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Non-invasive Functional Electrical Stimulation in Rehabilitation Engineering

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Abstract. Transcutaneous (non-invasive) functional electrical stimulation (FES) activates the ascending and descending neural pathways in persons with diminished sensory and motor control after a central nervous system (CNS) disease or injury. Application of FES in early phases of rehabilitation (acute and sub-acute) has a carry-over effect in decreasing motor impairment. FES is applied to the peripheral nervous system to activate the nerves and muscles, generate functional movements, and activate efferent and afferent neural pathways to close the biological motor-sensory loop. This promotes brain plasticity, the most important mechanism in rehabilitation after brain injuries. In the case of Spinal Cord Injuries (SCI), the functional recovery is less pronounced; however, the influence on the reduction of secondary complications of paralysis (e.g., loss of muscle bulk and strength, pressure sores, cardio-vascular deterioration, diminished gastric and urinary functioning, spasticity, reduced range of movement in joints, etc.) is pronounced. The most common applications of non-invasive FES are the restoration of standing and walking, the generation of cyclic movements for pedaling or rowing, and manipulation and grasping.

Keywords: Functional Electrical Stimulation, Rehabilitation, Neuroprosthesis.

1 FES fundamentals

Functional electrical stimulation is a method of external activation of sensory-motor systems to generate the missing or augment the diminished sensory or motor functions [1]. FES device can be described as a pacemaker that generates activities of the muscles in a time order that maximally mimics the activities of a healthy person when performing the same functions. The non-invasive FES pacemaker generates pulses of electrical charge that are delivered to the body via the electrodes on the skin. Electrical pulses generate action potentials (AP) in the motor and sensory nerve cells beneath the skin. The muscle receives both a direct descending AP and a reflexive AP initiated by the ascending AP in the spinal circuitry. The most efficient place to position the electrodes on the skin is close to the motor point, where the nerve endings enter the muscle and the descending path of AP is the shortest. If the muscle is denervated it can still be activated by surface FES, but with up to 3 orders of magnitude more power [2].

2 Beginnings of non-invasive FES neuroprostheses

The concept of neuroprosthesis (NP) based on FES was introduced by James Reswick and colleagues in the sixties of the last century [3]. The first non-invasive FES NP device was used to correct the drop foot syndrome in stroke patients in 1967 [4]. The device used two surface electrodes to stimulate the peroneal nerve and activate dorsiflexion based on the command signal from the switch placed under the heel (Fig.1). The stimulation started when the switch detected the heel-off phase and lasted for the predefined time.

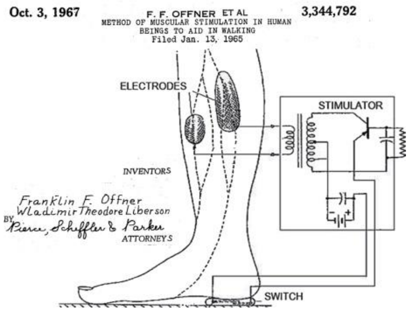

Fig. 1. First FES neuroprosthesis. Correction of the drop-foot syndrome. Modified from patent application US3344792A.

Between the sixties and eighties of the 20th century, the group from Ljubljana Faculty of Electrical Engineering, Slovenia, studied the application of multi-channel FES to help patients with leg paralysis to stand up and ambulate [5-7]. They stimulated major muscle groups (predominantly Quadriceps m., Hamstrings m., and Tibialis Anterior m.) with 6-channel programmable stimulators controlled by the hand switches. The patients learned how to timely control the stimulation and increase the efficiency by the proper posture of the upper body, which included hip hyperextension in the stance phases that led to biomechanical knee locking. They studied the use of this simple system in hundreds of subjects (spinal cord injury, cerebral palsy, stroke, etc.). In the nineties, the group from the University of Alberta, Edmonton, AB, Canada, and Miami Project to Cure Paralysis, USA, developed an automatic gait control for paraplegics by closed-loop control of 6 FES channels based on sensors for hip and knee angles (goniometers) and FSRs (force-resisting sensors) inside the shoes [8]. Paralyzed patients walked at speeds up to 1m/s, which is close to normal speeds, but the lack of proprioception was perceived as uncomfortable for the users (Fig.2).

Fig. 2. Paraplegic patient walking with automatic FES gait based on closed-loop control with joints angle and GRF sensors

The first upper extremities NP allowed prehension and release for a person with tetraplegia and had a splint with a spring to close the hand and electrical stimulation of the thumb extensor to release the object [9].

3 FES neurorehabilitation

The use of peripheral FES as orthotic devices is still very limited due to several bottlenecks which prevent the popularization of this approach compared to implantable devices, such as time-consuming positioning of the electrodes and setting of parameters, fast muscle fatigue, etc. However, the peripheral FES became a standard tool for neurorehabilitation, especially when combined with intensive exercise and/or robotic aid.

FES is a powerful tool to enhance brain plasticity in the early phases of recovery (acute and sub-acute) after a brain injury, such as a stroke. FES is applied to the peripheral nervous system to activate the nerves and muscles, generate functional movements, and activate efferent and afferent neural pathways to close the biological motor-sensory loop (Fig.3) even when the motor command is missing or compromised. The brain can change, adapt and regain the lost functions with intensive exercise. Popovic et al [10] showed that a 3-week FES program for grasping in the acute phase after stroke significantly increases functions, with a carry-over effect after 12 months. Application of FES in chronic patients after 12 months leads to non-significant improvements.

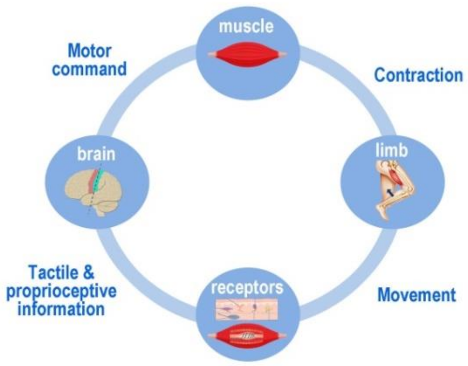

Fig. 3. Biological motor-sensory loop

In the case of Spinal Cord Injuries (SCI), less significant functional recovery can be achieved at spinal levels close to the level of injury; however, the influence on the reduction of secondary complications of paralysis (e.g., loss of muscle bulk and strength, pressure sores, cardio-vascular deterioration, diminished gastric and urinary functioning, spasticity, reduced range of movement in joints, etc.) is well pronounced. Table 1 summarizes the benefits of FES in stroke and SCI patients and the general constraints of the technology.

Table 1. Peripheral FES benefits and constraints

		Benefits	Constraints
SPINAL CORD INJURIES	---STROKE----	Physical activity, endurance, muscle power	Fast muscle fatigue
		The practice of a range of motion	Time-consuming positioning of electrodes
		Improved cardiovascular health	The time-consuming setting of parameters
		Enhance of brain plasticity	Personalization of stimulation sequence
		Reduction of spasticity	Only superficial muscles can be activated
		Prevention of pressure sores	
		Prevention of osteoporosis	
		Reduction of urinary infections	

Currently available commercial devices are general-purpose stimulators with programmable stimulation sequences and cables for connection to multi-use electrodes [11-15] or compact systems focused on the correction of the drop-foot [16-18] or grasp [19-21]. In addition, sometimes FES is combined with robotic systems to provide guided cyclic or target-oriented movements and assist high-intensity and repetitive exercise of coordinated limb motion. Examples are FES-cycling [22-26] and FES-rowing [25] ergometers, FES-walking, or grasping combined with lower and upper extremity exoskeletons [27].

Fig. 4. FES devices: A) NESS H200, Bioness, USA B) Concept 2 rower with Motimove stimulator by Kurage, France, C) Feasia Grasp, Fesia Technology, Spain, D) RT300, Restorative Therapies, USA, E) Neuroskin, Kurage, France.

4 FES constraints and solutions

Although FES can bring many benefits to the user, the complexity of use for this technology is still not at the level that allows acceptable setup time for the rehabilitation of many different patients in clinical settings or prolonged periods of use as an orthotic device. Reduction of setup time can be achieved with garments with incorporated electrodes, preferably dry electrodes that do not require a layer of sticky gel in contact with skin, as shown in Fig.4E. However, this is feasible only in lower extremities, where the muscles are big and small mistakes in electrode positioning do not lead to a drastic reduction of selectivity. In the upper extremities, muscles are narrow and very close, where differences of less than 1 cm for electrode positioning make a noticeable difference in the resulting movement. In this case, a promising solution is the use of muti-pad electrodes [21, 28-29], as shown in Fig.4C. Multi-pad electrodes allow the selection of one or more distinct active pads to produce the desired movement. On the other hand, applications on the upper extremities do not deal with a problem of fast muscle fatigue, as high-intensity stimulations of lower extremity muscles. Muscle fatigue is very fast due to FES because of the high rates of motor unit recruitments, all units being recruited simultaneously, and a reversed recruitment order compared to CNS strategies. Surface-distributed asynchronous stimulation [30-32] is one way to delay muscle fatigue, later named spatially distributed sequential stimulation (SDSS). This method uses four closely positioned smaller electrodes instead of one large electrode to deliver stimulation pulses at four times lower frequencies each, resulting in the same level of fused contraction and up to 250% longer fatigue periods. The rationale behind this approach is that each small electrode activates a different pool of motor units of the same muscle or the synergistic muscles and this way mimics the natural strategy of the CNS.

5 Conclusion

FES is a powerful tool for rehabilitation after a disease or injury of the central nervous system. The most significant effects are achieved in the acute phases. However, the devices based on FES are still not in the development stage where this technology can be introduced in everyday practice in typical clinical environments because of the constraints of time-consuming setup, fast muscle fatigue, and, sometimes, inconvenient generated sensations. Therefore, special care has to be taken to ensure that the devices based on FES are easy to use, fast to set up, and allow a certain level of autonomy in adjusting and personalizing the parameters to each user.

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