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Functional Electrical Stimulation (FES): Review

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Abstract: Action potential from the control system (central nervous system) travels along the axons of motor neurons to innervate muscle cells and so as to cause muscle contraction in a coordinated fashion, though cardiac muscles are self-excitable; sinoatrial (SA) node is responsible to generate the impulse for contraction of cardiac muscles. Nerve related diseases stroke and spinal cord lesions result loss of the peripheral nerves system, which stimulate the muscular system. In this case, scholars developed a technique called functional electrical stimulation (FES) to replicate the role of motor neurons for activation of muscle cells). Highlighting what functional electrical stimulations are, the paper tries to elaborate the working principle behind FES followed by their applications. Dictating the current technologies and associated future works, it finally draws a succinct conclusion.

Keywords: *FES, Neuromuscular stimulation, Electrode, myelinated fiber, unmyelinated fiber*

I. INTRODUCTION

Excitable cells are a special set of cells found in nervous, muscular and glandular tissues. They exhibit a steady resting membrane potential in the range of -50 and -100mV and conduct action potential when sufficiently stimulated resulting an all-or-none response [14].Referring Wikipedia, Functional electrical stimulation (FES) is "a technique that uses electrical currents to activate nerves innervating extremities affected by paralysis resulting from spinal cord injury (SCI), head injury, stroke and other neurological disorders" (Functional electrical stimulation n.d.). It is also defined as a treatment that improves mobility by utilizing a small electrical charge [1]. FES is a technique used to restore impaired function through electrical stimulation [13]. Also known as neuro-prosthesis [4] and was initially referred to as Functional Electrotherapy by Liberson, FES historically dates back to 1967 where Moe and Post coined the name Functional Electrical Stimulation. Ran by dorsally located (heel) on-off switch on the user's shoes, the first FES was aimed at correcting foot drop [2, 10].

II. BASIC PRINCIPLES OF FES

AS one of the direct applications for therapeutic use of electricity [5], functional electric stimulation, involves applying a low frequency [13] electric current on or around a nerve to cause muscle contraction [11].Hence, low-frequency currents and neuromuscular electrical stimulation are the core principles for the proper operation of FES.

The invention of Faradic simulator in the 1800s marked utilization of electric current for stimulation of nerve fibers. After the discovery of alternating current (AC) in the early period of 1900, different scholars studied the physiological response to AC stimulation, d'Arsonval being the first [12]. In the clinical world, wide varieties 'low-frequency currents' are used to stimulate muscle, nerve or both [13].

If an AC is used to excite nerve fibers, the frequency should be less than 10 KHz due to two important factors. The firs valid reason is that excitability of nerve fibers decreases for increasing frequency and the second being immediate burning of tissues when a higher frequency AC is utilized as a means of excitation. Modulated either in rectangular or sinusoidal form, the AC used in the clinical application has four important parameters; carrier frequency, burst frequency, ramping of the burst intensity and on-off duty cycle. Apart from direct current (DC) and AC, pulsed current is used for clinical application as defined by the Clinical Electrophysiology Section of the American Physical Therapy Association. The Pulse can be monophasic or biphasic. Biphasic pulse in turn,can be either balanced (symmetrical) or unbalanced (asymmetrical) [12, 13].

Effective utilization of electric current for neuromuscular innervation requires understanding of the basics of how action potential is used to stimulate muscles [12]; hence electrical neuromuscular excitation hinges on the basic understanding of the nerve fibers to be excited, the electrodes and electrode-tissue interactions [5].

Based on the principle of Electrophysiology, there are some modalities of nerve stimulation. Taking a single axon of a myelinated fiber and a pint current I placed near to it, a model is developed by McNeal [5] which assumes that "transmembrane current flows between the intracellular and extracellular medium only at the nodes" [8].The innervation of a single unmyelinated fiber is similar to simulation of a myelinated fiber [5].

A bidirectional pulse is used for nerve stimulation; a primary pulse intended to depolarize and a secondary pulse to re-polarize the nerve. As a basic requirement, the primary pulse should deliver the minimum threshold charge necessary to excite the nerve fiber before the secondary pulse is applied [8].

Quoted from Robert Plonsey and Barr, "a key element in functional electrical stimulation (FES) is the initiation of an action potential on a desired nerve, while at the same time refraining from stimulating other nerves nearby"[8]; hence the achievement of this goal relays on the type of electrode, its size, shape and placement site [12].

Electrodes has different components. To start with the first component, type of electrodes, they can be either unipolar or bipolar. The electrode itself that can be either cuf, epineural or intraneuralelectode[8] and the coupling mechanisms are the two most important components of the electrode system. The size of electrodes, on the other hand, determines the current densities at the point of interest; the larger the electrode the lower the current density and hence results a much more comfortable stimulation [12]. Again, the shape of the electrode determines the mechanical interaction between the electrode and the surrounding tissues as well as the level of trauma [8, 5]. Finally, the location of electrodes is often dependent on the treatment aims. It affects the current density and determines the nerve, which is going to be stimulated [8].

The following factors taken from Robert Plonsey and Barr, are the key criteria for electrode selection [8]:

- *Passive compatibility of the material with tissue.*
- *Extent of reversible behavior (capacitative region and region of reversible electrochemical reactions).*
- *Mechanical compatibility with the tissue.*

Bing biocompatible, strong, be able to be engineered for tissue in growth and better mechanical stability, platinum, platinum-iridium, and 316 stainless steel (SUS 316L) are used to produce electrodes. The electrochemical effect at the metal-electrolyte interface is responsible to convert the conduction current of the electrodes to ionic current in the tissues. Though idealized, the following model is used to represent the electrode-tissue interface [5, 8].

III. TYPES OF FES

In the domain of Electrophysiology, the term functional electrical stimulation (FES) is used when the aim of the treatment is to augment or produce functional movement. Though there is no a clear classification of FES, upper limb and lower limb FES, Bladder and Bowel FES as well as Respiratory FES systems will be addressed.

According to P. Hunter Peckham and Knutson, the objective of upper extremity neuro-prostheses (FES) is "to enable individuals with upper extremity paralysis to use their hands in activities of daily living (ADL)".Using surface electrode as a means of stimulation to open and close the hand, the first upper-extremity FES was developed in the 1960s which leads to the invention of surface, percutaneous and implanted hand graspsystems. Currently Handmaster, Bionic Glove, FESMate and the Freehand system are the common upper extremity neuro-prostheses [7].

Being an FDA approved therapy that provides hand function to individuals with C5 tetraplegia or hemiplegia caused by stroke, the Handmaster is composed of adjustable wrist-had orthosis and five built in stimulation surface electrodes. Through a push button on the control interface, the user is expected to initiate a hand movement stimulation sequence that will be picked up and addressed by the control system. The second available surface system, the Bionic Glove, is developed at the University of Alberta and consists of "a fingerless glove with a forearm sleeve that is worn over three or four self-adhesive electrodes previously placed on the hand and forearm" (P. Hunter Peckham and Knutson 2005). The displacement transducers that covers the wrist joint detects movement and initiates an of/on automatic ramping up and down stimulation in such a way that wrist extension beyond a certain angle triggers of grasp while the flexion triggers hand opening. Therefore, it improves the person's ability tenodesis grasp with lower cervical spinal cord injury (SCI) [7].

The percutaneous system FESMate, is developed by NEC Medical Systems, which uses up to 30 percutaneous electrodes for stimulate varieties of hand grip and upper extremity movements for individuals with cervical SCI (C4 to C6) and hemiplegia. It is commercially available in Japan. Case Western Reserve University (CWRU) and the Cleveland VA Medical Center developed the implanted Freehand system which is becoming one of the widely available upper assists. It received an FDA approval in 1997 and it provides lateral and palmar grasp to persons with C5 or C6 tetraplegia. Figure one, below summarizes the features of the Freehand implanted system [7].

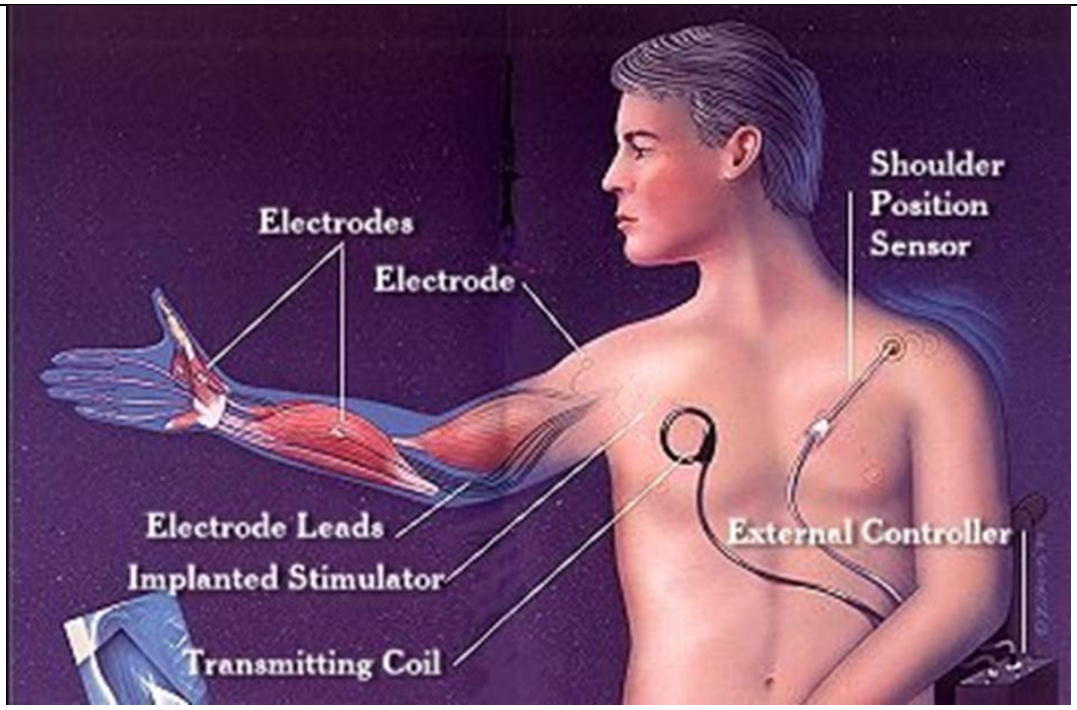

Figure 1: Major components of the Freehand FES system designed to provide hand function following spinal cord injury (Watson 2008).

The same investigator developed a 12-channel second-generationFreehand system, which utilizes implantable joint angle transducer (IJAT) wrist movements' detector, and extracts control signals from myoelectric (EMG) signals to provide greater upper extremity functionalities [7].

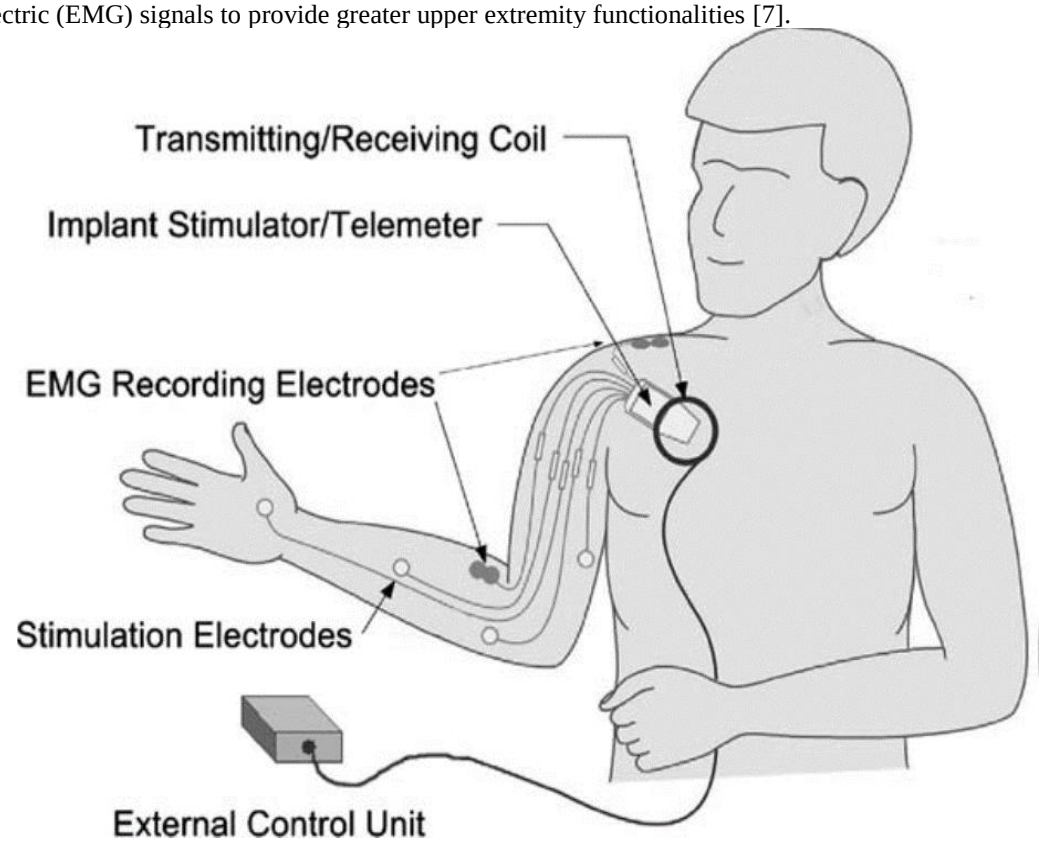

Figure 2: Schematic representation of the CWRU/VA 12-channel implanted upper extremity neuroprosthesis with myoelectric control capability (P. Hunter Peckham and Knutson 2005).

Even though many scholars conducted research in the lower limb functional electrical stimulation, the paper merely address foot-drop, standing/transfer and ambulation systems.

To start with foot-drop systems, Liberson was the first to come up with the pioneering foot-drop FES system in 1961 [15, 7, 13]. Being a stepping stone for further development, the earlier models utilizes either surface, cuff or epineural electrode that stimulated the peroneal nerve directly and an external heel switch for control with the following shortcomings [7]:

- *Properly placing the surface electrodes,*
- *False triggering of the stimulation*
- *Inadvertent elicitation of reflex spasms in the plantarflexor muscles*
- *Pain or discomfort from the stimulation, mechanical failure of the switch and other components*
- *Difficulty in achieving balanced dorsiflexion with a single electrode*
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Used by more than 3500 Danish patients, the single channel surface system, Foot-lifter is one of the commercially available products. The recently FDA approved Walkaide is another self-contained foot-drop system developed at the University of Alberta while the OdstockFootdrop, a single-channel foot switch triggered Stimulator (ODFS), is developed in Salisbury , U.K. The implanted ActiGait (Neurodan A/S,Aalborg, Denmark) which received the CE mark, uses a four-channel cuff around the common peroneal nerve. Additionally the University of Twente, Netherlands developed the Finetech Dropped Foot System; dual-channel stimulator implanted below the knee which is under trial for SCI correction [6, 7].

The second groups of lower limb assists are the standing/transfer systems intended to enable persons with paraplegia to stand from a seated position and transfer to another surface. The implantable standing neuroprosthesis developed at the Cleveland VA Medical Center and CWRU, which uses 8-channel stimulator/receiver, is on the final stage of clinical trial for commercialization [5].

The other groups of lower limb FES are ambulation systems. Though there are verities of FES, the microprocessor based percutaneous technique developed by Cleveland VA Medical Center and CWRU, which can stimulate up to 48 muscles, is the only FDA approved system for ambulation. All of the FES systems for standing and walking require the use of a walker or standing frame for stability [7].

On top the aforementioned FES, balder FES is developedto reproduce the lost micturition while bowel FES tend to improve bowl function [6, 7]. Giles Brindley of the U.K highly improves the bladder FES systems; the Finetech-Brindley implanted System is a one of the famous bladder FES that enables micturition by innervating sacral spinal nerve roots for detrusor contraction for proper micturition and provides bowel evacuation and penile erection as a secondary uses. Therefore, it reduces urinary tract infections and the use of catheters. Known as Vocare, Finetech-Brindley system is approved by the FDA for SCI and has been used by individuals with multiple sclerosis, spinal cord tumors, transverse myelitis, cerebral palsy and meningomyelocele [7]. In summary bladder and bowl FES, implants are backed by “posterior sacral rhizotomy to increase bladder capacity and abolish reflex incontinence and sphincter contraction” [6].

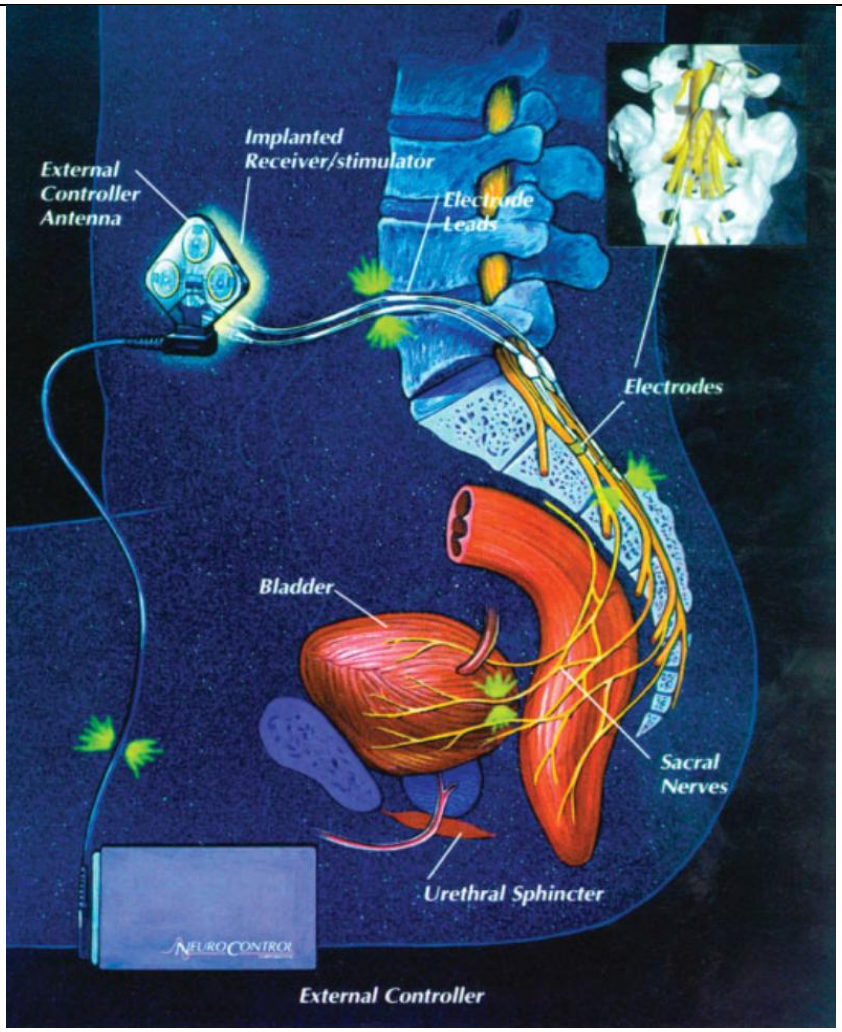

Figure 3: The implanted bladder neuroprosthesis system (Vocare, courtesy of NeuroControl, North Ridgeville, OH) [6].

Even if the bladder and bowl implants effectively restores micturition and bowl function and avoids the prevalence of catheter related infections, the rhizotomy requirements has unfavorable impact on both patients and clinicians preference towards the systems and hence different scholars are working hard to make the implants more comfortable [6].

The final functionality that can be achieved by FES and used to assist individuals with high cervical SCI or central alveolar hypoventilation (CAH) who are dependent on ventilation machine is a respiratory neuro-prosthesis.Commonly known as phrenic pacing systems, which restore lung function by stimulating the diaphragm via phrenic nerve. The type of electrodes and stimulation strategies used being their major differences; the Avery Mark IV and the Atrostim system are the two common commercially available diaphragm pacing FES [7]. In most of the respiratory FES systems, two electrodes are implanted on each phrenic nerve that are connected to the distally implanted receiver. The external antenna is responsible to link the implanted receiver and the external control unit [6, 7].

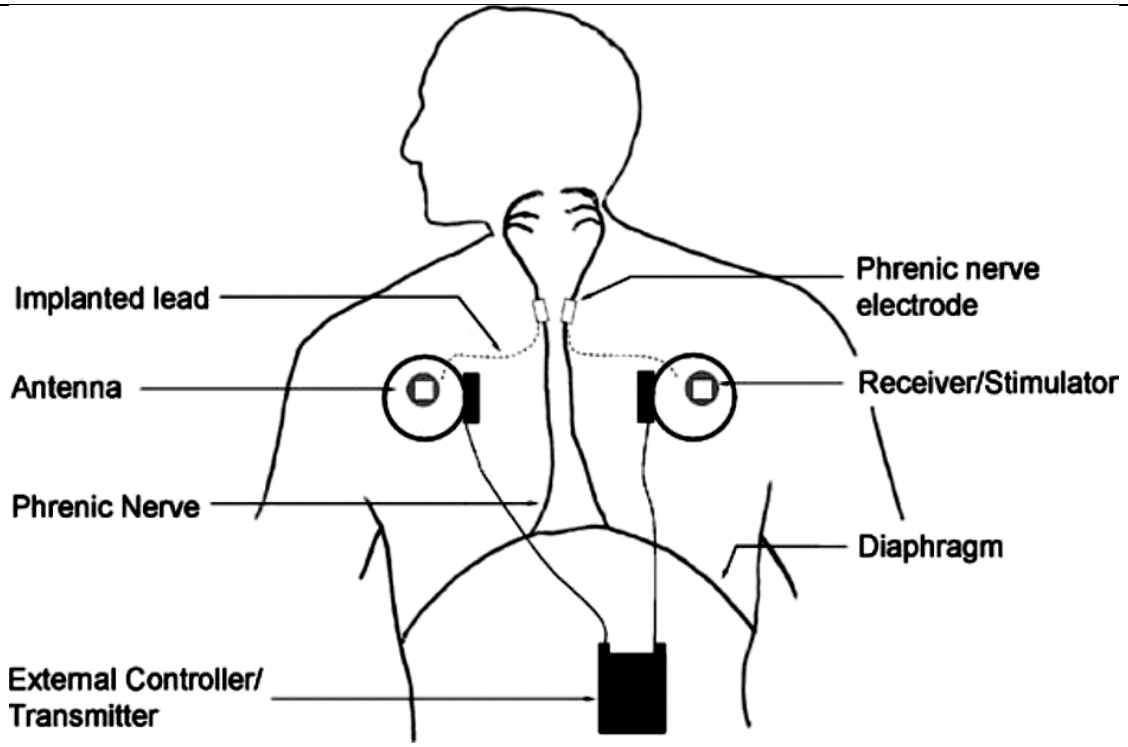

Figure 4: Bilateral phrenic nerve pacing system [7].

Though not commercially available, the MedImplant, which is developed in Austria, uses four electrodes sutured to the epineurium of each phrenic nerve from a single 8-channel receiver/stimulator to restore lost lung function. Apart from the surgical related complications, the major shortcoming for phrenic pacing systems is that individuals with either complete phrenic nerve can only use them though individuals with partial phrenic nerve can use the system if assisted by the inspiratory intercostal muscles [7].

IV. FUTURE DIRECTIONS

Amazingly, varieties of FES are being invented which are superior either in technology, control techniques or both. Directly quoting from P. Hunter Peckham and Knutson, "future systems will be designed around a platform technology, where numerous neuromuscular deficits will be treated using the same basic neuro-prosthetic system or a subset of the possible components of an entire system". Hence further refinement of system configuration as well as introduction of more reliable stimulating and recording electrodes are inevitable. From control topology point of, development and integration of implantable control sensors as well as control algorithms for intuitive operation are future directions of FES systems [7].

V. CONCLUSION

Functional electrical stimulation (FES) is a technique that uses electrical currents to activate nerves innervating extremities affected by paralysis resulting from spinal cord injury (SCI), head injury, stroke and other neurological disorders. Being one of the direct applications for therapeutic use of electricity, FES involves applying a low frequency electric current on or around a nerve to cause muscle contraction.

Currently there are varieties of upper limb and lower limb FES used to restore the lost function of individuals with upper and lower extremity paralysis, Bladder and Bowel FES and Respiratory FES systems aimed at reinstating a compromised bladder and bowl function as well as respiratory system due to neuromuscular defects. To sum up, varieties of FES systems are being invented which are superior either in technology, control techniques or both which indicates that future FES systems will be able to handle numerous neuromuscular deficits.

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