the automatic Mode (EMG 1- channels)	FES 1 Chanel (80 Hz (3 sec) and 2 Hz (2 sec) Manual control system preset mode and the automatic Mode (EMG 1- channels)
Guo et al. [27]	NMES + Robot.	DC Motor (motor servo MX-106)	Wrist (EF)	1-Active	Wrist joint mechanical design Controlled by voluntary EMG 2 channels and EEG 15 channels. visual feedback, closed-loop	NMES 1 channel (0–300 µs, 70V, 40Hz) ECU-ED muscle Controlled by voluntary EMG 2 channels and EEG 15 channels. visual feedback, closed-loop

Meaning of abbreviations and acronyms: Ekstensi/Fleksi (EF); Pronasi/Supinasi (PS); Otot Ekstensor Carpi Ulnaris (ECU) and Ekstensor Digitorum (ED); Neuromuscular Electrical Stimulation (NMES); Electrical Stimulation (ES); Electromyography (EMG); Degree of Freedom (DOF)

The literature from the articles identified in Table 1 was then redesigned based on an experimental scheme, which was used as a representation to make it easier to understand the use of the technology being developed. Figure 3 is a design and practical method from the literature that has been identified in Table 1, namely a control system that integrates FES and a robot arm with an active actuator using a DC motor.



Meaning of abbreviations and acronyms: Neuromuscular Electrical Stimulation (NMES); Function Electrical Stimulation (FES); Electromyography (EMG)

Fig. 3. Schematic representation of the FES integration design and robot arm using an active actuator with a DC motor adopted from literature articles

The schematic representation of a design that integrates FES and a robot arm using an active actuator with a DC motor in Figure 3 is adopted from literature articles identified in Table 1. Several research groups have investigated the implementation of devices that integrate FES and a robot arm using an active actuator with a DC motor as upper limb rehabilitation. The use of FES combined with a robot arm using a DC motor actuator has been reported by Qian et al. [14] and Rong et al. [22] was able to help post-stroke patients to generate muscle contractions through electrical stimulation using multi-joint NMES supported by robot arm movements which produce flexion/extension movements at the wrist and elbow using a DC motor actuator type MX 106. The robot arm design uses joints 2-Dof, as shown in Figure 3A.

Meanwhile, electrical stimulation to generate muscle contractions in post-stroke patients uses NMES 4 channels; each channel has a constant amplitude value of 80 V with a stimulation frequency of 40 Hz and a pulse width set between 0 and 200 s. The developed rehabilitation scheme uses a control system via electromyography (EMG) signals, which have been classified to provide tracking tasks according to the rehabilitation needs. The EMG control system can be considered a combination of control systems capable of joint control between the FES device and the robot arm, with movement between segments controlled directly.

Guo et al. [27] developed the same rehabilitation scheme by adding a control system using a 15-channel Electroencephalogram (EEG) and 2-channel EMG or what could be called a CMC-EMG control system to control 1-channel NMES and an active 1-DoF robot arm shown in Figure 3C. The control system using CMC-EMG allows the intensity of neural synchronization between cortical and muscle activity during voluntary movements, verified by corticomuscular coherence and spectral correlation between EEG and EMG. The NMES device developed has a constant amplitude value of 70 V with a frequency of 40 Hz and a pulse width set between 0-300 s to provide electrical stimulation to the extensor carpi ulnaris and extensor digitorum muscles, thereby producing muscle contractions to move the wrist. At the same time, the DC motor actuator used in the robot arm device uses the MX 106 motor type. The integration between NMES and the robot arm that has been developed is capable of producing flexion and extension movements at the wrist that reach angles of 45^{o} to 60^{o} with a constant angular speed of 10o/s.

Another rehabilitation scheme was carried out in [26] by integrating FES and a new design of an active 7-Dof robotic arm for upper limb rehabilitation. The exoskeleton-based robot design mechanism uses a NEMA-23 stepper motor actuator. The advantage of the robot arm design is that the link of the robot arm can automatically lengthen and shorten according to the length of the patient's arm with a drive mechanism using the HS-805BB servo motor. However, the proposed design is too large and heavy, so the impedance is too high for portable rehabilitation applications. Another advantage offered in their research is that there are several control system modes for integrating the FES and robot arm, as shown in Figure 3B. The first control system mode offered uses a manual preset mode to control FES with several control system menu options, including a pain relief mode menu, a relaxation mode menu, and a massage mode menu, each stimulation mode using a frequency parameter of 80 Hz (3 sec) and 2 Hz (2 sec). In addition, the preset manual mode can also be used to determine the robot arm angle parameters that can be adjusted to suit rehabilitation needs. The second control system mode offered is the automatic control system mode, which uses a classified one-channel EMG signal to control the FES and robot arm simultaneously. This automatic mode is designed with a monitoring system capable of producing a 3D virtual environment from the perspective of the movement of the rehabilitation robot arm.

3.3 Integration of FES and robot arm with Pneumatic (active) actuator

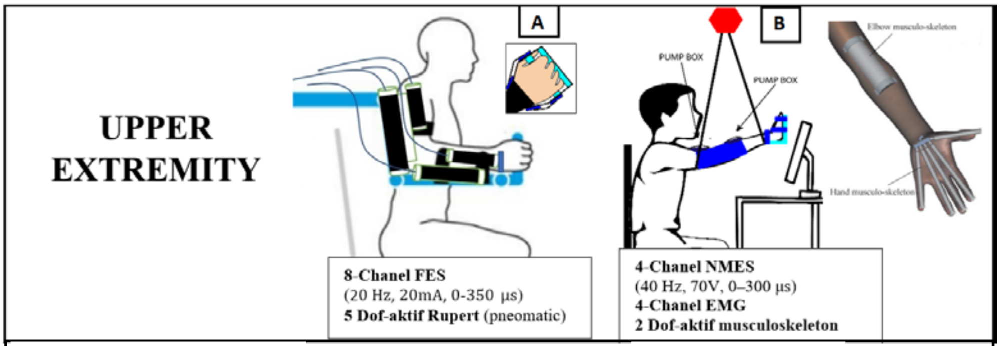
A total of two systems using pneumatic actuators as robot arm drives integrated with FES are identified in this article. Pneumatic actuators are an alternative that can be adopted as a robot arm driver that is combined with FES. The advantage of the actuator is that it has a high ratio and torque because it is powered using air pressure [29]. Table 2 is the identification result of several articles that discuss the integration of FES with a robot arm using pneumatic actuators.

Table 2. Integrating FES and the robot arm based on active exoskeleton actuators with pneumatics

Reference	Type Of Robot	Actuation	Supported Movements	DoF	Robot device	Electrical Stimulation Device
Tu et, al. [28]	Rupert + FES	PAM Pneumatic	Shoulder (EF-internal/ external rotation) Elbow (EF-PS) Wrist (EF)	5-Active	Mechanical design of two elbow, wrist and finger orthotic limb extensions Iterative learning control (ILC) sistem for trajectory tracking	8 chanel (20 Hz, 20mA, 0-350 μs) Iterative learning control (ILC) sistem for trajectory tracking
Nam et al. [29]	Exoskeleton + NMES	Pneumatic Pressures = <100 kPa	Elbow (EF) Wrist (E (hand-open) ; F (hand-closed)	2-Active	Mechanical design of leg flexion/extension elbow, wrist, and finger orthotics Controlled using EMG 4 channels	4 channels (0–300 μs, 70 V, 40 Hz) Controlled using EMG 4 channels

Meaning of abbreviations and acronyms: Extension/Flexion (EF); Pronation/Supination (PS); Extensor Carpi Ulnaris (ECU) and Extensor Digitorum (ED) muscles; Neuromuscular Electrical Stimulation (NMES); Functional Electrical Stimulation (FES); Electromyography (EMG); Degree of Freedom (DOF)

The literature articles described in Table 2 were then adopted to create a design and experimental scheme to make understanding the identified research developments easier. Figure 3 represents the design scheme, integrating the FES and robot arm using a pneumatic (active) actuator.



TECHNOLOGY REVIEWS	**A.** [28]	**B** [29].

Meaning of abbreviations and acronyms: Neuromuscular Electrical Stimulation (NMES); Function Electrical Stimulation (FES); Electromyography (EMG)

Fig. 4. Schematic representation of the integration design of FES and robot arm with pneumatic actuators adopted from literature articles

The design scheme in Figure 4 is adapted from the identified articles and then represents the experimental scheme used. Several research groups are discussing several research groups discuss integrating FES with robotic arms with pneumatic actuators for upper limb rehabilitation. Tu et al. [28] in their research, they developed a RUPERT robot design integrated with FES, shown in the schematic representation in Figure 4A. The RUPERT robot developed has 5-DoF and is relatively large, but it has a dynamic model because it uses pneumatic muscles to provide external power to achieve arm training movements. In addition, the FES being developed has eight channels with constant stimulus amplitude parameters of 20 mA, stimulation frequency of 20 Hz, and pulse width between 0-350 μs. The control system scheme used to carry out the integration between the RUPERT and FES robots is carried out with an Iterative learning control (ILC) system for trajectory tracking to achieve shoulder flexion/extension movements, humeral internal/external rotation, elbow flexion/extension and pronation/supination, flexion/ wrist extension or what can be called Reach-to-Grasp training.

Another experimental scheme was carried out by Nam et al. [29], who developed a control system using EMG 4 Chanel, as shown in Figure 4B. EMG control system has been classified as providing information about muscle activation status in real-time to be used in carrying out commands on the four-channel NMES device and robotic arm to train flexion/extension movements of the wrist and the patient. Electrical stimulation in NMES has a constant amplitude with a voltage value of 70 V, a stimulation frequency of 40 Hz, and a pulse width of 0-300 μs. The developed robot arm produces air bubbles to apply pressure to move the hand to make opening and closing movements.

3.4 Integration of FES and robot arm with passive actuators

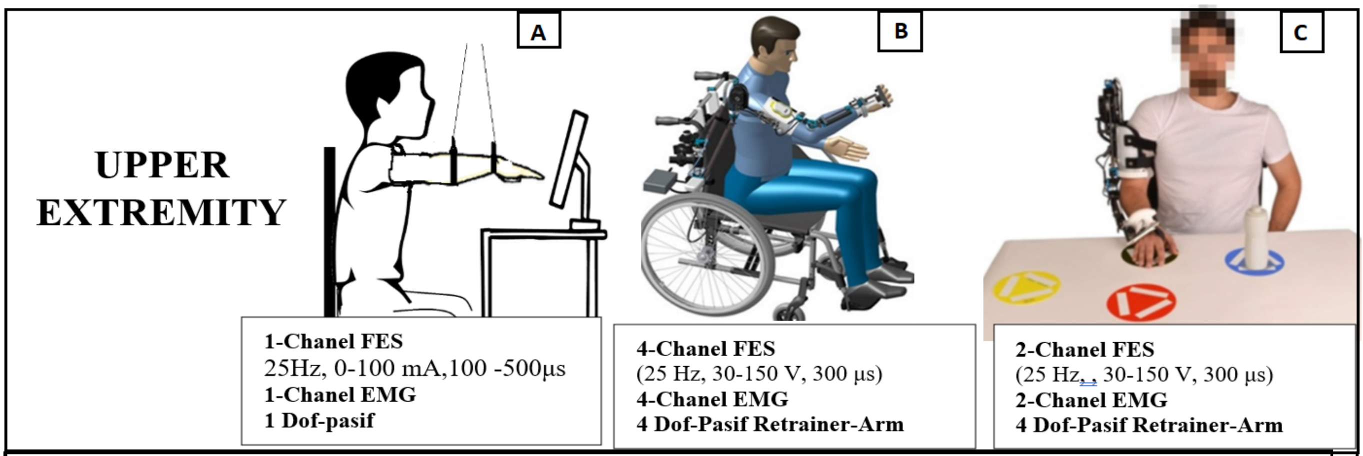
Several articles were identified, explained in Table 3, which discusses using FES integrated with a robot arm with passive actuators. The use of passive actuators on the robotic arm, which is integrated with FES, allows adaptation of arm movements resulting from electrical stimulation, which provides better muscle contractions because it can carry out more dynamic activities and prevents degenerative changes in the peripheral nervous system [30]. Table 3 explains several studies integrating FES and robot arms using identified passive actuators.

Table 3. Integrating FES and the robot arm based on passive actuator exoskeletons

Reference	Type Of Robot	Actuation	Supported Movements	DoF	Robot device	Electrical Stimulation Device
Meyer-Rachner et al.[31]	RehaStim + ROBOT	-	Elbow (EF)	1-passive	Using static arm straps visual feedback interface	1 channel 25Hz, 0-100 mA,100 - 500µs Controlled using EMG 1 channels
Ambrosini et al.[32]	RETRAINER-Arm + FES	spring	Shoulder (EF, AA, IE rotation), 2DOF for Shoulder girdle Elbow (EF, PS)	4-passive	Mechanical design with a mechanism using springs as suspension to produce movement that is contrary to gravity	4 channels (150 mA, 30 V -150 V, 25 Hz and 300 µs pulse width) Controlled by voluntary EMG 4 channels
Ambrosini et al.[33]	RETRAINER-Arm + FES	spring	Wrist (PS) Hand (E) Elbow (EF) Shoulder (Elevation/ rotation),	4-passive	Mechanical design with a mechanism using springs as suspension to produce movement that is contrary to gravity	2 channels (150 mA, 30 V -150 V, 25 Hz and 300 µs pulse width) Controlled by voluntary EMG 2 channels

Meaning of abbreviations and acronyms: Ekstensi/Fleksi (EF); Pronasi/Supinasi (PS); Function Electrical Stimulation (FES); Electromyography (EMG); Degree of Freedom (DOF)

The design and experimental scheme were adopted from the literature articles in Table 3, which are identified and explained in Figure 5. The FES design scheme is integrated with a robot arm using a passive actuator, which was carried out to make it easier to understand the technological developments employed.



TECHNOLOGY REVIEWS	**A.** [31]	**B.** [32]	**C**. [33]
Meaning of abbreviations and acronyms: Function Electrical Stimulation (FES); Electromyography (EMG)			

Fig. 5. Schematic representation of the integration design of FES and robot arm with passive actuators adopted from literature articles

The design and experiment schematic representation in Figure 5 is adapted from the identified article, with a schematic design adapted to the experiments carried out in Table 3. It is recognized that several research groups discuss the integration of FES with robotic arms with passive actuators. In their research, Meyer-Rachner et al. [31] developed a computerized system using a rope as an arm support, shown in the schematic representation in Figure 5A. Rope support is applied to robotics to support the gravitational force of the arm with an adjusted rope load calculated using a static arm model in a hanging position and moving horizontally to achieve a forearm posture. Using a rope as a support reduces fatigue due to electrical stimulation produced by FES. The electrical stimulation used has one channel with an amplitude that can be adjusted based on the patient's level of fatigue when stimulated. The amplitude setting is between 0-100 mA with a stimulation frequency 25Hz and a pulse width of 100 -500 µs. System control for running FES and the robotic arm uses a one-channel EMG signal. Reading the signal from the EMG will give orders and allow the patient's muscles to be adjusted. The control algorithm used in the rope support robot system calculates the rope tension needed to support the arm when making movements. It determines the load factor on the user's arm to automatically read the required hand weight and the angle required for the subject's arm.

Another rehabilitation scheme was carried out by Ambrosini et al.[32]; [33] In their research, they developed an FES integrated with a robotic system called Retrainer-arm, shown in schematic representations in Figures 5B and 5C. The developed arm-retrainer has a passive 4-Dof with a mechanism using a spring as a suspension to move contrary to gravity. This suspension works when resisting movement due to electrical stimulation, which contracts the muscles, resulting in a reverse direction when the electrical stimulation is stopped. The developed Electrical Stimulation has four channels with a constant amplitude of between 30 V and 150 V, a frequency of 25 Hz, and a pulse width of 300 µs with a maximum stimulation current of 150 mA. The target movements produced by FES are wrist (Pronation/Suspension), hand (Extension), elbow (Extension/flexion), and shoulder (Elevation/rotation) movements. Classified EMG is a control system that operates the FES device according to the patient's desired actions.

3.5 Outcome Scale Evaluation

This section provides a brief overview of the potential use of integrating FES and robot arm technology to perform clinical repair and identify muscle activity using EMG signals. Several clinical evaluations were identified, such as the Fugl-Meyer Assessment (FMA) clinical evaluation, which is used for performance-based measurements of multisensory function in post-stroke hemiplegia [34], the Action Research Arm Test (ARAT), which is used to measure the function of a person's hand with various parameters of size, weight, and shape (43), the Function Independence Measurement (FIM), which is used to evaluate the patient's daily living activities (ADL) (44), and the Modified Ashworth The MAS scale was applied to evaluate post-stroke spasticity of the elbows, wrists, and fingers (40). The Wolf Motor Function Test (WMFT) was applied before and after training, and the Structure Domain and ADL (MAL) were performed to assess the strength and number of movements during 30 ADLs. Box and Blocks Test (BBT) to evaluate unilateral gross manual dexterity based on the number of objects carried from one place to another within 60 seconds, the Stroke Specific Quality of Life Scale (SSQoL) to assess the patient's health-related quality of life, and EMG signal measurements were used for arm evaluation in each session to simulate upper limb movement in daily activities. Table 4 presents a summary of the experiments and scaled results using hybrid robotic systems.

Table 4. Integrating FES and the robot arm based on a passive actuator exoskeleton

Patient	Control group	Yield scale
24 post-stroke patients [14] 11 post-stroke patients [22]	2 control groubs; 1) NMES and robot-assisted experimental group; 2) Control group with traditional rehabilitation [14] There aren't any [22]	Clinical: FMA, MAS, ARAT, FIM [14] Clinical: FMA, MAS, ARAT, WMFT [22]
16 post-ischemic type stroke patients [27]	There aren't any	Clinical: CMC-EMG, FMA, MAS, ARAT
1 patient with a fractured forearm after one week of plaster removal [26]	There aren't any	MVC-EMG measurements
3 healthy subjects [28]	There aren't any	TaskPerformance
10 chronic stroke patients [29]	4 tests 1) No intervention 2) NMES users 3) Musculoskeletal users 4) Hybrid system users	Clinical: FMA, MAS, ARAT, MVC-EMG
1 healthy subject [31]	There aren't any	EMG signal measurement
7 post-stroke patients [32]	There aren’t any	Clinical: ARAT, MI, MAL, BBT. SUS and Kinematics
72 post-stroke patients [33]	2 control groups. 1) the experimental group did task-oriented exercises assisted by RETRAINER. 2) the control group did conventional ACT therapy	trials randomized controlled trial (RCT) CLINICAL: ARAT, MI, MAL, BBT, and SSQoL

Meaning of abbreviations and acronyms: Neuromuscular Electrical Stimulation (NMES); Function Electrical Stimulation (FES); Electromyography (EMG); Fugl-Meyer Assessment (FMA); Action Research Arm Test (ARAT); Function Independence Measurement (FIM); Modified Ashworth Scale (MAS); Wolf Motor Function Test (WMFT); Structure domain and ADL (MAL); Box and Blocks Test (BBT); Motricity Index (MI); System Usability Scale (SUS); Stroke Specific Quality of Life Scale (SSQoL)

3.5.1 Results Scale Integrating FES and the robot arm based on a DC motor active actuator exoskeleton

Evaluation of the NMES robot was implemented in three different studies Qian et al. [14] that reported a rehabilitation system using the NMES robot in 24 post-stroke patients. Patients were randomly divided into two groups. Group 1 trained the upper limbs with the NMES robot arm (n=14) and Group 2 used the traditional therapy/control group (n=10). The results of the evaluation of the training group were carried out with clinical assessments of FMA, ARAT, MAS, and FIM. There was a significant increase in the clinical assessment of FMA, ARAT, and FIM (shoulders and elbows; $P<0.001$) in both treatment groups. In contrast to the clinical assessment of the wrist, a significant increase in the clinical trials of FMA only occurred in group 1 or the group using the NMES robot ($P<0.001$). Meanwhile, a significant decrease also occurred in the wrist in the MAS clinical trial group 1 ($P<0.05$), but in group 2 the MAS clinical trial score ($P<0.05$). 05) remained at a high level when assessed after 3 months of rehabilitation. The developed NMES robotic assistance system can effectively increase patient independence in daily life compared to traditional physical therapy. The NMES robotic assist system allows for achieving higher motor output in the distal joints and more effective release of muscle tone than traditional therapy.

Rong et al. [22] reported the evaluation of 11 post-stroke patients using the NMES robot. In the evaluation, movement accuracy was measured by the root mean squared error (RMSE) during tracking. Support from robots and NMES significantly increased compared to that without assistance from the system ($P <0.05$). In clinical evaluation, patients were tested before and after rehabilitation of the upper limbs assisted by the NMES robot. In the observation of the clinical trial MAS (elbow and wrist) experienced a significant reduction ($P <0.05$), in contrast to the finger which did not experience a reduction in the MAS clinical trial. Significant improvement also occurred in all upper limbs undergoing rehabilitation using robot assistance and NMES in the clinical trials of FMA, ARAT, and Wolf Motor Function Test (WMFT) with a significance level ($P <0.05$).

Guo et al. [27] reported the results of using the NMES robot with 16 post-ischemic type stroke patients. The effectiveness of rehabilitation was evaluated through clinical assessment of corticomuscular coherence (CMC) and electromyography (EMG) activation levels, The Fugl-Meyer Assessment (FMA), the modified Ashworth scale (MAS), and action research arm test (ARAT). After three months of rehabilitation, the CMC trigger success rate and EMG activation rate ($p < 0.05$) increased significantly, similar increases occurred in the evaluation of FMA ($p < 0.05$) and ARAT scores ($p < 0.01$). Meanwhile, a significant decrease was observed in the MAS score ($p < 0.01$). Rehabilitation of the wrist through the developed system provides an improvement in all upper extremity muscles.

Bouteraa et al. [26] reported the use of an exoskeleton integrated with FES which was evaluated in 1 patient with a fractured forearm category after one week of plaster removal. During training in the first rehabilitation session, the robotic system managed to increase ROM up to 75 degrees as measured using the EMG signal response. The increase occurred on average one degree for every 50 iterations of flexion and extension in the two weeks of the rehabilitation process. A similar increase also occurred in the RoM of the elbow, from pre-training only reaching an RoM of almost 70 degrees to 125 degrees. Experimental tests carried out on hybrid robots show that the system works effectively.

3.5.2 Hybrid Robotic Outcome Scale Based on active actuator exoskeleton with Pneumatics

Tu et al. [28] in their study reported the results of using the RUPERT robot integrated with FES to realize active reach-to-grasp training. The evaluation was carried out on three healthy subjects who performed the grasping and releasing task using electrical stimulation with different electrode placements. Subjects try to complete the assigned tasks with the help of RUPERT and FES. The tracking task is performed by assessing the desired trajectory motion error and the actual trajectory. The experimental results show that the stimulus threshold for each subject is not the same. The resulting differences are due to several reasons, including the morphology of the arms, the location of the placement of the array electrodes, and neuromuscular activation.

Nam et al.[29] in their research study reported the results of using an exo neuromusculoskeletal integrated with NMES. The evaluation was carried out on 10 post-stroke patients with four tests, namely no intervention, use of NMES, use of a musculoskeletal, and use of a hybrid system. The clinical score normality test and EMG signal data were evaluated using the Lilliefors method with a significance level of 0.05. The results of clinical assessments (FMA, ARAT, and MAS) using integrating FES and the robot arm were able to improve the patient's motor skills. A significant increase was observed in the full FMA score (p£: 0.001, EF: 0.293, F: 7.27, one-way ANOVA with Bonferroni post hoc test). Meanwhile, the ARAT score increased significantly after 3 months of training (p£0.001, EF = 0.262F = 6.23, one-way ANOVA with Bonferroni post hoc test). The resulting MAS score at the elbow decreased significantly after 3 months of training (p£0.001, EF = 0.366, F =10.1, one-way ANOVA with Bonferroni post hoc test). On testing the normalized EMG parameters showed no significant increase or decrease was detected in the EMG parameters of the target muscles.

3.5.3 Hybrid Robotic Outcome Scale based on a passive actuator exoskeleton

Meyer-Rachner et al. [31] in their research, they reported the results of using two straps as actuators of a robotic system mounted on the elbow, forearm, and wrist joints integrated with FES. The evaluation of the trial was carried out with one healthy subject doing repetitive lifting of the arm, the EMG was recorded and processed to obtain signals of FES-induced muscle activity. FES-induced muscle fatigue occurs from iterations of around 90-100 seconds. As a result, the FES scale factor began to be reduced gradually until it was back below the original threshold.

Evaluation of the RETRAINER-ARM robot integrated with FES was implemented in two different studies [32] their study reported evaluating the use of integrating FES and the robot arm in seven post-stroke patients. Clinical characteristics before and after the training program were evaluated by assessing the ARAT, Motricity Index (MI), System Usability Scale (SUS), and Box and Blocks Test (BBT). the results of all clinical measures statistically showed that patients experienced significant improvement after the training was carried out. In addition, kinematics-based measurements were also carried out in their research. The results of kinematic measurements showed that all patients improved significantly, their performance included faster and smoother movements. The EMG-based measurements show that most of the tasks are successfully triggered by EMG in the form of a median value for all tasks and exercises reaching 92%.

Ambrosini et al. [33] their study reported evaluating the use of RETRAINER-ARM integrated with FES performed on 72 post-stroke patients. Patients were randomly divided into two groups: the first was the experimental group, which was doing task-oriented exercises assisted by RETRAINER for 30 minutes plus ACT for 60 minutes, and the two control groups were doing conventional ACT therapy for 90 minutes. The results showed clinical assessments included the Action Research Arm Test (ARAT), Motricity Index, Motor Activity Log, Box and Blocks Test (BBT), and Stroke Specific Quality of Life Scale (SSQoL). The results of the clinical assessment showed a significant increase over time in both groups except SSQoL with a significance level (P<.001). The experimental group in the ARAT clinical trial showed a change between groups of 11.5 points (P = .010) at the end of the intervention, an increase of 13.6 points after one month after training. The use of RETRAINER is clinically superior to 15% of training using ACT.

4 DISCUSSION

A systematic review of nine technologies identified to the best of our knowledge reports the development of technologies integrating robotic devices and FES for upper limb rehabilitation.

4.1 Technical aspects and technological challenges of integration between FES and Arm Robot Rehabilitation

Selection of alternative actuators to run the robot arm to determine a high power-to-weight ratio and produce precise torque according to the patient's arm weight requirements. There are three identified uses of actuators; the first is the use of active actuators with DC motors, as reported in [14], [22], [26] and [27].. DC motor actuators are effective because the control system is easy to control with low cost and back drivability. The second actuator uses pneumatics, as reported in [28] and [29]. Using pneumatic actuators refers to using compressed air to carry out the necessary actions; besides that, pneumatic actuators can produce greater torque. The third is the use of passive actuators, as done by [31], [32] and [33]. Passive systems store potential energy, such as springs or other elastic materials, and can work without electricity. Exoskeletons with passive actuators are highly adaptable to the patient's anthropometric measurements, strengthening motor skills and muscles of impaired limbs. According to Zhang et al. [20]. The amount of torque and quality of movement in the robot arm makes it possible to delay muscle fatigue due to electrical stimulation from FES.

The FES device that is integrated with the robotic arm has the advantage that the movement of the arm does not only depend on the actuator capacity of the robotic arm because the resulting electrical stimulation can provide muscle contractions to the patient, thereby moving [35]. The FES system has pulses using a sine wave, peak, or square pattern. The identification results of the stimulation frequency in the FES used range from 25 to 80 Hz and can be adjusted depending on the specific treatment goals. FES frequency affects patient fatigue; appropriate frequency adjustments are needed to produce smooth muscle contraction strength. The smaller the frequency, the lower the force of muscle contraction. The use of FES is also influenced by the amplitude used as the FES input intensity. The amplitude effect influences the strength of the resulting depolarization as well as the stimulation pattern and total stimulation time in the targeted muscle. The identification of several studies using stimulation amplitudes between 0 and 150 mA. According to Ibitoye et al. [36], The selection of amplitude must be done appropriately because high amplitude can increase the strength of FES stimulation by activating more nerves, but excessive amplitude can limit signal input to the patient's central nervous system. In addition, the pulse width available on FES devices is between 300 and 600 microseconds (μs), and variations in pulse width can have different effects on the target muscle [37]. According to Arpin et al. [38] electrical stimulation with low frequencies and longer pulse widths between 500 and 1000 μs can produce lower levels of muscle fatigue. Several studies identified in the literature review show that the use of amplitude is carried out constantly with an amplitude value of 70 volts and 80 volts with a frequency set at 40 Hz [14]; [22]; [27]; [29]. Several other studies show the use of varying amplitudes with values between 25 volts and 150 volts and frequency values determined between 20 Hz and 25 Hz [28]; [33]; [32]; [28]; [28]. Each amplitude quantity used has a weakness, namely that if excessive amplitude is used, it can limit signal input to the patient's central nervous system and can cause pain in the patient [39]. According to Abe et al. [40], Skin impedance and other physical properties of skin tissue have a strong influence on the current path. The skin exhibits both resistive and capacitive properties. Hair follicles and sweat glands show resistive properties, while the lipid bilayer shows capacitive properties. [41].

The next research challenge will need to provide important insights for designing efficient FES systems and minimizing excessive stress due to stimulation. Electrical voltage is applied in a varied manner depending on the thickness of the skin the patient has, so that it is indirectly possible to adjust the voltage. Electrical stimulation provides comfortable muscle force contractions for the patient to achieve appropriate contractions to restore residue in the patient's muscles. The electrical voltage in the FES can be adjusted by classifying the thickness of the arm circumference of the upper limbs to determine the amount of electrical stimulation voltage needed in post-stroke patients. The thickness of the arm circumference of the upper limbs can be determined through several tests so that the amount of electrical stimulation voltage can be categorized into several categories, such as low, medium, and high. The amount of electrical stimulation voltage makes it possible to adjust the electrical stimulation needs of post-stroke patients. Another consideration that needs to be taken into account is the need for actuators, whether DC motors, pneumatic motors, or passive actuators, so that the actuator capacity of the robotic arm can be adjusted to the torque requirements of the upper limbs of post stroke patients. The control system being developed is expected to be able to adjust the kinematic movements produced by the FES and the robotic arm so that when run together, it can minimize co-contraction of opposing muscles between the wrist and elbow in the upper limbs of post stroke patients.

4.2 Human-Robot Interface using Biosignal

The human-robot interface (HRI) is essential in integrating FES and the robot arm because it is an interaction medium that directly influences the stimulation process and actuators as a rehabilitation strategy. The role of HRI is an essential factor for communication between robots and humans through adapted algorithms; besides that, HRI also functions as an effort for patient safety and comfort [5] Several kinds of literature identified using biosignals to detect user intentions by measuring muscle activity in the forearm as a control system media to activate the device, then HRI observes the signals produced from certain motor and muscle functions.

The system control strategy, as defined in this review article, is a technology that integrates FES and robot arms with various actuators, such as active actuators using DC motor actuators, pneumatic actuators, and passive actuators. A popular field of research today is biosignal control, with the most popular types of signals mostly being EEG, electromyography (EMG), and electrooculography (EOG). These signals can be obtained through a non-invasive process, allowing the user to continue interacting with the device. The primary use of these signals is to sense user intent and apply specified actions to the robot and FES. The control system usually uses a microcontroller to process sensor information and provide commands to the actuator unit. Data processing is carried out with specific algorithms to process sensor data further so that it can give feedback to therapists about patient progress. Several studies have investigated the possibility of improving the performance of systems that integrate FES and robot arms for upper limb rehabilitation needs. The identified literature shows the feasibility of a control system using EMG signals as a control algorithm for combining FES and robot arms using DC motor actuators [14];[22]; [26]. The authors proposed several experiments using EMG signals from patient muscles that could be used for clinical and biomedical applications, evolvable hardware chip (EHW) development, and modern human-computer interactions. EMG signals obtained from muscles require sophisticated methods for detection, decomposition, processing, and classification. A biomedical signal is a collective electrical signal obtained from any organ representing a physical variable that is actuated at will. The use of EMG signals has proven capable of activating the FES device, which sends an electrical stimulus, and the robot arm to move the actuator via a DC motor. Guo et al. [27] developed a control system using brain signals via an electroencephalography (EEG) device, recording the user's brain activity via an amplifier. They translated using an online classification algorithm to drive the FES device and robot arm. The FES device and robot arm output are fed back using signals. EMG to the user, allowing them to know the progress of their muscle activity.

The feasibility of a control system with biosignals is not only able to be used on DC motors but can also be used on other actuators, as done by Nam et al. [29] , which uses EMG signals as a control algorithm to integrate FES and robot arms using pneumatic actuators. According to Iandolo et al. [42], a control system using biosignals has the potential to produce a more adaptive robotic device, resulting in a more precise control system than using a robot arm without FES or an FES device without a robot arm. However, several studies show that the use of biosignals as a control system to move the FES and robot arm was not evaluated based on the amount of actuator torque that suits the patient's needs. According to Li et al. [43], torque requirements will influence the quality of the resulting movement and the position error of the targeted movement. This evaluation is important to identify how well the performance of the biosignal control system can provide adaptive commands to the device to complete movements by predetermined target parameters.

The next research challenge needs to be to identify the use of EMG to control the dynamics of the interaction of the robot arm and FES by considering the actuator torque according to the patient's needs through calculations and actuator alternatives to achieve movement quality and avoid errors in the position of the targeted movement. Another approach can also be taken through control system modeling to confirm that the device used is safe based on recommendations from several theories developed. Control system modeling can be done with several tools, such as Matlab or Simulink, or using professional Proteus software [44]; [45]. Future research needs to make extensive efforts to develop better algorithms, improve existing methodologies, improve detection techniques to reduce noise, and obtain accurate EMG signals. Transformation of non-stationary signals using EMG with a time-frequency approach using Wigner-Ville Distribution (WVD) in hardware can enable real-time instruments that can be used for specific motor unit training in biofeedback situations. High-order statistics (HOS) methods can be used to analyze EMG signals due to the unique properties of HOS applied to random time series. The bispectrum, or third-order spectrum, has the advantage of suppressing Gaussian.

4.3 Rehabilitation results

Published systematic reviews report the use of integrating FES and the robot arm in stroke patients experiencing increased functional motor skills. There are several clinical assessments used to evaluate the usefulness and effectiveness of hybrid robotic systems, including the Fugl-Meyer Assessment (FMA), Modified Ashworth Scale (MAS), Action Research Arm Test (ARAT), and Functional Independence Measurement (FIM). In addition, the use of EMG parameters from each session is also considered. The use of normalized EMG with the co-contraction index of target muscle activity is applied to monitor recovery progress through the muscle coordination patterns of post-stroke patients [22].

There are various clinical evaluations used to identify the level of effectiveness of using integrating FES and the robot arm. Regardless of the use of the actuator, the main focus observed in post-stroke patients is task performance before and after rehabilitation using integrating FES and the robot Arm [33]. According to [46] Explaining that clinical evaluation requires a wide range of variables makes it difficult to compare the performance of integrating FES and the robot arm that will be developed in the future. There is a need for an integrated evaluation to identify a system to be able to adapt to the post-stroke patient's condition. Clinical evaluation through EMG devices is possible by providing information about the status of muscle activation in real-time. Information on muscle activation status makes it easier for physiotherapists to control activities during rehabilitation. With an available control interface, the therapist can set the parameters of the exercise movement, define the stimulation mode, and record the patient's training in real time.

5 CONCLUSIONS

This article presents literature on technology integrating FES and a rehabilitation robot arm to rehabilitate upper limb motor function in post-stroke patients. Several reports have identified the current state of using HRI via a multi-channel EMG device, which allows it to control interaction dynamics according to the patient's wishes by classifying several upper limb muscles in post-stroke patients. The type of activity of several muscles using a multi-channel EMG device is used to support a control system that integrates FES and the rehabilitation robot arm, thereby enabling the reduction of opposing muscle co-contraction in post-stroke patients. Through technological developments identified by HRI, multi-channel EMG devices are used to integrate FES and arm robot rehabilitation. This approach aims to combine two different but complementary methods to improve the rehabilitation capabilities of post-stroke patients. The identification results showed that the use of FES was carried out. Most of the literature uses a constant amplitude voltage ranging from 30 volts to 150 volts. It does not consider skin impedance so that stimulation can be adjusted to the patient's muscle needs. The challenge for future research is to select the appropriate amplitude and adjust the patient's skin impedance because high amplitude can increase the strength of FES stimulation in activating more nerves. Still, excessive use of amplitude can limit signal input to the patient's central nervous system. An estimate of the use of FES must be carried out to stimulate muscle activation due to post-stroke residue to improve rehabilitation performance significantly. The results of the identification of the literature review also found several designs and actuators, components, technological aspects, and technological challenges that can be developed in the future. However, in selecting the actuator, an alternative that is tailored to the torque and kinematic requirements of the robot arm design is needed so that it can produce an ergonomic device that suits the needs of post-stroke patients.

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Paper submitted: 23.05.2023.

Paper accepted: 21.02.2024.