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Functional Electrical Stimulation as a Significant Bioelectronic Intervention in the Domain of Fitness: A Review

Ritwik Raj Saxena[1,*], Ritcha Saxena[2], Akash Patel[3]

[1]Department of Computer Science, University of Minnesota Duluth, Minnesota, United States of America.
[2]Department of Biomedical Sciences, University of Minnesota, Minneapolis, United States of America.
[3]Department of Clinical Sciences, Medical University of the Americas, St. Christopher and Nevis, United States of America.
saxen130@d.umn.edu[1], rsaxena@d.umn.edu[2], apatel@mua.edu[3]

Abstract: This review aims to evaluate how far functional electrical stimulation (FES) can serve as a replacement for training to improve muscle strength and hypertrophy metrics in people who lack the time to attend gym training sessions. We conducted a Preferred Reporting Systems for Systematic Reviews and Meta-Analyses (PRISMA) review to identify those documents that provide relevant information about our objectives. We isolated seven relevant documents in this regard. We studied them, specifically their results, to identify pertinent points that assisted our understanding of FES as a tool that can improve fitness. Our study demonstrates that FES can augment many of the factors that motivate individuals to go to the gym and engage in workouts. FES serves to improve contractile strength, hypertrophy, endurance, muscle mass, and overall functionality of muscles in individuals. Science offers a positive outlook on FES and its ability to improve voluntary muscle activation. However, FES suffices to fulfill such functions in an adjunct capacity and is better suited for people who, due to old age or physical reasons like paralysis or other reasons leading to weakness or immobility, cannot go to the gym or engage in adequate strength or hypertrophy exercises. We found that while FES offers strong opportunities to improve muscle mass contractile strength and combat muscle fatigue in workout-deprived individuals, its effectiveness compared to actual gym workouts fails to reach the levels where we could term it a worthwhile replacement to gym training.

Keywords: Functional Electrical Stimulation; Contractile Strength; Hypertrophy and Endurance; Muscle Mass; Muscle Fatigue; Bioelectric Impedance; Neuromodulation and Neuroplasticity; Bioelectronic and Duty Cycle; Maximal Voluntary Contractions.

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1. Introduction

In an increasingly time-constrained society where a busy lifestyle causes regular gym attendance to be a challenging aspect, the pursuit of fitness goals continues to stay paramount. It becomes important to delve into the potential of Functional Electrical Stimulation (FES) as a solution to bridge the gap between hectic schedules and the imperative need for improvement of muscle strength and hypertrophy. FES, known for its ability to activate muscles through electrical currents, offers promise in aiding muscle strength and hypertrophy. In this context, it is imperative to critically assess the extent to which FES can serve as a viable alternative to traditional gym workouts, examining its efficacy in targeting muscles, inducing muscle growth, and addressing limitations compared to conventional resistance training. We elucidate the role of FES in meeting fitness demands amidst time limitations.

*Corresponding author.

2. Functional Electrical Stimulation

Functional Electrical Stimulation can be described as the process of electrically stimulating a part of the human body, most often referred to as one that targets neuromuscular tissue to manifest or improve a certain combination of bodily functions, typically to induce muscle contraction and facilitate joint movement.

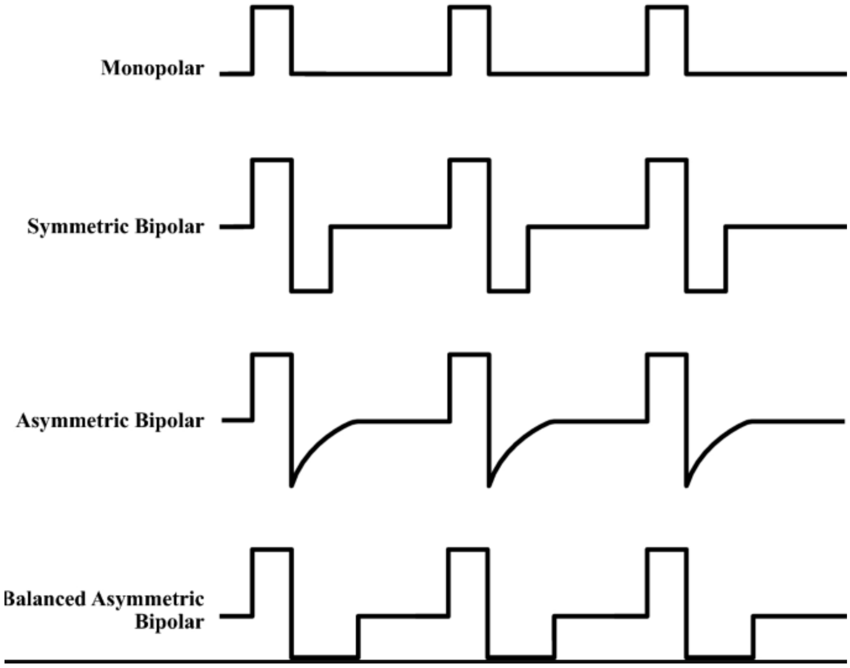

Figure 1: Some types of pulses, and whose variations, are used in Functional Electrical Stimulation [1]

Functional Electrical Stimulation (FES) was devised as a treatment method to be used on muscles weakened or paralyzed due to Central Nervous System (CNS) issues or upper motor neuron injuries. It is a bioelectronic assistive technology and a rehabilitation technique that may employ a wide range of frequencies and pulse durations, including higher frequencies for direct nerve stimulation. It often uses monophasic (or monopolar) pulsed current, biphasic (or bipolar) pulsed current, burst-modulated alternating current (for example, Russian current), or Faradic current (which is an interrupted direct current) to excite undamaged lower motor neurons. This process creates muscle contractions in weakened muscles to perform a voluntary bodily function, which is essential to lead a normal life. Figure 1 describes a few basic varieties of currents or pulses used in FES.

FES can directly or indirectly target peripheral motor nerves or even the spinal cord. FES utilizes minute electrical impulses that are directed into target muscles, which are those muscles that have lost function resulting from brain or spinal cord damage or sometimes from musculoskeletal impairments. FES encompasses various electrical stimulation techniques to activate muscles and elicit functional movements. FES can be used for a wide range of purposes, including assisting with gait, controlling prosthetics, restoring motor function and movement, improving muscle strength, or facilitating specific tasks such as grasping.

Widely employed in cases of Multiple Sclerosis (MS), FES is often used to treat instances of foot drop, where the ability to lift or dorsiflex the forefoot adequately during walking is restricted, resulting from the dysfunction of dorsiflexion. Stimulation is applied to the peroneal nerve, a branch of the sciatic nerve, to lift the foot during walking, aiding in restoring functional mobility and addressing the gait-related challenges posed by foot drop in individuals afflicted with MS. Many other neurologic conditions can mimic peroneal nerve injury, which include Parkinson’s disease and amyotrophic lateral sclerosis ALS or Lou Gehrig’s disease.

By administering controlled electrical charges, FES prompts the affected muscles to execute their typical movement, commonly catalyzing some degree of neuroplastic restoration and adaptation and serving a neuromodulatory function. This has also shown improvement in the restoration of pain sensation in patients with analgesia. Therefore, an FES device may be used as a sensory rehabilitation neuroprosthesis as well. Neuroplastic adaptation achieved with FES has been shown to help amputees and the suchlike adjust to a life without a limb or to the use of prosthetics. FES can target specific muscles instead of muscle groups.

With FES, the need for strenuous and repetitive movements is eliminated. This makes it an ideal option for individuals with injuries that result in physical disabilities.

2.1. Types of Functional Electrical Stimulation

FES can be classified under various categories. Surface FES is a vital therapy that involves placing electrodes on the skin's surface over targeted muscles. It is used for muscle activation and functional movement. On the other hand, there is an implanted FES. Epidural stimulation [2], transcutaneous stimulation [3], and intramuscular stimulation are special cases of it. Implanted FES involves surgically implanting electrodes near affected nerves within the muscular tissue. It allows for more targeted therapeutic therapy. It was built to be utilized for individuals with spinal cord injuries, most commonly paraplegia, to restore motor function, bladder control, or limb movement, most commonly in lower limbs. However, evidence suggests that it has largely been used for experimental and research purposes so far.

In Transcutaneous Electrical Nerve Stimulation (TENS), low-voltage electrical currents are applied, as the word transcutaneous suggests, through the skin to stimulate nerves. It can be used for pain relief and can be used to indirectly affect muscle contraction by modulating pain perception and nerve activity. It has been shown to enhance voluntary muscle performance in patients with incomplete spinal cord injury [3]. Intramuscular stimulation (IMES), also termed intramuscular FES, is characterized by electrodes that are implanted directly into specific muscles. It is employed for precise muscle activation in conditions such as limb paralysis, targeting specific muscle groups for controlled movement.

Neuromuscular Stimulation (NMES) [4] may be considered a subcategory under FES, although some experts consider it a standalone concept. It has therapeutic functions, as it assists in palliative care, pain management, strengthening weakened muscles, and promoting intramuscular blood flow and, thereby, oxygen supply. It stimulates peripheral motor nerves for indirect muscle activation. It is often used in rehabilitation settings, including physiotherapy and sports medicine, to prevent disuse atrophy. It is also used as part of a regimen to strengthen muscles after neuromuscular trauma or surgery. It typically uses low-frequency current, mostly burst-modulating alternating current, and short pulse durations. Longer pulse durations in NMES have been shown to be able to better target deeper muscles, but that is something that has been used less commonly.

Application-based classification of FES includes but is not limited to Closed-Loop FES, Functional Electrical Stimulation-Cycling (FES-Cycling), Functional Electrical Stimulation for Swallowing (FES-Swallowing), Phrenic Nerve Pacing, Diaphragm Motor Point acing (DMPP) and so on.

Closed-loop FES involves dynamic, real-time feedback mechanisms that adjust stimulation based on sensor input, such as muscle activity, joint position, torque, or cadence (which is the average number of steps per minute that a person takes or can take while running) [5]. It is applied where we need to provide adaptive, personalized, and more precise stimulation to enhance control and function in movements. A group of researchers [6] have developed a control design of a closed-loop FES system specifically targeting the position control of the wrist articulation when movement is induced by FES, utilizing a PID (Proportional-Integral-Derivative) controller and fine-tuning it for each test subject. FES-Cycling and FES-Swallowing are usually closed-loop FES systems.

FES-Cycling Involves stimulating leg muscles to facilitate cycling movements on a stationary bike and is used in rehabilitation for individuals with spinal cord injuries, stroke, or other conditions affecting lower limb function to improve muscle strength and cardiovascular fitness. FES-Swallowing utilizes electrical stimulation to improve swallowing function and is applied in dysphagia therapy to assist in retraining swallowing muscles and improving swallowing coordination.

Phrenic Nerve Pacing (PNP) is a technique employed as an alternative to mechanical ventilation in patients suffering from neuromuscular respiratory insufficiency. In this, the phrenic nerve is electrically stimulated with the help of a surgically implanted subcutaneous radiofrequency receiver and an external transmitter. The transmitter sends radio waves to the implanted receivers just under the skin. The receivers transform the radiofrequency electromagnetic energy into electrical pulses. The stimulating pulses are sent through the electrodes to the phrenic nerve, which contracts the diaphragm muscle. Diaphragm Motor Point Pacing (DMPP) is a substitute for PNP. In DMPP, the diaphragm is directly stimulated at the locations (motor points), which are the points where phrenic nerve endings are found in the diaphragm. Unlike PNP, DMPP circumvents the need to activate a portion of the phrenic nerve. Therefore, in DMPP, as compared to PNP, the probability of lower motor neuron injury is diminished. Electrical stimulation, with the help of a pacemaker, has also been shown to improve the rhythm of ventricular cardiomyocytes.

2.2. Basic Mechanism of Functional Electrical Stimulation

These electrodes are placed upon motor nerves and muscle fibers. The current aligns the cations and anions in the neuron-muscle junction, leading to the flow of electricity through the muscle, a process that is termed electrical stimulation. A noteworthy aspect of electrical stimulation of muscle is that the electric field density diminishes with the depth of the neuromuscular tissue.

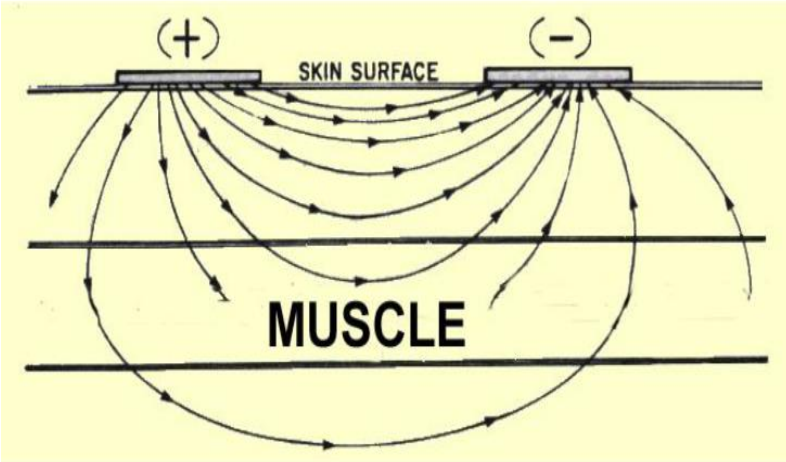

Figure 2: A diagram showing the electrical field generated when a stimulating current is applied to surface electrodes [7]; [8]

In the case of an unparalyzed muscle, the brain (or spinal cord in case of reflex action) sends signals down the motor neurons in the form of an electrical current, which results from the alignment and movement of ions. This current excites the myocytic cell membrane (sarcolemma), allowing for an action potential that triggers contraction. The transduction between the action potential produced in the sarcolemma and the beginning of a muscular contraction is called the excitation-contraction coupling. In a paralyzed muscle, the signaling pathway from the brain to the muscle is broken, and the electrical current in the neuron must be generated through electrical stimulation to generate this transduction, as shown in Figure 2.

2.3. Motor Unit Recruitment and Muscle Recruitment Curve

Motor unit recruitment is an estimation of how many motor neurons, and thereby how many muscle fibers, are recruited or activated in response to a stimulus to assemble the necessary amount of contractile strength or isometric joint torque to successfully perform a particular voluntary task [9]. When this stimulus is electrical stimulation, in cases of neurorehabilitation [10], we encounter the concept of muscle recruitment curve, which graphs the relationship between the voltage of the electrical stimulation applied and the contractile capability achieved.

In connection with the isometric recruitment of motor units in electrically stimulated muscles [11], the concepts of threshold nonlinearity and saturation nonlinearity assume importance. The threshold here refers to the minimum stimulation intensity required to recruit muscle fibers. As the electrical stimulation's amplitude enhances, new nerve fibers within the ambit of the electric field applied are activated, causing an increase in the isometric joint torque [7]. However, not all nerve fibers have the same stimulation threshold. Fibers closer to the electrodes and those with larger diameters are stimulated first as they have lower thresholds, while others require higher stimulation intensities [12]. Additionally, beyond a certain stimulation intensity, the force of muscle contraction reaches a saturation point, and this intensity is termed the saturation threshold. At this level of stimulation, all available nerve fibers are excited, and further increases in stimulus intensity do not lead to additional muscle contraction. This saturation value indicates the maximum achievable joint torque through electrical stimulation. The fact that the contractile strength reaches a saturation point or a plateau suggests that there is a limit to which FES can serve to replace workouts in bettering the muscle parameters, whose improvement is what prompts people to attend gyms.

2.4. Key Parameters in Functional Electrical Stimulation

The effects of the augmentation of FES involve optimizing three key parameters: pulse width, frequency, and amplitude, which significantly influence muscle contraction and fatigue reduction. Pulse widths typically range between 300 and 600 μs, with longer widths (500-1000 μs) shown to reduce muscle fatigue, while shorter widths (10-50 μs) potentially recruit more muscle fibers and generate larger joint torques. Stimulation frequency, varying from 20 to 50 Hz, is adjusted for specific treatment objectives; lower frequencies prevent fatigue and produce smoother contractions, whereas higher frequencies offer smoother force responses and increased comfort. Altering frequency patterns can affect fatigue resistance. Amplitude, typically between 0 and 100 mA, determines FES intensity, with higher amplitudes activating more muscle fibers, although excessive levels might limit central nervous system signal input. Varying amplitudes, rather than constant ones, have shown increased contractions while reducing amplitude might not notably impact fatigue reduction. The personalized selection of these parameters based on individual rehabilitation goals is crucial for optimizing FES outcomes [10] (Figure 3).

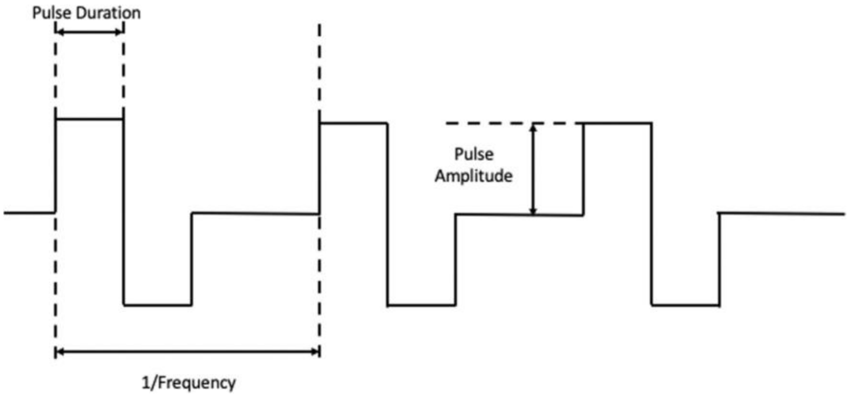

Figure 3: The main parameters of FES, pulse duration, pulse amplitude, and frequency [12]

Pulse duration and frequency are two distinct parameters commonly associated with electrical stimulation. Pulse duration refers to the length of time for which each pulse of electrical stimulation occurs. It represents the duration of the electrical pulse delivered during one cycle. Ordinarily measured in microseconds (μs) or milliseconds (ms), pulse duration determines how long the electrical current is applied in an instance of the application. Longer pulse durations typically deliver more charge and can affect factors such as the recruitment of nerve fibers, muscle contraction strength, and comfort levels for the individual receiving the stimulation. Pulse duration relates to the duration of each pulse of electrical stimulation, determining the time the electrical signal is active, and frequency refers to the number of pulses delivered within a specific period, influencing how often the electrical pulses occur. Frequency is usually measured in Hertz (Hz) or pulses per second (pps). Higher frequencies imply a more rapid succession of pulses within a given time frame. The frequency of electrical stimulation influences physiological responses such as isometric muscle moment, fatigue, and the types of nerve fibers recruited. Lower frequencies are shown to induce fasciculation or twitching muscle contractions, where the muscle contracts for a short duration and then relaxes. Higher frequencies lead to summative or tetanic muscle contractions. In these contractions, a subsequent contraction begins before the muscle relaxes from the previous contraction, leading to a sustained contraction. The frequency at which such contractions start occurring can be called summation frequency. These differences in muscle response serve therapeutic and diagnostic purposes in clinical settings.

In the same way as the strength of an electrical pulse influences factors associated with muscle contraction, like torque and fatigue, the duration of the pulse also impacts the way a muscle contracts. The effect of pulse duration is determined by the minimum level of stimulation needed for a muscle to react and the point at which the muscle can’t respond any further. When using surface stimulation on the skin, longer pulses can cause discomfort or even damage the skin. Therefore, shorter pulse durations (lasting between 0.1 to 0.5 milliseconds) are preferred to avoid these issues [7]. If someone has a paralyzed limb, increasing the strength of the stimulus controls the muscle’s force. However, changing the pulse duration does not seem to affect how quickly the muscle fatigues. To make a paralyzed limb move, it’s not enough to use just one electrical pulse. Instead, a series of electrical pulses, known as a stimulation pulse train, is required [7, 10]. During FES training for weakened muscles, this pulse train is followed by a break, followed by another pulse train. The relationship between how long the pulse train lasts and the break in between is called the duty cycle. The duty cycle is the ratio of time when the muscle is actively stimulated to the summation of the time when the muscle is electrically stimulated and the time when the muscle is not electrically stimulated, and it is expressed as a percentage. The duty cycle affects how tired the stimulated muscle gets. Adjusting this cycle can help manage muscle fatigue during FES training to improve the effectiveness of the muscle’s response to electrical stimulation.

2.5. A Broad Classification of Muscle Contractions

Fasciculation-type muscle contractions and summation-type muscle contractions are the different patterns of muscle activation produced by electrical physiological stimulation. Fasciculation-type muscle contractions occur when a muscle responds to a single, brief stimulus or nerve impulse [13]. They involve a single, isolated contraction-relaxation cycle of the muscle fibers in response to a single action potential. Twitch contractions are typically seen at lower frequencies of electrical stimulation or nerve firing rates. These contractions are momentary and do not sustain for an extended duration. They are characteristic of the initial, individual muscle responses before sustained muscle activation occurs.

Summation-type muscle contractions are seamless and result from a series of rapidly delivered electrical stimuli or nerve impulses that occur at a frequency high enough to fuse individual twitches into a sustained contraction. During tetanic contractions, the muscle fibers are stimulated at a high frequency, which prevents the muscle from fully relaxing between individual contractions. As a result, the muscle sustains a steady contraction. Tetanic contractions are stronger and more forceful than individual twitches and are often seen at higher frequencies of electrical stimulation or nerve firing rates. Witches are often seen at higher frequencies of electrical stimulation or nerve firing rates (Figure 4).

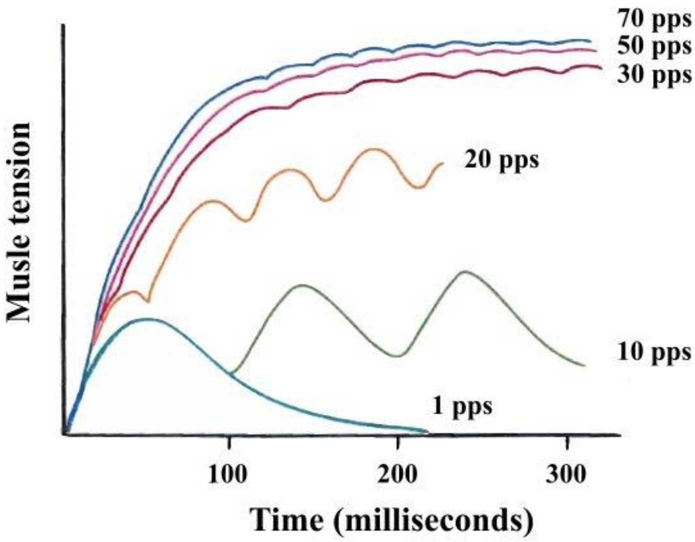

Figure 4: Type of muscle contractions in relation to the frequency of stimulation [14]

At lower frequencies, fasciculations occur, and at higher frequencies, tetanic contractions happen due to the fusion of twitches.

2.6. Post-activation Potentiation and Muscle Fatigue

The concept of post-activation potentiation suggests that the contractile history of a muscle influences the muscle activation rates and, thereby, the mechanical performance of further muscle contractions. In post-activation potentiation, the contractile force of a muscle is increased because of its previous contraction [15]; [16]. Muscle contractions that, instead of fatiguing muscles, causing them to depict improvement in exerting joint torque are characterized by their brief duration and increased loads and are referred to as maximum voluntary contractions [16].

In the case of electrical stimulation, it has been observed that while an increase in frequency improves the contractile force of a muscle, it also fatigues it. The lower the frequency, the lower the rate of fatigue. However, it has been noted that when muscles are stimulated with electricity, they tire out more quickly compared to when they contract voluntarily [7, 10]. Our muscles have two types of fibers: slow-twitch ones (type I fibers) that can exert for a long time without getting tired, and fast-twitch ones (type IIA and type IIB) that can produce strong torques but tire out more rapidly than the fast-twitch ones [17]. Some muscles, like the triceps surae, whose main function is to perform plantar flexion of the foot during walking and to lock the foot when a person stands, have more slow-twitch fibers. Some, like the biceps brachii, have more of the fast fibers.

Each group of muscle fibers controlled by the same nerve follows the same pattern. In normal situations, when we move voluntarily, our slow-twitch fibers are activated first, and as we need more strength, the fast ones join in. But with electrical stimulation, the order is reversed; the bigger, fast-twitch fibers get activated first. This reversal leads to faster fatigue in the electrically stimulated muscle because the fast-twitch fibers tire quickly [7]. Also, when we move voluntarily, different parts of our muscles get used in turns, but with electrical stimulation, the same part gets used repeatedly, leading to quicker fatigue. The frequent electrical stimulation can also exhaust the transmitter at the nerve-muscle connection, causing the stimulated muscle to fatigue faster. Faster fast-twitch fiber fatigue is another reason why FES cannot be an effective replacement for gym workouts, which are used to particularly target the fast-twitch fibers.

2.7. Electrodes in FES

Electrodes serve as the interface through which electrical current moves from the stimulator into the body's tissues. This involves a conversion of electron current in the wires to ionic current in the tissues. Electrodes can be made from metals or nonmetals like graphite, an isotope of carbon. Current travels from a point of higher electrical potential, that is, anode, which is the positively charged electrode, to a point of lower electrical potential, that is, cathode, which is the negatively charged electrode. From the anode, the current flows into the tissue, and at the cathode, the current flows from the tissue back into the conductor.

Larger electrodes are used to stimulate wider areas and provide stronger muscle contractions with less sensation on the skin. In comparison, smaller electrodes are used for targeted nerve stimulation near the surface of the skin. The size of electrodes varies depending on the muscle group and location. Cathode and anode are positioned in specific ways to optimize functional movement, often with the anode placed distally for stronger contractions. The lower the electrode resistance, the lesser the energy loss [18]; [19].

The impedance between the electrode and skin varies with frequency, with DC impedance being significantly higher. Moistening electrodes with water or conductive gels can reduce impedance [20]. Adipose tissue and bone can impede electrical current, and this phenomenon is called bioelectric impedance. A high bioelectric impedance typically demands higher stimulation amplitudes, which may cause discomfort. Smaller, closely spaced electrodes stimulate superficial tissues due to lower impedance paths. Larger distances between electrodes allow for deeper tissue stimulation and potentially stronger muscle contractions. The clamminess of skin between electrodes can potentially redirect and distort the path of current inside the neuromuscular tissue, causing discomfort and reducing the muscle contraction efficiency [21]; [22].

Electrodes used in functional electrical can be differentiated based on their placement and invasiveness. Implanted electrodes are more deeply invasive, while percutaneous ones are less deeply invasive. Transcutaneous electrodes are placed on the surface of the body. Implanted electrodes, surgically inserted near nerves, offer high selectivity for specific muscle stimulation but pose infection risks and higher costs. They require less time to be inserted but lack adjustability once embedded [1]; [23].

Percutaneous electrodes, which are in the form of wires penetrating the skin near motor neurons, are used for short-term applications with a stimulation current of around 25 mA. Transcutaneous electrodes, placed on the skin's surface, offer non-invasive use and immediate repositioning for desired stimulation responses. Ideal for short-term interventions and early-stage rehabilitation in stroke or spinal cord injury patients, they allow readjustment and use currents varying from 2 to 120 mA. However, their limitation lies in stimulating deep muscles effectively, requiring higher intensities that might engage unintended muscles. While each type has distinct advantages and limitations, their suitability depends on the specific needs of the individual and the intended application in FES interventions [1].

Improper handling of electrodes in FES can lead to various challenges. Burns are more likely to occur underneath the anode rather than the cathode when identical surface electrodes are used. Precise positioning along a muscle is crucial; even a small displacement can drastically alter the muscle response, especially when targeting specific nerves like the peroneal nerve. Surface electrodes might trigger pain receptors in the skin, although reduced patient sensitivity can mitigate the sensation of pain. Undesired skin motion relative to neuromuscular tissue can affect stimulation efficacy and reproducibility. Selective activation of small muscles or stimulation of deep muscles without involving superficial muscles is challenging [7].

High voltages (exceeding 100V) between electrode pairs pose hazards for patients and personnel. Fixation problems with surface electrodes have led to the development of stretchable garments and specially designed clothing with integrated electrodes to simplify application. While most inconveniences of surface electrodes could be addressed using implanted electrodes, surface electrodes, owing to their simple non-invasive application, remain useful in treatments and neuroprosthesis applications, especially for lower limb stimulation and upper limb splint-based systems, which offer comfort, ease of use, and quick positioning [7].

2.8. Unipolar & Bipolar Stimulations

In unipolar stimulation, a small active cathode and a larger indifferent anode are involved. The smaller electrode is placed near the motor point for precise stimulation of nerves. The motor point is the optimal site on the skin for electrode placement, where nerve fibers are closest to the surface, requiring minimal stimulus amplitude for muscle activation. Bipolar stimulation utilizes two electrodes of the same size placed along the muscle to create a current path between them [23].

2.9. FES and Myoelectric Activity

Myoelectric activity measured through EMG signals plays a crucial role in assessing, controlling, and optimizing the effectiveness of FES interventions in neuromuscular rehabilitation. The relationship between FES and myoelectric activity is essential for understanding and improving the outcomes of FES treatments aimed at restoring muscle function and mobility [24].

Myoelectric activity refers to the electrical signals generated by muscle fibers during contraction. These signals, known as electromyographic (EMG) signals, can be detected and measured using electrodes placed on the skin overlying the muscles. EMG signals provide information about muscle activity, such as the timing, intensity, and patterns of muscle contractions.

When studying muscle response in cases of FES application, myoelectric activity measurement is assumed to be important. FES directly induces muscle contractions by delivering electrical stimulation to the nerves or muscles. This stimulation generates myoelectric signals as the muscles contract in response to the electrical impulses. EMG can be used to record, monitor, and analyze the muscle response to FES. EMG signals can be utilized to evaluate the effectiveness of FES. By monitoring the myoelectric activity feedback during FES application, clinicians can assess the muscle response and adjust the stimulation parameters (such as frequency, intensity, and duration) to optimize muscle activation and functional outcomes.

Understanding myoelectric activity through EMG signals helps in designing FES protocols for rehabilitation and training purposes. By analyzing the patterns of muscle activation, therapists can tailor FES interventions to target specific muscle groups and enhance functional movements in individuals with conditions like paralysis or muscle weakness.

According to Chin and Popovic [1], a three-channel electrical stimulator was built in the early 1970s at the University of Ljubliana. It could be regulated with inputs from various sensors, including sensors for electromyographic recording and a sliding resistor, which was used to adjust the stimulation intensity.

Electromyography-based electrical stimulation, which is also called biofeedback-mediated neuromuscular electrical stimulation, involves a closed-loop FES that uses electromyographic feedback as a modulating input to FES therapy. Sheffer *et al.* [25] have reviewed many studies that have shown varied degrees of effectiveness and improved outcomes in patients requiring upper-limb motor relearning. However, methodological limitations have prevented the researchers from coming to conclusive inferences regarding the success of biofeedback-mediated neuromuscular electrical stimulation**.**

2.10. Miscellaneous Categorizations of FES

Fabric-based FES involves textile electrodes. According to Chin and Popovic [1], such electrodes offer several potential advantages. They offer heightened user comfort and mechanical compliance. They also offer a reduced risk of skin irritation by engendering enhanced ventilation compared to hydrogen gel-based electrodes and offer the convenience of being washable. A significant benefit lies in their integration into regular clothing, simplifying the delivery of FES and encouraging widespread use. The mass production feasibility of garments further supports the seamless incorporation of textile-based electrodes into everyday wear, marking a promising development in the field. Electrodes constructed out of Lycra are gaining much popularity nowadays.

Chin and Popovic have also talked about Brain-Computer Interface-based FES, in which the involuntary intent of a person is directly converted into FES activity without the need for voluntary directions from the individual. This would prove to be a quantum leap in the field of FES because it would be of great assistance to those people who have limited muscle capability in all their limbs or most of their limbs or have generalized muscle weakness all over their body. According to Chin and Popovic, the integration of Brain-Computer Interface (BCI) and FES devices in neurorehabilitation is propelled by the logic that the co-occurrence of a motor command generated from a person’s attempt to move and the sensory information arising from FES-induced movement (including proprioceptive and somatosensory feedback) can facilitate neuroplastic changes. These changes in the nervous system are anticipated to contribute to the restoration of voluntary movement. By combining the input from the user’s intention to move with the sensory feedback provided by FES, a synergistic approach is employed to enhance the effectiveness of neurorehabilitation and support the recovery of motor function.

Electroencephalogram (EEG)-driven FES represents an example of BCI-based FES. It is an innovative approach to neurorehabilitation. It provides the prospect of restoring voluntary motor function in individuals with severe limb impairments like paraplegia. In the context of neurological conditions such as hemiplegia following a stroke, the combination of EEG and

FES aims to capitalize on the brain's motor commands and sensory feedback to induce therapeutic changes in the nervous system. There is huge potential for EEG-driven FES to achieve significant improvements in limb motor function.

The technology relies on real-time monitoring of brain activity through EEG electrodes, capturing the intricate interplay of neuronal signals associated with motor intentions. By decoding these signals, the system identifies specific patterns related to the desired movements of the impaired limb. This neurofeedback loop enables precise synchronization between the user's intent and the application of FES. Unlike conventional FES, which may lack specificity in targeting desired motor tasks, the EEG-driven approach offers a more nuanced and individualized intervention. Moreover, the adaptability of this technology allows for dynamic adjustments, accommodating variations in the user's cognitive state and optimizing the rehabilitation process over time.

3. Methods

A literature review was conducted to gauge the efficacy of Functional Electrical Stimulation in achieving the fitness goals that one attends the gym to accomplish. The PRISMA format was followed to search and evaluate the literature about Functional Electrical Stimulation and the role it can play in helping an individual avoid going to the gym. The primary search engine used was Google Scholar, and the primary databases searched were PubMed Central (PMC) and Scopus. The keywords used in search queries were Functional Electrical Stimulation, taken with hypertrophy and muscle strength.

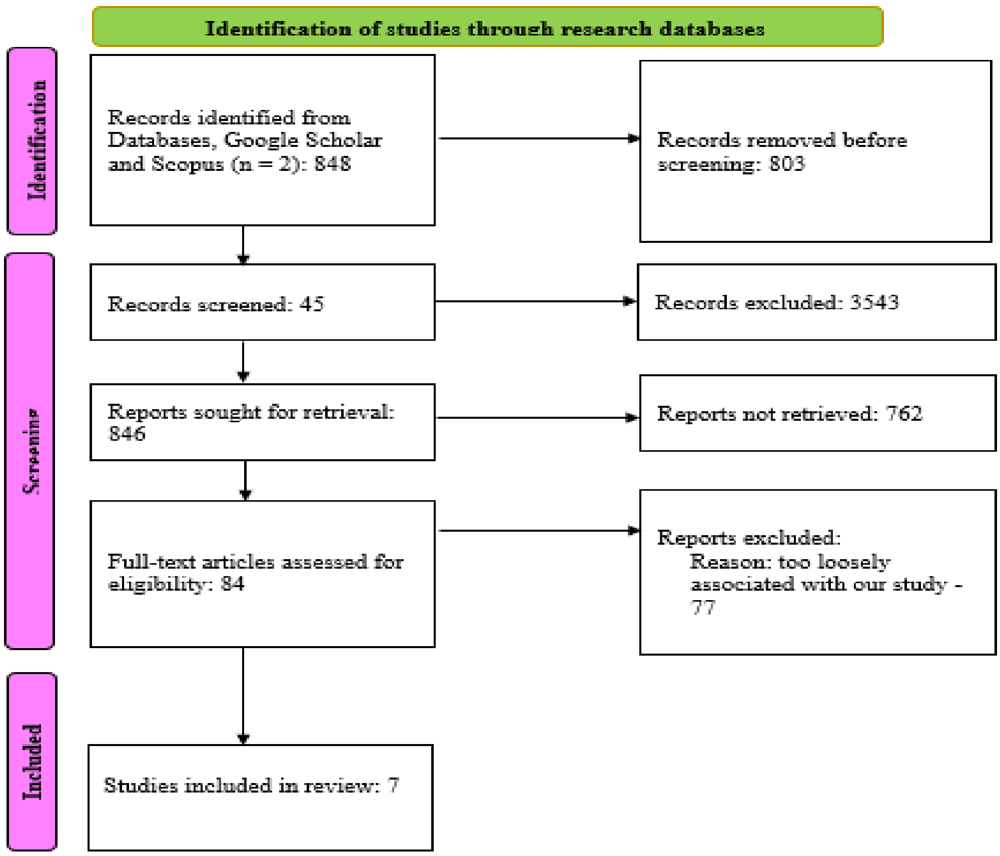

Figure 5: PRISMA flowchart for our literature review

As an alternative to hypertrophy, if a publication contained the phrase muscle mass, along with Functional Electrical Stimulation and muscle strength, it was also included. Finally, seven articles were chosen for review. The inclusion criterion was modified so that only those publications were chosen where all the keywords were found in the abstract. This was done because many of the papers that contained the keywords in their body were found to throw no light or very little light on the solution to our research question, while those that had all the keywords in the abstract were found to be the most closely aligned with our research question. The following PRISMA flowchart summarizes our identification, screening, and exclusion procedures (Figure 5).

4. Discussion

In the context of the utility of Functional Electrical Stimulation being studied in relation to improving fitness parameters in individuals, not many studies have been conducted since Functional Electrical Stimulation has found major usage only as a device that serves assistive, rehabilitative, and therapeutic purposes. However, some studies have been carried out with regard to in-bed gyms [26] for people who cannot exercise in regular gym settings, especially those belonging to advanced age groups or those with muscle weaknesses due to reasons like stroke, amputations, MS, cardiac insufficiency and so on. Many of these studies have shown improved outcomes for patients.

Ramezani et al. [27] conducted a study on patients of advanced age groups who had COVID-19. They divided them into two groups: an intervention group consisting of twenty individuals and a control group, which also consisted of twenty participants. The intervention group received actual FES, and the control group received placebo FES. The members of the intervention group were found to have significant improvements in muscle mass, muscle strength, chronic fatigue, and overall quality of life.

Woo et al. [28] examined the application of in-bed cycling in combination with and without FES on critically ill patients who experience muscle weakness. Ten patients were enrolled in the study. The researchers concluded that in-bed cycling increased thigh circumferences with respect to the muscle rectus femoris. The intervention also led to an acute enhancement of lower limb muscle mass as measured by ultrasonography. However, adding FES did not show any marked differences.

Schardong et al. [29] conducted a study where twenty patients were enrolled, with ten patients being allocated to a group that received FES to the quadriceps (FES group or FESG) and ten to the group that received FES placebo (FES placebo group or FESPG). Functional capacity was assessed using the six-minute walk test (6MWT), lower limb muscle strength using the one repetition maximum test (1RM), endurance using the sit-and-stand test (SST), and muscle using the perimeter of the thighs. The researchers observed significant differences between the groups with regard to quadriceps muscle strength and muscle endurance. All these attributes were better for the FES group.

Guiraud et al. [30] elaborated a case study of a paraplegic patient suffering from complete spinal cord injury (SCI). Their study showed that a reduction in the frequency of usage of FES led to a deterioration of muscle response, resulting in a significant reduction in gait performances arising from muscle fatigue and loss of muscle mass.

Glaser [31] has, in his article, outlined how FES techniques can stimulate exercise in the paralyzed lower-limb muscles of individuals with SCI. The article attempts to address the challenges faced by individuals with lower-limb paralysis in developing aerobic fitness and maintaining an active lifestyle due to factors such as reduced muscle mass and impaired cardiovascular responses. Various FES techniques discussed in the paper include rhythmic isometric contractions to aid venous return, weight training, leg cycle ergometer exercises, and combined FES leg cycling with voluntary arm cranking exercises. According to the article, FES exercise offers advantages by activating dormant muscle groups, enhancing peripheral and central hemodynamic responses, and potentially increasing muscle strength, endurance, and cardiopulmonary fitness. It describes that FES-induced exercise may provide more effective training than voluntary arm exercises alone, especially benefiting quadriplegic individuals.

It argues that the utilization of FES in exercising paralyzed leg muscles engages a larger muscle mass than the non-utilization of FES. It claims that FES weight training has shown enhancements in strength, endurance, and muscle size in paralyzed skeletal muscles. Additionally, the paper reports that FES leg cycling exhibits sufficient metabolic and cardiopulmonary responses to stimulate aerobic training effects, which is especially beneficial for people with quadriplegia. However, the paper emphasizes the potential synergy of combining FES leg and arm exercises to optimize upper and lower-body fitness and cardiovascular health. It concludes that hybrid exercise combining both upper and lower body FES exercises may offer the most promising approach for enhancing cardiopulmonary fitness in paraplegic and quadriplegic individuals. While recognizing the potential of FES exercises in improving health, fitness, and rehabilitation prospects for SCI individuals, the paper calls for further research to establish safe and effective FES techniques, document long-term training benefits, and reduce secondary health issues in these populations.

Parry et al. [32], in their 2012 paper, have discussed a protocol for a randomized controlled trial (RCT) called the Early Rehabilitation in Critical Care (eRiCC) trial, which aims to investigate the effectiveness of FES-assisted cycling and cycling alone compared to standard care in individuals with sepsis. The trial aims to assess muscle mass, strength, and physical function as primary outcome measures using various assessment tools, including bioelectrical impedance spectroscopy, quadriceps ultrasonography, hand-held dynamometry, and different physical function tests. Additionally, the trial will evaluate the cellular and molecular mechanisms responsible for muscle changes in sepsis.

The trial promises to shed light on how FES can help improve muscle mass and other fitness-related metrics. However, we could not find out whether the trial has concluded and, if it has, what its final findings are.

4.1. Electrical Stimulation for Abdominal Muscle Fitness

Neuromuscular Electrical Stimulation, in the realm of fitness, is most often discussed and studied and has been more commonly utilized, commercially as well as otherwise, in the context of improving fitness parameters of abdominal muscles like rectus abdominis. One of the most examined studies in this regard is the one conducted by investigators at the University of Wisconsin-La Crosse [33].

In this study, an abdominal stimulation belt was used to measure the effects of controlled electrical stimulation on abdominal muscles. Twenty-four healthy adults between twenty-five and fifty years of age and body mass index between eighteen and thirty were included in the study. They were included so that none of them had undergone any formal abdominal training regime in the six months just before the study was conducted. They were divided into two groups: an intervention group and a control group. The intervention group used some abdominal stimulation belt five days a week for eight weeks, while the control group did not. Neither of the groups performed any additional exercises during the study period. The subjects were tested using questionnaires, skinfold measurements, circumference measurements, abdominal strength assessment, and measurement of abdominal endurance. For each participant, height and weight were also estimated using standard laboratory scales.

The intervention group experienced notable improvements in various aspects of abdominal fitness and appearance. Their use resulted in enhanced posture and a remarkable 58% increase in abdominal strength. Additionally, these individuals observed a significant 100% increase in abdominal endurance and, on average, reduced their waist circumference by approximately 3.5 centimeters. All participants who used abdominal stimulation belts registered improvements in posture, firmer abdominal muscles, and a more toned appearance in their abdominal region. These positive outcomes suggest that abdominal stimulation belts played a beneficial role in enhancing abdominal strength, endurance, and physical appearance for the individuals who incorporated them into their fitness routines.

However, with only twenty-four individuals involved, the study was considered too small for its observations to result in meaningful and generalizable conclusions. A previous study conducted by researchers at the same university found no significant improvement in fitness parameters, including body weight, body fat, muscular girth, isometric and isokinetic strength, and body appearance after a controlled application of electrical stimulation to various muscles of the body. Many other studies have found similar results in relation to muscle activation with electrical stimulation.

The book Fit Not Fat at 40-Plus: Shape-Up Plan that Balances Your Hormones, Boosts Your Metabolism, and Fights Female Fat in Your Forties [34] quotes Dr. Mary O'Toole as she refutes electrical stimulation as an efficient method of inducing muscle contractions which are strong enough to make a difference to an individual's fitness. It further states that abdominal stimulation belts fail to assist with burning excess body fat and shedding unwanted body weight. Lee Bell, in her full-on review of Slendertone's Abs8 Toning Belt [35], stays inconclusive about its efficacy in abdominal muscle toning.

5. Conclusion

Our study concludes that while Functional Electrical Stimulation can benefit those with weakened muscles due to various factors like paraplegia, quadriplegia, cardiac insufficiency (which leads to poor muscular perfusion), stroke, SCI, being bed-ridden for a long time due to surgery or other medical procedures or reasons, it cannot effectively serve as a replacement to gym-based workouts, especially for healthy people, who usually can effect better and more forceful muscle contractions through workouts than FES can provide them. In patients with weakened muscles, FES can cause improvements in fitness criteria like muscle endurance, muscle mass, muscle hypertrophy, isometric, isotonic, and isokinetic muscle strength, muscle capacity to affect joint movement (torque), body fat percentage, and muscle fatigue. While FES can enhance the effect of a formal physical exercise regimen, it cannot, on its own, serve as a complete substitute for exercise. Healthy people widely use electrical stimulation to improve fitness criteria in relation to their abdominal muscles, and they use abdominal stimulation contraptions (belts) for this purpose. However, for achieving fitness goals effectively using abdominal stimulation belts, one must have a limited amount of fat over the abdominal area so that bioelectric impedance posed by the adipose tissue is minimized and the desired influence of electrical stimulation reaches the rectus abdominis muscle.

The second consideration arises with regard to the Maximal Voluntary Contraction or Maximal Voluntary Isometric Contraction value. Maximal Voluntary Contraction (MVC) is the maximum force-generating capacity of a muscle or a group of muscles without external assistance. In the context of MVC, the individuals targeting to achieve real benefits from electrical stimulation of abdominal muscles should have a sufficiently high MVC value (60-80 percent) [33]. This means that they must not be completely deconditioned. That is, they must have some previous abdominal muscle training, which must improve their

MVC value to the required level. Thirdly, electrical stimulation of abdominal muscles gives the best results if used in combination with the actual exercise of rectus abdominis, for example, crunches or planks. This is because FES is far more helpful in improving the efficiency of sufficiently strong muscle contractions than leading to strong enough muscle contractions. Only adequately powerful muscle contractions can lead to visible fitness results for any muscle or muscle group in general and abdominal muscles in particular. These conclusions are recommendatory and are not exhaustive. Further research is needed to confirm these findings and reveal further insights into the applications of FES in serving as an alternative for gym workouts.

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