Muscle Function Restoration by Bioelectrical Stimulation

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Abstract: There are millions of people who are suffered from neurological diseases such as stroke and spinal cord injury, and their nervous systems are damaged from rapid muscle denervation, caused by neurological diseases, which results paralysis or muscle weakness. In order to solve these problems and meditate inconvenience of patients, muscle refunction and rehabilitation are necessary to be introduced. Besides, as human stepping into electrical age, bioelectrical stimulation is developed. This paper covers the effect of bioelectrical stimulation on muscle refunction and rehabilitation, as well as different applications for bioelectrical stimulation. In addition, different topologies for bioelectrical stimulation are also included.

1 INTRODUCTION

Nerve cells and muscle cells are significant to human body and these two types of cells are deeply correlated with each other. Nervous system is combined by Central Nervous System (CNS) and Peripheral Nervous System (PNS). Central Nervous system includes brain and spinal cord, and Peripheral Nervous System includes autonomic nervous system, which is involuntary, and somatic nervous system, which is voluntary. CNS receives the sensory signals from PNS, and also sends motor signals to PNS to trigger movements. Neuron has three main parts. Dendrites receive chemical input from other neurons; soma, the main body of neuron, integrates the information received from dendrites; and Axon conveys electrical signals out of the cell. Electrical signals include the signal which triggers muscle contraction (Malmivuo et al. 1995).

From the perspective of biology, Nerves always work along with action potentials, and damaged nerves are not able to perform action potentials regularly by themselves. Thus, electrical stimulation is introduced to depolarizes neuron cell membrane, by creating a localized electric field, to reach a critical threshold and generate action potential which propagates in both directions away from where it stimulated. Stimulation to motor nerves triggers muscle contraction which can be used to rehabilitate muscle functions. Luigi Galvani applied electrical wires to leg muscles which cleaved from the frog body in 1790 and the motion was observed. Michael Faraday demonstrated that movement can be created by using electrical currents to stimulate nerves in 1831 (Cambridge NA, 1997). Moreover, Electrical stimulation for peroneal nerve in hemiplegia patients attempted to correct foot drop during ambulation in early clinical experiments (Liberson et al. 1961). Thus, electrical stimulation has the great potential in the field of rehabilitation recovery, including muscle strength improvement, range of motion increment, edema reducing, tissue healing, pain relieving, etc. (Doucet et al. 2012).

In this paper, the topic is focused on how to use bioelectrical stimulation to help people with mobility dysfunction, such as patients with spinal cord injuries, to reactivate muscle contraction and partially restore their mobility. This review firstly aims to introduce backgrounds for bioelectrical stimulation, mainly functional electrical stimulation, which pairing a functional task with electrical stimulation, as well as implantable FES. Secondly, this review explains how to stimulate tissues by electrical input with examples of different topologies. Moreover, prospects for the future of this technology are also included in the conclusion aiming to provide any constructive suggestions for future studies.

2 FUNCTIONAL ELECTRICAL STIMULATION

Functional electrical stimulation (FES), which is similar to neuromuscular electrical stimulation but

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pairing the stimulation with a functional task. Paralyzed muscle contractions, triggered by using short electrical pulses, is programed to fit with different tasks. For instance, multiple muscles, flexor muscles and extensor muscles, connected with the joint are stimulated with different stimulation intensity delivered to achieve different joint angles. Wrist extensors and finger flexors are stimulated to contract the fingers around an object in order to facilitate a grasping task. Flexion of the shoulder and elbow extension is also triggered by FES to produce a forward reaching motion. FES is used most commonly for spinal cord injured (SCI) individuals to improve their motor functions. For example, FES can be used to reproduce the activation pattern of lower extremity muscles to produce human gait (Lynch et al. 2008).

Electrical pulses are delivered via electrodes. Electrodes can be placed in four ways: transcutaneous (on the skin surface), epimysial (on the surface of the muscle), percutaneous (in the muscle), or cuff (motor nerve surrounding) (Popovic et al. 2000). Frequency and intensity, which is the amount of charge input in muscle, of stimulation decide the level of the contraction (Lynch et al. 2008).

The stimulus pulses for FES usually have both cathodic phase and anodic phase. Cathodic phase triggers the action potential along with harmful electrochemical processes occurred at the interface between electrode and tissue. Anodic phase followed by cathodic phase reverses those damage by neutralizing the charge accumulated during cathodic phase, to avoid tissue damage, and the charge of two phases are ideally equal. Figure 1 illustrated three types of stimulus waveforms.

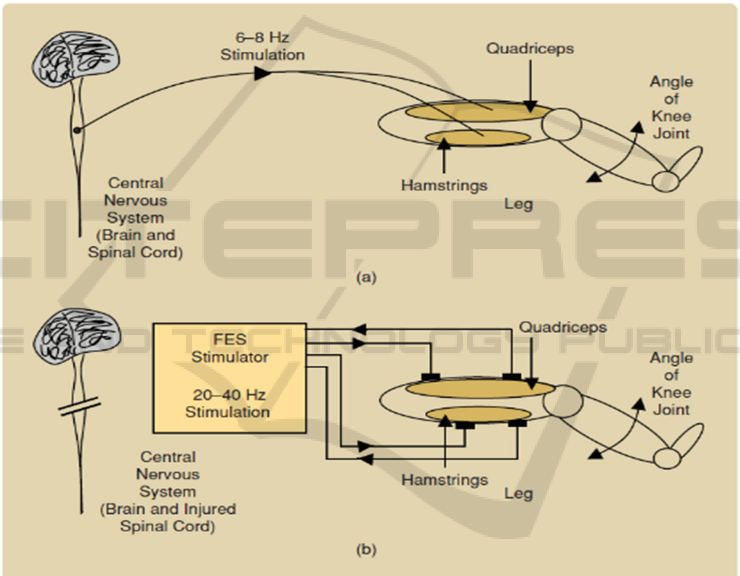

Figure 1: Stimulus waveforms. (a) Monophasic. (b) Biphasic with active cathodic and active anodic phases. (c) Biphasic with active cathodic phase and passive anodic phase (exponential decay) (Demosthenous, 2014).

People with spinal cord injury might not able to complete fundamental behavior tasks such as walking, standing, jumping, due to their insufficiency of lower extremities strength. Thus, FES is introduced to facilitated with finishing fundamental tasks. Figure 2(b) shows how FES works to compensate the nonfunction of muscle caused by injury. For intact nervous system, each motor unit are stimulated at a frequency of 6-8 Hz, and adjacent units are sequentially stimulated, which overall triggers muscles to produce tetanic contractions, and finally triggers the change of knee angle. Previous mechanism is called asynchronous recruitment. For SCI individuals, motor units are stimulated by FES at the same time, which what we called synchronous recruitment, and different from the asynchronous recruitment happens in complete nervous system. Because FES has to stimulate the motor units synchronously, a higher frequency is required which ranges from 20 to 40 Hz to trigger tetanic contractions.

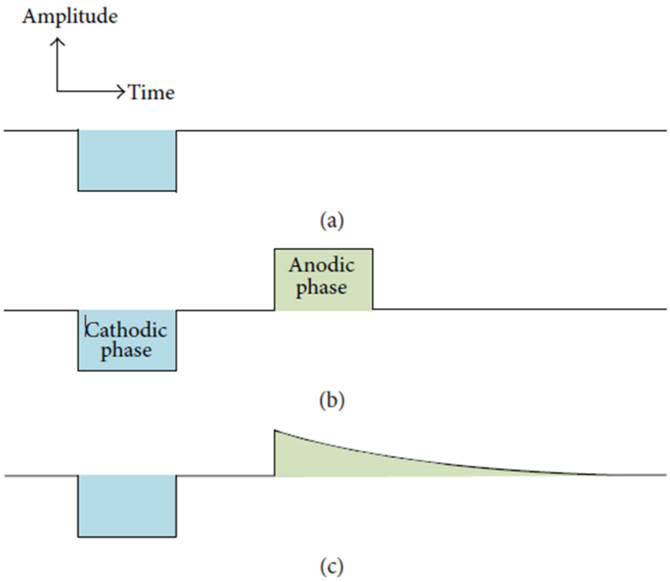

Figure 2: Different mechanisms for the production of tension in intact nerve system individuals and spinal cord injury individuals.

A further application for FES is FES facilitated muscle rehabilitation. As mentioned previously, SCI individuals might not able to complete fundamental behavior tasks. Thus, immobility will directly cause insufficiency of physical activity which is always a problem along with multiple syndromes such as muscular atrophy, cardiovascular disease, type 2 diabetes, etc. To increase the level of physical activities of SCI individual, FES training machine, which is the combination of typical training machine and FES system, is introduced. FES triggers paralyzed muscles to produce tetanic contractions, which is crucial for SCI individuals to complete the training tasks. One representative product for FES training machine is motor driven FES rowing machine. SCI individuals are not able to complete normal rowing machine training due to their insufficiency of low extremities strength. Thus, motor-driven FES machine is able to support them to complete the rowing. This machine is constructed by a chair with inclination control, control program, leg supporter, motor system, and the most importantly, the four-channel FES system (MEGA XP, Cybermedic Corp.) which is surrounding the legs to stimulate hamstring and quadriceps muscles. As mentioned previously, FES synchronously stimulates the motor units which leads the frequency ranging from 20 to 40 Hz. The FES rowing machine stimulates through surface electrodes to the hamstring and quadriceps muscles with a frequency of 30 Hz. An optical encoder which senses the seat position and controls the input of stimulation is used to construct a closed-loop and feedback control FES system (Kim et al. 2014).

3 STIMULATION CIRCUIT

To achieve stimulation, at least two electrodes are needed in the circuit to produce current flow. Current stimulation mode and voltage stimulation mode, which is shown in Figure 3, are two main stimulation modes. voltage stimulation use voltage as its output and current stimulation use current. The output of voltage is constant, thus the generated current delivered to the tissue, depends on the inter-electrode impedance. A sequence of voltage steps has to be introduced to control the charge supply, which requires large number of capacitors and not able to be on-chip. Thus, voltage stimulators usually use with surface electrodes. The magnitude of the current delivered to the tissue is controlled by current stimulation and not dependents with inter-electrode impedance, and current stimulation is suitable with implanted electrodes.

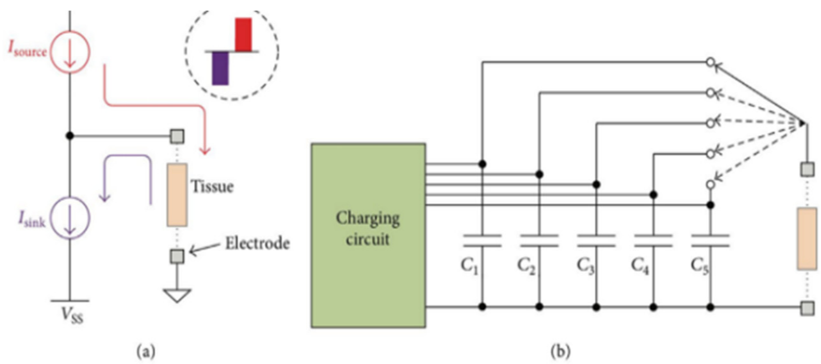

Figure 3: (a) current stimulation circuit. (b) voltage stimulation circuit (Suo et al. 2013).

As mentioned previously, biphasic stimulus pulses are usually used in bioelectrical stimulation because anodic phase followed by cathodic phase neutralizing the accumulated charge and avoid tissue damage. Thus, the total charge in cathodic phase and anodic phase has to be balanced. To achieve charge balancing, three classic biphasic current stimulators topologies are introduced below in Figure 4.

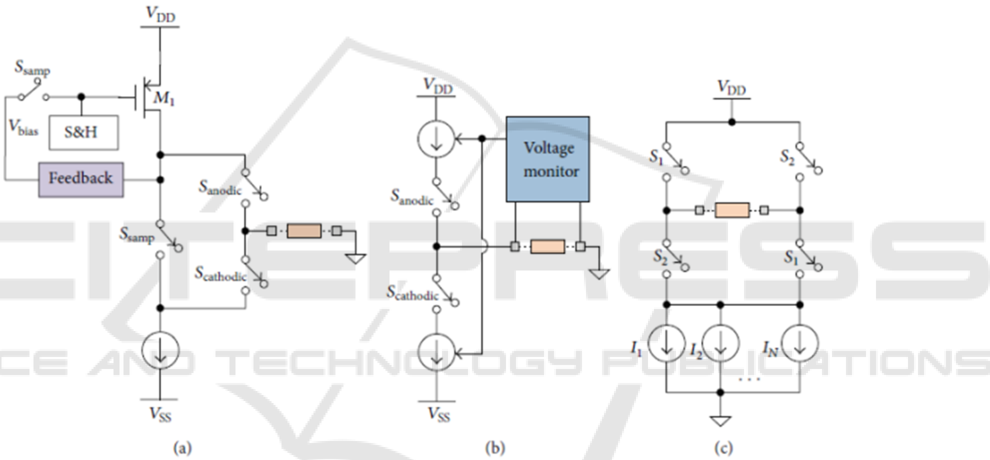

Figure 4: Three main topologies for charge balancing. (a) Dynamic current balancer (Sit et al. 2007); (b) Active charge balancer (Ortmanns et al. 2007); (c) H-bridge with multiple current sinks (Williams et al. 2013)

Dynamic current balancer includes two sampling switches, and two more switches for cathodic phase and anodic phase respectively. Two Ssamp close to form a close circuit. Because of feedback, the amplitude of M1 drain current is equals to the current sink, and the bias voltage on M1 is sampled and held. Then, two Ssamp open and only Scathodic closes to form the current which stimulates the tissue. Then Sanodic closes and Scathodic opens, and the held bias voltage results the anodic current has the same amplitude with cathodic current to reach charge balancing. Active charge balancer combines voltage monitor on electrodes and uses two switches, Sanodic and Scathodic, to manipulate the circuit to achieve charge balancing. only Scathodic closes firstly and the current, get measured by Voltage Monitor, reaches to the tissue and go to VSS; then during anodic phase, Sanodic closes and Scathodic opens, the monitored amount of charges are coming out from VDD to the tissue for the neutralization. "H-bridge" configuration uses four switches in two groups to form cathodic current and anodic current. S1 and S4 firstly close to form cathodic current. Then, S1, S4 open and S2, S3 close to form anodic current to neutralize the accumulated charge.

Blocking capacitors are usually used in stimulator circuits. When the circuit failed, blocking capacitors avoid DC connection to supplies to ensure safety. Secondly, they also ensure the electrodes have no net charge. In addition, adding blocking capacitors into stimulation circuit realize active discharge function.

4 IMPLANTABLE FUNCTIONAL ELECTRICAL STIMULATION

Implantable functional electrical stimulation is becoming a more popular direction of research due to its high mobility. Moreover, because the FES devices are implanted into human body, not percutaneous, the impedance is lower which leads to a lower power consumption directly. A typical example for implantable FES is implantable device for hand grasping which is shown in Figure 5. The hand grasping device uses an external control unit, which provides energy source and particular program, that connects to an implantable stimulator. The implantable stimulator connects with group of electrodes used for neuromuscular stimulation to trigger muscle contraction and finish tasks. The stimulator also connects with electromyography (EMG) recording electrodes to measure the electrical activities of muscle in responding to nerve stimulation. The connection between external control unit and implant stimulator can be wireless. The data and power transfer are via inductively coupled power transfer. The efficiency of Inductively coupled power transfer in its working range is really high, especially for high power delivery, which has a total efficiency to be greater than 95%. Moreover, the range of its output power levels is from milliwatts to tens of watts which indicates that it can be used in a huge variety of implantable devices (Schormans et al. 2018).

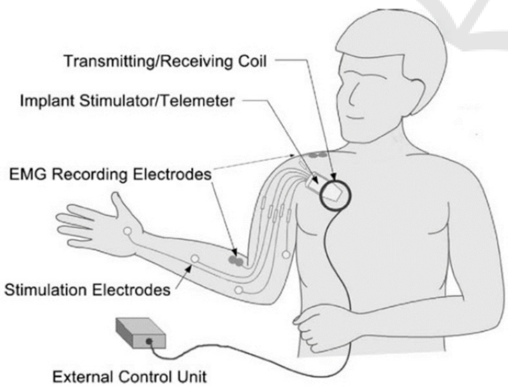

Figure 5: Diagram of implantable hand grasping FES device (Hart et al. 1998).

5 CONCLUSIONS

In this paper, the fundamental principles and applications about bioelectrical stimulation is introduced. The development of bioelectrical stimulation is boosted in these two decades. However, the space of bioelectrical stimulation development and application is big. For instance, one problem for stimulator is power consumption. Bioelectrical stimulation can be divided into implanted and not implanted. The power consumption for implanted stimulator is always a breakthrough point because no direct power transmission cable is connected. Thus, to achieve wireless power transfer. Inductively coupled power transfer (ICPT) is introduced as the most capable way of power transfer for implanted stimulator (Schormans et al. 2018). With the correct way of power transfer, the efficiency of ICPT is the biggest research field currently. The realization of wireless fast charging safely is a meaningful goal. The combination of bioelectrical stimulation with close-loop control has brought bioelectrical stimulation into the cross field of biotechnology, electronic engineering, and programing. The monitor can track different behaviors and muscle movements and upload the feedback into computer, and software engineers can analysis the big data and development different programs which is able to simulate the muscle movement. The simulation program can be updated and transmitted back into the stimulator to realize iteration.

In the future, big data analysis is able to prognosis the next muscle movement and stimulate with less lag to reduce delay of actions. Moreover, a new innovation for bioelectrical stimulation is the application of brain-computer interface (BCI) and nanorobots. Trillions of nanorobots which controlled and monitored by brain-computer interface is launched into different part of human body. For instance, when a SCI individual is willing to move legs, electrical signal from brain is recorded and decoded into binary language which controls nanorobots, located on paralyzed leg muscle, to stimulate the neuron and trigger muscle contraction, and overall realize the leg movement. The innovation sounds surrealistic, but with the rapid development of scientific and technological level, BCI and nanorobotic induced bioelectrical stimulation is feasible and is able to be popularized in several decades.

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