CHAPTER

Hybrid FES-robot devices for training of activities of daily living

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INTRODUCTION

Research and clinical results suggest that intensive exercise of functions significantly contributes to the rehabilitation of persons with sensorimotor impairment caused by lesions of the central nervous system (CNS). Voluntary or externally augmented motor activity of paralyzed limbs leads to the reorganization of the sensory-motor systems. Movement can be augmented by two methods, which can be used either in parallel or independently: (1) powered robotic devices (exoskeletons—EXO) controlling the joint angles by acting on the body segments and (2) functional electric stimulation (FES), which controls joint angles by activating paralyzed muscles.

An EXO substitutes the lost function by controlling the joint angles, thus assisting limb movements. It can be a single module attached to two neighboring segments (e.g., an ankle-foot orthosis—AFO) or a more complex mechanism that controls several joints (knee-ankle-foot orthosis—KAFO and reciprocating gait orthosis—RGO). Early EXO versions had simple joints, with brakes to lock a joint angle in a fixed position. Humanoid robotics research led to actuated EXOs [1]. Significant problems in the daily use of EXOs for training are (i) the weight of the exoskeleton, (ii) the need to fit the exoskeletal axes to the biological joints' axes, (iii) the large interface forces between the exoskeletal and bodily segments, (iv) the considerable power and joint torque requirements ($P \approx 150\,\mathrm{W}$ and $M = 100\,\mathrm{Nm}$ per joint for standing and gait), and (v) the control, which needs to be integrated into the preserved sensory-motor systems of the user. A particular problem is related to the process of donning and doffing when an EXO is used for standing and gait restoration.

Functional electric stimulation (FES) was found useful for the control of paralyzed extremities [2]. The alternative term neuromuscular electric stimulation (NMES), often used in literature, emphasizes the target of the stimulation, yet the term FES includes the word “functional” being essential for the recovery of function (Fig. 1).

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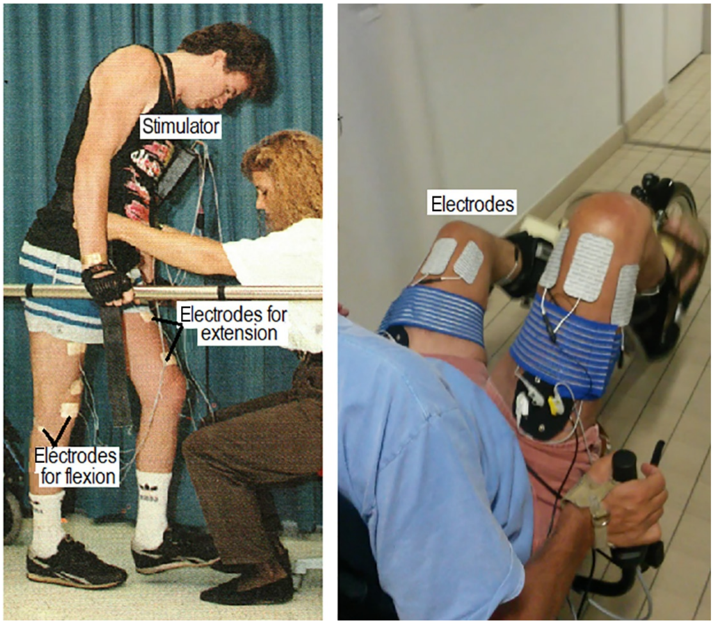

FIG. 1

FES with surface electrodes used for the control of gait and pedaling (tricycle).

An FES system interfaces the sensory-motor systems via surface or implantable electrodes. Surface electrodes of the appropriate size need to be positioned in the vicinity of the innervations of the target muscles. Electric stimulation generates an electric field in the surrounding tissue that is a function of the size and position of the electrodes and of the intensity of stimulation. Most sensory and motor nerves that are within the space where the electric field is generated by stimulation will be activated. This nonspecific activation is a problem for direct motor or reflexive selective activation of synergistic muscles. The use of implantable electrodes improves selectivity since the electrodes can be positioned close to the target nerves, but does not eliminate the problem entirely, since a nerve is composed of ascending and descending pathways that are anatomically organized in fascicles that innervate various muscles (synergist and nonsynergists) and communicate with the higher levels of the CNS.

To generate a fused muscle contraction, a minimum frequency of 20 pps is required. The external activation recruits neural fibers in the reversed order compared with the natural order of the recruitment, which is determined by the size principle [3]. These issues limit the practical use of FES, because high pulse rate causes muscle fatigue. A way to postpone the onset of fatigue is to use asynchronous activation of different motor units of a single muscle at a lower pulse rate (e.g., 8–10 pps) by using multicontact electrodes. The intensity of stimulation (pulse amplitude) is much lower for implantable FES (1–10 mA), if compared with surface FES (20–140 mA). The typical pulse duration of charge compensated pulses is between 10 and 500 μs.

The product of pulse amplitude and pulse duration ($Q = I \cdot T$) must be above the chronaxie (strength-duration or *I-T* curve) for the stimulated structure. Recent research suggests that the amount of charge can be reduced if the stimulating pulse has very steep rise edge (in the ns range), yet this needs to be validated.

Implantable systems have advantages compared with surface FES systems for long-term daily usage (e.g., control of grasping in tetraplegic patients and control of walking and standing in complete paraplegic patients). Current implantable systems are still not perfect since the power source is outside the body; hence, the energy must be transmitted wirelessly between the power unit and the implanted output stage. Surface FES is a preferred solution for the training (therapy) of persons with a CNS lesion. Nevertheless, surface FES is not applicable to the many muscles that are located deep in the body (e.g., iliopsoas muscle).

HYBRID ASSISTIVE SYSTEMS

The idea of using a combination of FES and EXO was first proposed in the 1970s [4] based on the observation that each of the components had functional limitations. An hybrid assistive systems (HAS) could be built starting from the FES as the core and adding minimal hardware (modular EXO) to assist only the functions that are not achievable by FES [5,6].

The first system that combined four-channel stimulation with an unilateral self-fitting modular orthosis with a powered knee joint was tested in a complete SCI subject whose voluntary activation of muscles for extending and flexing one leg was compromised due to muscle denervation. The system used rule-based control based on the finite-state model of gait [6].

A different approach to HAS is to use EXOs as the core and add FES for the functions that are not feasible using the EXOs [7]. More specifically, joint stability and prevention from unwanted movements were delegated to the EXO, while the FES was envisioned as the actuation system of selected functions. Solomonow and associates used a reciprocating gait orthosis (RGO) and a hip guidance orthosis (HGO) enhanced by a four-channel FES [8]. Clinical results reported that ambulating with the Louisiana State University RGO (LSU RGO) were associated with high energy cost. Also, most subjects were unable to stand up without assistance. To reduce the load over upper extremities and to reduce the energy requirements during the walking surface, electric stimulation of the rectus femoris and hamstrings muscles was added. The stimulation electrodes were incorporated in a plastic polymer cuff. Phillips [9], in addition to the stimulation of hamstring muscles, stimulated the ipsilateral gluteal muscle to improve hip extension during the stance leg. The system using three-electrode configuration with two channels for the knee extension for each leg activated the entire bulk of the quadricep muscle. Two stimulators were used to activate paralyzed hamstrings and gluteal muscle.

A version of the hybrid system is shown in Fig. 2 [5]. The hybrid device combines two implantable stimulators (one per leg) and the exoskeleton that controls the hip and knee joints.

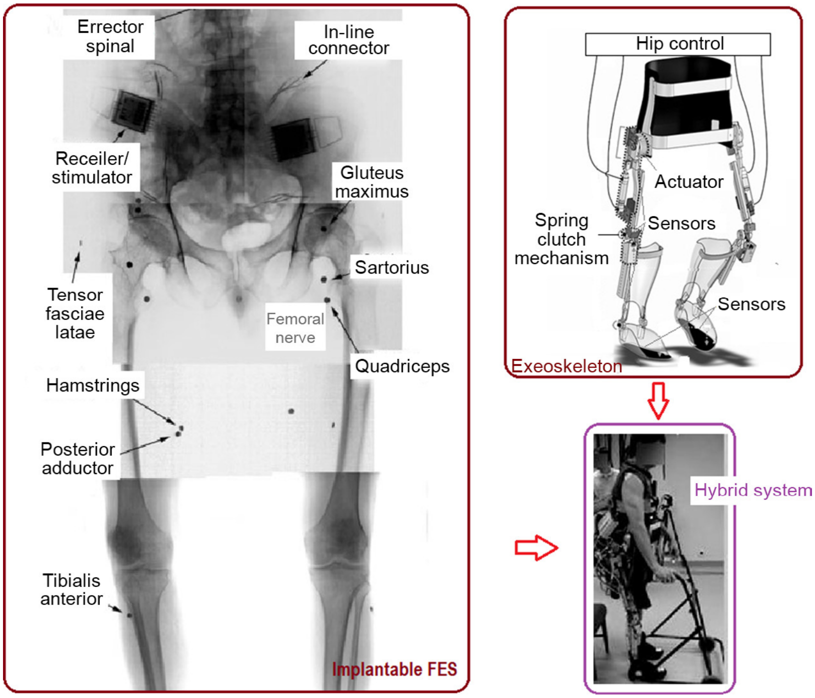

FIG. 2

The implantable FES for activation of paralyzed muscles and the exoskeleton controlling the hip and knee joints. The sensor-driven control based on a finite-state model of gait was used for control.

Modified from Solomonow M, Aguilar E, Reisin E, Baratta RV, Best R, Coetzee T. Reciprocating gait orthosis powered with electrical muscle stimulation (RGO II). Part I: performance evaluation of 70 paraplegic patients. Orthopedics 1997;20(4):315–324, IEEE©.

A critical component for hybrid assistive systems is the controller of the EXO joints.

Goldfarb and Durfee designed and evaluated a magnetic particle brake for FES-aided walking [10]. Parallel operation of the EXO and body parts was the basis for the design of a joint-coupled orthosis (JCO) [11].

Upper extremity assistive systems are much more complex in comparison with those for the lower extremities. No existing exoskeleton perfectly fits all the degrees of freedom of the human arm. The exoskeletons designed to support manipulation control either the end point (single contact cuff near the wrist) or the relative orientations of arm segments (rings or cuffs in touch with the arm and forearm). There are as yet no exoskeletons that are capable of controlling fingers and thumb movements during grasp/release operation. Mechanisms that can partly replicate the movements of the fingers and the thumb have been designed, but they are not practical. The main technical difficulty comes from the fact that the hand must contact objects during operation; hence, the exoskeleton can only be mounted on the volar side of the hand.

Digits of the hand (fingers and thumb) can be controlled using FES. The resulting motions are not the same as in healthy humans, yet they allow prehension of the hand, grasp, hold, and release of objects. The idea of using surface stimulation has been exploited, and there are commercial products allowing synchronized finger extension/flexion and thumb extension/opposition allowing the prehension, grasp, and release of various objects used in daily life [12]. The development of a FES system for upper extremities was motivated by the lack of ability of tetraplegic population to grasp and release resulting in a total dependence from caregivers. The main application of FES for upper extremities today is as training devices, which aim at facilitating the recovery of function.

The commercially available device NESS H200 is an FES system integrated into a splint to hold the wrist in a neutral position. The stimulation module uses a preprogrammed sequence for opening and closing of the hand, holding the object and finally releasing it (Fig. 3, left panel). The NESS H200 can be classified as a hybrid system since it combines FES with an EXO. The alternative to splint-based control of the wrist posture is a more sophisticated FES system, which activates the wrist muscles (Fig. 3, right panel). The cocontraction of agonists and antagonists increases the stiffness and holds the wrist in the desired orientation. The muscles controlling fingers and thumb extension and flexion are activated in parallel, thus enabling grasp/hold and release functions.

The combination of wrist, fingers, and thumb control is feasible through asynchronously distributed stimulation over an array of electrodes and implementation of the triphasic stimulation pattern [13,14]. The development and design of a system that benefits from array electrodes are carried by the company Tecnalia, San Sebastian, Spain [15].

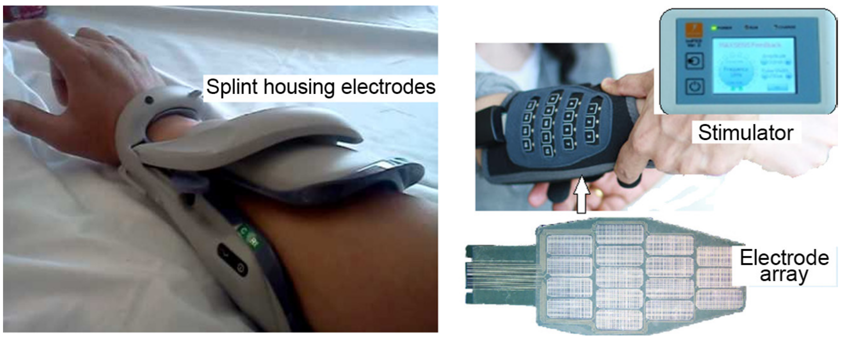

FIG. 3

NESS H200 (left panel) for the control of hand opening and closing and FES-A from Tecnalia, Spain (right panel), allowing the control of the wrist and fingers with the free wrist.

The control of shoulder rotations has never been accomplished in a useful manner using FES, but the control of the elbow joint was shown to be feasible. Stimulation of the shoulder joint has been incorporated into the therapy for the strengthening of muscles to reduce the shoulder subluxation caused pain. Implantable systems for restoration of arm and hand movement [15] are not described in this chapter as these systems are meant for the life-long substitution of function, and are not practical for the training alone. The clinical findings related to the prolonged use of implantable systems showed carryover effects leading to a substantial increase of the reaching and grasping abilities.

HYBRID ASSISTIVE SYSTEMS FOR THE FUTURE

Two types of hybrid systems are of interest for neurorehabilitation: (i) systems for clinical use in the early phases of rehabilitation and (ii) systems for home use for prolonged rehabilitation in chronic conditions. The selection of which exoskeleton is the best candidate for the home activities must take a number of constraints into consideration. The basis for the selection of the appropriate design of exoskeleton are (i) the system must be wearable, comfortable for daily use, and cosmetically acceptable by the user; (ii) modularity must be a desirable feature since various types of disability require different types of assistance; (iii) control must consider that many functions are under biological (volitional or reflex) control that is different from control in healthy persons; and (iv) compensatory movements imposed by the impairment must be anticipated. The systems for clinical use are much less constrained since they are meant to be used for a shorter time.

We discuss first the clinical systems for assisting gait. A robotic platform that partially supports body weight and controls the motion of the leg segments has been developed and translated into a commercial product (i.e., Lokomat, Hocoma, Switzerland). This robotic system demonstrated that intensive training of the gait is beneficial for the recovery of function [16]. The Lokomat system can be hybridized by adding the FES for the control of leg movements aiming to strengthen the neural activation, thereby increasing CNS excitability and facilitating cortical plasticity [17].

FES eliminates the need for external actuators; thus, EXOs should operate as a balance assistant and partial body-weight supporting platform during the stance phase of the gait (Fig. 4). This approach has been tested, for instance, in combining the Walkaround system [18] with multichannel FES. The postural assistant Walkaround (lumbar belt, connected with springs to the powered walker) fits the body contours and orients the trunk in the space. Four-channel FES per leg provides sufficient balance control during gait over the ground and allows the CNS to develop new motor control strategies.

The home usage of hybrid systems needs to provide simple donning and doffing and comfort that fits into the tolerance boundaries of the patient and the environment. The definite preference goes to modular multijoint systems, allowing synergistic control of the neighboring joints (i.e., JCO). The activation of the exoskeleton should

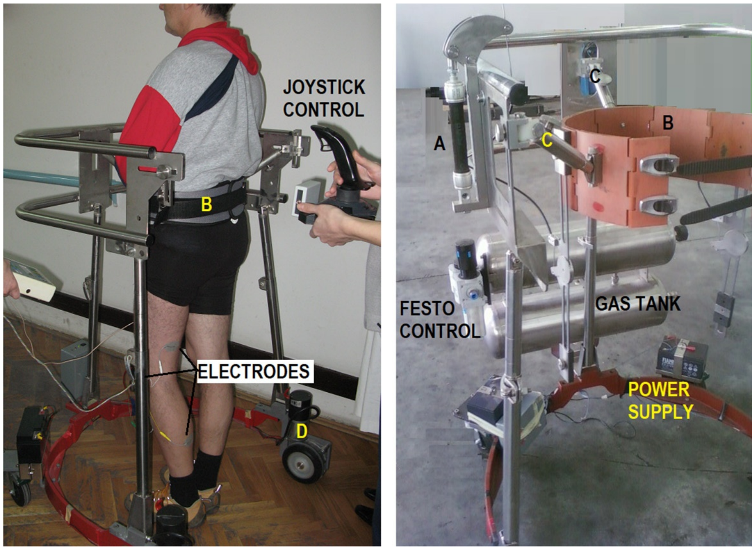

FIG. 4

A hemiplegic patient assisted by four-channel FES supported by the Walkaround. The powered walking support is providing posture orientation and preventing fall with the control of pelvic motions utilizing a pneumatic actuator. A—one of three pneumatic actuators for the control of pelvic region action; B—postural lumbar belt; C—adjustable spring; and D—actuators for the motion of the Walkaround controlled remotely via joystick.

incorporate as much self-powering as possible. The soft interfaces replace rings and cuffs, thus providing cosmetically more appealing systems, while guaranteeing distributed interface forces between the EXO and the body.

Soft robotics is introducing new types of actuators that fit much better into the EXOs when compared with electric or hydraulic actuators. Soft actuators operating like muscle-tendon systems provide joint stability and control of the stiffness resulting with smooth, powerful joint rotations [19]. Futuristic ideas on how to increase the support zone have been suggested, and most likely, they will be integrated into hybrid systems.

Hybrid systems for upper extremities are in their pioneering phase. There are no clinical systems with the fully integrated FES and exoskeletons; however, the platform for combining operations has been established. The hybrid system would use the FES for the control of the hand functions and the exoskeleton for the control of the position and orientation of the hand. The best candidates are systems (Fig. 5) that provide powered assistance [19]. The FES system to be combined with these devices should use the concepts that have been integrated into systems like NESS H200 and STIWELL med4 [20].

The reason behind the hybridizations is that the stimulation modality used in the paradigm termed functional electric therapy [21] leads to the recovery of function in

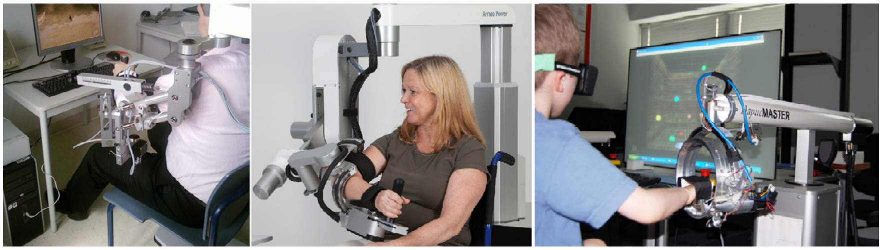

FIG. 5

Exoskeletons for the control of the position and orientation of the hand: Armeo Spring (left panel), Armeo Power (middle panel), and Haptic Master (right panel).

patients who had control of manipulation, yet it has a subtle impact on the recovery of functions in individuals who could lack control of arm movements. The training of arm movements with robotic systems was tested with systems like InMotion ARM [22]. Training with these devices showed temporary improvements in the manipulation, but the regained ability to control the movement was diminished shortly after the therapy. The most likely reason is that the function regained was not useful for daily life. In fact, the treatment needs to bring the motor functions above the level required for regular usage; otherwise, nonuse will counteract the gains.

Another excellent example of improvements by using soft actuators is an OrthoJacket exoskeleton that was tested in combination with the FES using array electrodes.

One final issue in this chapter relates to control. The major challenge for conventional control methods is the accurate estimation of the parameters characterizing the sensory-motor system of the user. Therefore, the hybrid control (Fig. 5) with the top level using rule-based control and the lower level using the model-based control has a better chance to be applied [23] This hybrid system mimics the natural motor control.

Future systems will benefit from the direct brain-derived signals for interfacing voluntary and external control and sensory feedback for the integration of the hybrid system and the body.

An option that needs to be considered is the tonic stimulation of the central nervous system above the lesion added to the phasic stimulation below the lesion [24].

TAKE-HOME MESSAGE

Providing forms of assistance that allow patients with paralysis to regain function is a valuable element for the rehabilitation. Intensive exercise of functions is a key to regaining control of paralyzed extremities. The recovered condition needs to be maintained through a regular usage of the regained function to prevent the consequences of nonuse. Assistance can be maximized by using hybrid systems that combine EXO and FES.

Future hybrids (Fig. 6) should implement light exoskeletons that (1) provide assistance to motor function that cannot be established by FES (e.g., flaccid paralysis), (2) control stiffness of joints that is unfeasible by FES due to the muscle fatigue

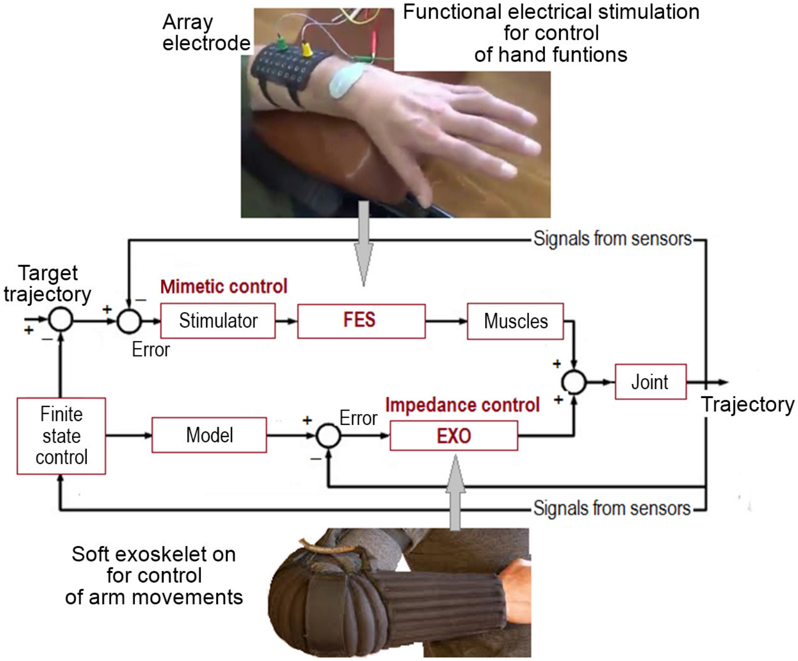

FIG. 6

The schema of a desirable hybrid for the training of activities of daily living and the hierarchical control for the FES-EXO.

associated with prolonged electric stimulation, and (3) reduce the number of degrees of freedom to facilitate control. Future hybrids should use multichannel FES with asynchronously distributed activation of muscles *via* arrays built into the garment. Hierarchical hybrid control needs to mimic biological control and respond to the commands from the user to accommodate environmental requirements.

The communication link for selecting the activity and triggering the start and end should be designed to allow operation at the subconscious level. The particular link that is adding value to the neurorehabilitation is the use of the brain-derived signals (brain-computer interface, myoelectric control, etc.).

Finally, the new hybrid systems need to include sensors that are used not only for the control of the actuation of the hybrid but also for the assessment of the regained function. The assessment needs to be communicated with the rehabilitation expert (telerehabilitation).

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