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A Survey of Lower Limb Rehabilitation Systems and Algorithms Based on Functional Electrical Stimulation

Mingxu Sun^{1,*}, Xueyan Wu² and Qi Liu^{3,*}

Abstract: Functional electrical stimulation is a method of repairing a dysfunctional limb in a stroke patient by using low-intensity electrical stimulation. Currently, it is widely used in smart medical treatment for limb rehabilitation in stroke patients. In this paper, the development of FES systems is sorted out and analyzed in a time order. Then, the progress of functional electrical stimulation in the field of rehabilitation is reviewed in details in two aspects, i.e., system development and algorithm progress. In the system aspect, the development of the first FES control and stimulation system, the core of the lower limb-based neuroprosthesis system and the system based on brain-computer interface are introduced. The algorithm optimization for control strategy is introduced in the algorithm. Asynchronous stimulation to prolong the function time of the lower limbs and a method to improve the robustness of knee joint modeling using neural networks. Representative applications in each of these aspects have been investigated and analyzed.

Keywords: Functional electrical stimulation, lower limb systems, algorithms, rehabilitation.

1 Introduction

According to the China Stroke Prevention Report 2016 [Wang, Wang, Peng et al. (2017)], China has the highest incidence of stroke in the world. The number of people over 40 years old in China who have suffered from strokes is 12.42 million. About 1.5 million new patients are found each year. The proportion of people who can't take care of themselves is 43.2%. There are more than 10 million new strokes every year in the world [Pandian, Gall, Kate et al. (2018)]. The recovery of limb function in stroke patients is the most important part of rehabilitation. Currently, the commonly used rehabilitation methods include exercise restriction therapy, electromyography feedback therapy, electrical stimulation therapy, exercise imaging psychological training therapy, etc., of which the most particular important one is functional electrical stimulation. In recent years, more research activities have been applied to the application of FES systems to the recovery of limb function, and significant results have been achieved.

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According to an article published in Nature in 1974 on the role of neurons in electrical stimulation of muscles [Murphey and Palka (1974)], Functional electrical stimulation (FES) can be briefly understood as a targeted method to electrically stimulate human body, e.g., a limb. The stimulating electrode worn on the limb of a stroke patient is stimulated by a controller to electrically stimulate specific muscles for limbs. Various types of limb function rehabilitation training or daily activities have to be taken to achieve the purpose of limb function recovery.

When a stroke patient develops a disease, the originally normal brain cells will die due to hemorrhage or ischemia, as seen in Fig. 1(a), which will eventually lead to necrosis. The endogenous stem cells with differentiation function will automatically move to the vicinity of the necrotic nerve to repair the necrotic nerve, and the repair speed will be reduced by 50%-60% without external stimulation, only to maintain the system's self-sustainability (see Fig. 1(b)). After stimulation with FES, the nerves are activated, allowing endogenous stem cells to differentiate (see Fig. 1(c) below), repairing necrotic nerves and restoring function (see Fig. 1(d) below).

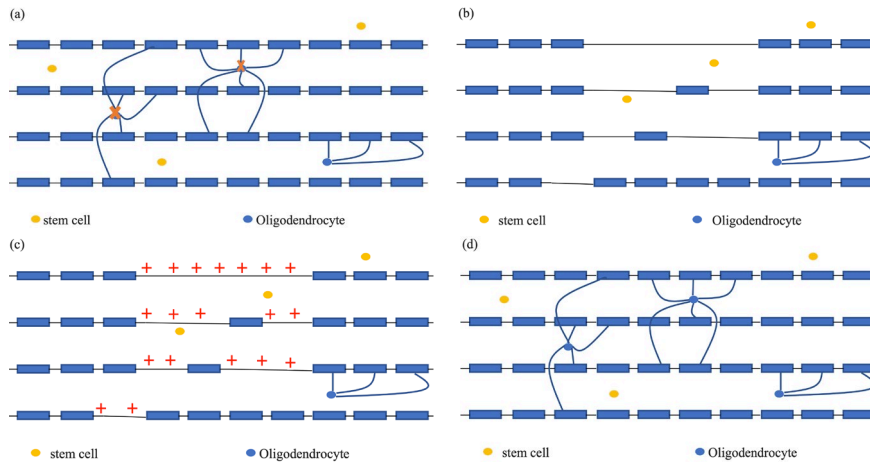


Figure 1: The function of FES on neurons

2 Research progress of FES systems

For the first time, FES was applied to lower limb rehabilitation in stroke patients in 1961, Burridge's team [Burridge and Etherington (2004)] used a single-channel functional electrical stimulation to develop a tactile interface for the humerus, triggered by a sensor placed on the sole of the foot. The system switched and measured the ankle angle to provide feedback and trigger electrical stimulation, which allowed the patient to produce dorsiflexion of the ankle joint by low frequency electrical stimulation during walking. As a basis for further research, this experiment provided a simulated test environment. This included the establishment of a computer model to simulate ankle joint activity through the characteristics of muscle groups, muscle fatigue and the characteristics of lameness. This pioneering experiment has laid a solid foundation for the development and application of FES as an established technique for lower limb rehabilitation.

In 1998, Chae and Hart's research [Chae and Hart (1998)] showed that electrical stimulation acts on nerve cells and naturally stimulates the action potential to produce a completely consistent nerve impulse, which means that the muscle contraction caused by the damaged muscle is stimulated by the action of external current. Muscle contraction was consistent with complete function. Moreover, neuromuscular stimulation could not only produce muscle contraction, but also promote the recovery of exercise after stroke or brain injury; that is, promote the repair of necrotic nerves. Since then, system research and algorithm improvement related to the FES have been improved increasingly.

When the muscles are weak, the system needs to provide some kind of support. From a biomechanical point of view, although the brace will reduce the freedom of lower limb activities, it will improve the stability of the limbs [Burridge and Etherington (2004)]. Based on this, in 2006, Hara et al. developed a hybrid assisted functional electrical stimulation [Hara, Ogawa and Muraoka (2006)] (Hybrid Power-Assisted FES) for the rehabilitation of patients with severe stroke. It combined two therapeutic factors. One of which was the inhibitory negative factor, i.e., the reduction of sputum production by the brace; the second was the positive factor of strengthening, i.e., to stimulate muscle movement through functional electrical stimulation. The synergy between the two works better than the individual effects.

FES's first relatively complete system was developed by Velloso et al. in 2007 [Velloso and Souza (2007)]. This emerging system communicated with the PC through a USB interface to control analog and digital circuits in the hardware, thus electrical stimulation was used to achieve functional recovery of the limbs. The experimental results have shown that such a system can be applied to any muscle group under the conditions of maintaining safety limits such as electrical safety and current density and are applied to rehabilitation of stroke patients. In the following years, the research team led by Mark developed a hardware and software system that automatically synchronized FES and robot-assisted treadmills [Dohring and Daly (2008)] to address the gait defects of stroke survivors. Functional electrical stimulation was performed using the intramuscular electrode (FES-IM) with the Lokomat robotic gait orthosis. Benchmark experiment showed that the accuracy of the automatic synchronizing device was much higher than the manual triggering, and the delay standard deviation was reduced by nearly 10 times. There is no stimulus that triggers premature or delayed gait during the step. This study has taken a major step in the application of functional electrical stimulation to the rehabilitation of lower limbs; that is, the passive movement of the lower limbs caused by the machine can induce FES induction together with muscle stimulation. In that case, the lower limb function problems caused by stroke can be better restored. However, the gait speed of the Lokomat robot in this study was limited to 1.5 km/h. It is a direction for the software to adjust the overall mode according to the different feedback received at different speeds to make it more user-friendly.

For the development of FES-assisted walking systems, in addition to the above non-implanted devices, a FES system for implants [Dutta, Kobetic and Triolo (2006)] has been developed to provide patients with an unsupported walking opportunity. By using an eight-channel implantable pulse generator to generate electrical stimulation from the bilateral muscles of the leg to activate the leg muscles and to integrate with the s-EMG

classifier while the FES system assists walking, the therapist enables the therapist through background algorithms. Real-time operation triggers the pre-programmed stimulation mode of the patient-implanted system, that is, after the first FES auxiliary step is activated by using the start switch, the classifier scans the muscle state after each stage and analyzes the feedback data to determine whether to trigger Next step. However, the risk of this method is that the algorithm whose immature algorithm is easy to cause the next step (false positive) to be triggered without expectation, the FES system must be manually stopped, so the developer sets the security interface in the system. Enables the subject to have higher authority to override the FES system when the FES controller is stopped and does not trigger the expected step, manually triggering the next step. This system enhances the coordination between the autonomic contraction muscle and the stimulated muscle, and the EMG model can analyze the fatigue and time-varying factors through the collected data to affect the classifier. Based on this, the subsequent research direction is more able to develop into implantable stimulation-remote sensing instruments.

In 2011, in order to promote reactive walking in stroke patients, Ming et al. proposed a FES-based lower limb motor neuroprosthesis system [Ming, Yuan, Li et al. (2011)]. The system's hardware consists of four independent channels and seven converters; the software first operates through a user graphical interface to connect communications between different modules. With the clinical application of the system, the subsequent research work is more focused on the introduction of kinetics and electrophysiological indicators as the evaluation criteria of the FES model, how to find more effective stimulation models and the optimal design of the system. With the steady increase in the importance of gait detection for FES-like devices, the stimulation sequence needs to be more consistent with the gait phase, but the role of Hull's plantar switch controller has not kept up. Hakansson et al. [Hakansson and Hull (2009)] uses an accelerometer. The array and tilt sensor are attached to the patient's lower leg while the electrical stimulation is triggered using a pressure sensor and gyroscope fixed in the insole. However, because this method is not reliable enough for the collected incomplete signal processing, it can only be applied to outdoor environments with strong signals.

After the first development of the software system and the application of sensors and gyroscopes, the systems and algorithms used by FES for lower limb rehabilitation have also been updated. For patients with long-term use, fully implanted systems were more convenient to use. The team [Johnston, Betz, Smith et al. (2005)] surgery implanted radio frequency receivers and stimulators through external remote control for rehabilitation. The effect is very significant, but the fly in the ointment is the life of the implant and some infection problems in the human body.

In 2015, Ibrahim et al. designed a system that allows a brain to communicate directly with external devices [Ibrahim and Sherwani (2014)], i.e., a Brain-Computer Interface (BCI). The system collected brain signals through electrodes placed on the scalp, enabling patients to send their brains. The signal is used as the electrical stimulation state of the data control system to achieve effective muscle control.

In 2017, the Kataoka team developed a task-oriented approach to perform FES rehabilitation training tasks [Kataoka, Hirai, Hamilton et al. (2017)] combined dynamics with kinematics [Szecsi and Krewer (2008)], allowing gait intervention based on different

conditions and conditions of the patient, and supporting the treadmill and FES through a combined saddle weigh, as the method of restoring the autonomous control function of stroke patients. The core of the system is to detect gait characteristics by using two different BWS (Body-Weight-Supported) methods (ground reaction and kinematics), to convert different modes through different walking speeds, and to correctly select FES stimuli in different modes. However, the shortcoming of this method is that patients have different requirements for saddle-type support machines, such as shape and material, so they have higher requirements for the design and commercialization of future product.

At present, FES has been applied to various types of muscle system diseases. A system consisting of a control device that can control different stimulation programs, a corresponding stimulation device that generally uses four or more stimulation channels, and sensors (for data feedback) are commonly used. A patient is connected to the system by different methods such as wearable, implantable or semi-implantable, and different procedures are set according to different patient conditions for limb function recovery.

3 System development and algorithm progress of FES

3.1 System development

3.1.1 A programmable system of functional electrical stimulation (PSFES)

The first set of relatively complete FES rehabilitation system was developed by Velloso team in 2007 [Velloso and Souza (2007)]. The system is mainly divided into two parts. The digital part is composed of modulators, USB interfaces and a clock generator; the control part is composed of a PC. The parameters of the digital terminal are controlled by the programmable counter and the potential control meter and transmitted to the PC through the USB port. Within the specified pulse amplitude and frequency range, the PC allows the user to customize the configuration file and start electrical stimulation for muscle con-traction testing. Different muscle responses were tested by varying pulse width, frequency and amplitude.

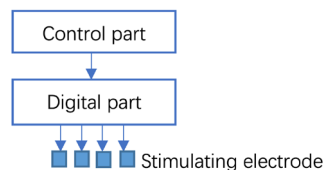


Figure 2: Logic diagram of FES programmable electrical stimulation

However, the electrical stimulator of this method is not safely set. When the current is large, the muscles and nervous system may be damaged, and a corresponding safety threshold is set for the current. And the problem that the test result is not accurate due to the large error in the transmission process needs to be solved.

3.1.2 Neuroprosthesis system for lower limbs action based on functional electrical stimulation (Neu4LL)

In 2011, Ming's team developed a portable FES-based lower limb neuroprosthesis system [Ming, Yuan, Li et al. (2011)], using a manual control mode to stimulate patients in vitro,

using different kinematic indicators to determine the patient's condition and according to different situations. The stimulator program modules are combined to find the most appropriate stimulation parameters for the patient to facilitate the rehabilitation of patients with moderate and severe stroke using FES. During this period, the user is given a higher authority to manually stop the FES system when the electrical stimulation is out of tolerance. Experiments have shown that judging the data of the patient during walking according to the kinematics index and changing the stimulation parameters accordingly and adjusting to the optimal threshold can improve the stability and safety of the patient in rehabilitation training.

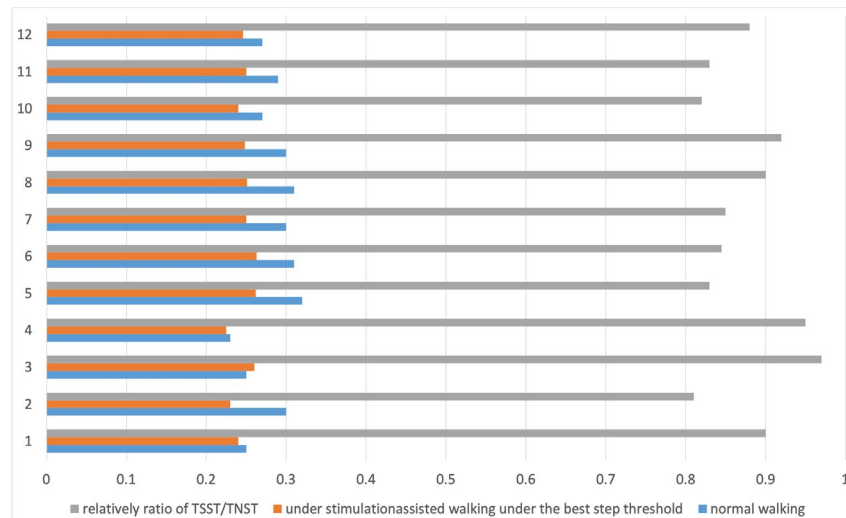


Figure 3: Normal walking and optimal threshold walking comparison histogram

However, how the evaluation indicators such as human kinematics and electrophysiology affect the adjustment of stimulation parameters and how to optimize the more complicated system is a further work.

3.1.3 Brain computer interface based functional electrical stimulation (BCI)

Since the previous FES rehabilitation system processed the collected data through different algorithms and generated “pseudo-brain similar signals” by the control system, the system cost is high and the system is complex, and the data reliability needs to be improved. In 2014, the Ibrahim team developed a brain-computer interface [Ibrahim and Sherwani (2014)] to use the patient's brain as a control system to send different stimulation commands directly to the FES device to stimulate different muscle groups. The circuit block diagram of the system is as follows:

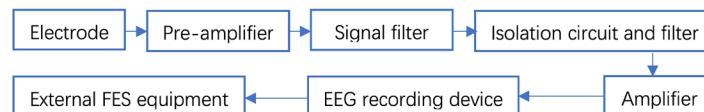


Figure 4: System circuit block diagram

When the patient needs to move the limb, the electrode covering the surface of the scalp collects an electroencephalogram (EEG) signal generated by the brain and transmits the signal to the FES device. The signal is read by the FES device and a corresponding pulse is generated to stimulate the muscle group. Activities are carried out, but how FES devices can be combined with brain-computer interfaces to control muscles more effectively is a major problem.

3.1.4 Summary

FES has different advantages and disadvantages between different systems for lower limb rehabilitation. The system can be selected according to the patient’s condition. Tab. 1 compares the above three different methods.

Table 1: Comparison of three FES methods

| Features | PSFES | Neu4LL | BCI |
|--|------------|------------|------------|
| Electrical Safety | NO | YES | NO |
| User Interfaces | YES | NO | NO |
| Multichannel Stimulation | YES | YES | YES |
| Parameter Robustness | NO | NO | YES |
| Auxiliary Walking Equipment | NO | YES | NO |
| Operates Independence of Motor Functions | NO | NO | YES |

3.2 Algorithm progress

3.2.1 Optimized proportional-integral-derivative control strategies and simulation for lower limb functional electrical stimulation

In 2011, Gu et al. proposed a lower limb FES control algorithm based on closed-loop feedback controller [Gu and Qian (2011)], Proportional-integral-derivative (PID), based on the nonlinear characteristics of muscle movement. Optimization is performed in the BP neural network to correct the error generated by the angle data. The use of nonlinear autoregressive models and single hidden layer neural networks to optimize the controller parameters is essentially a process of adjusting the weight of the parameters in the network by training the data to finally eliminate the data error. The structure of formula is showed below:

$$y_k = a_{1k}y_{k-1} + \dots + a_{n_a k}y_{k-n_a} + b_{0k}u_k + \dots + b_{n_b k}u_{k-n_b} + e_k \tag{1}$$

where n_a is the maximum output lag and n_b is the maximum input lag in the model. e_k incorporates modeling error and disturbance effects. The simulation results show that the BPPID control algorithm can effectively adjust the angle data, so that the relative error is less than 5%, but the neural network structure is not involved.

3.2.2 Influence of volitional contraction on muscle response to functional electrical stimulation

Both the contraction of the will and the contraction of the electrical stimulation can cause the muscles to react, and whether the two can be synergistically coordinated by the algorithm is the research direction of Gui et al. [Gui and Zhang (2014)], by using the Hammerstein model in which the static nonlinearity and the dynamic linear link are connected in series. Modeling, simulating nonlinear muscle activity generated by different will contractions, simulating dynamic linear parts through data such as device signals, and obtaining nonlinear parts by convolution algorithm. Fig. 5 below shows the muscle Hammerstein structure.

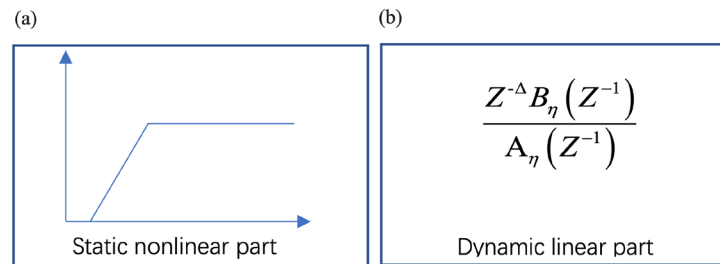


Figure 5: The muscle Hammerstein structure: (a) static nonlinearity; (b) dynamic linearity

Experiments have shown that due to the large influence of noise on convolution, it is difficult to maintain the torque of the will, the change of the area of muscle necrosis is not significant, and the subject indicates that the FES equipment is hindering the moment that they maintain the will, because FES disturbs the muscle contraction the loop.

3.2.3 Closed-loop asynchronous neuromuscular electrical stimulation prolongs functional movements in the lower body

In response to the fatigue-induced fatigue problem caused by FES, in 2015, the Downey team proposed a control algorithm that can be applied to asynchronous stimulation between different muscle groups [Downey, Cheng, Bellman et al. (2015)]. Since the torque is generated by the influence of three stimulation parameters, At least two parameters are kept constant during use, and the uncertain models are actually equivalent. Under this algorithm, the controller can simulate the knee joint data as hemispherical asymptotic tracking. A lower limb FES controller capable of using asynchronous stimulation was developed as a premise.

Table 2: Run time of lower limb in C64 and A16 by four patients (in second)

| Subject-Leg | C64 | A16 |
|-------------|------|-------|
| A-Left | 53.4 | 85.1 |
| A-Right | 37.3 | 76.3 |
| B-Left | 26.2 | 45.4 |
| B-Right | 21.3 | 64.7 |
| C-Left | 27.1 | 93.6 |
| C-Right | 20.9 | 66.6 |
| D-Left | 33.7 | 94.8 |
| D-Right | 34.0 | 113.4 |

where C64 represents a single channel 64 Hz stimulus and A16 represents a four channel 16 Hz asynchronous stimulus, the stimulation frequencies are actually equal, but according to the table it can be seen that asynchronous stimulation greatly prolongs the duration of functional motion over time.

The test results show that this algorithm effectively prolongs the time for muscles to undergo FES rehabilitation and the duration of functional exercise can be significantly increased. In the future, we will focus on how to synchronize the walking equipment with surgical methods to reduce the muscle fatigue caused by FES, which is widely used in the rehabilitation of stroke patients.

3.2.4 Adaptive sliding mode control of functional electrical stimulation (FES) for tracking knee joint movement

For the rehabilitation of lower extremity functional impairment caused by stroke, how to accurately collect and process the data generated by the knee joint is the biggest problem. In 2017, Li et al. published an adaptive sliding mode to track knee motion [Li, Meng, Hu et al. (2017)]. The adaptive radial basis function (RBF) neural network method was used to optimize the acquired parameters by genetic algorithm. The nonlinearity of the parameters, based on the kinematic equation of the knee, uses the regularization theory to find the optimal approximation function and controls the smoothness of the approximation function. Leg dynamics model equation as follows:

$$J\ddot{\theta}_v = -mgl\sin(\theta_v) - M_s - B\dot{\theta} + M_a \quad (2)$$

where J is the moment of inertia of the calf, the angle at which the knee is opened, and M_a is the knee torque caused by electrical stimulation. The RBF neural network compensates the error generated by the knee during modeling, and the calculation time is extremely fast. The test results show that this method can make the lower limb FES system more accurately adjust the knee joint angle and can adaptively adjust the stimulation parameters when the system is subjected to external interference to achieve precise motion.

3.2.5 Summary

The first optimization of the lower limb control strategy extends to the field of feedback and complex control. The proportional-integral-differential control is used as the core algorithm of the closed-loop feedback controller, and the error between the actual output and the required output is corrected in practice. The improvement of the two algorithms is to improve the stimulation of single channel to four-channel asynchronous stimulation. When the stimulation frequency is the same, the patient's tolerance to electrical stimulation is greatly improved. The time of functional exercise is greatly increased, and FES is improved. It is widely used in the down to rehabilitation system; modeling the knee trajectory through the neural network for error elimination solves the problem of the control strategy and data accuracy of the lower limb device for the knee. The FES algorithm applied to lower limb rehabilitation has not yet proposed a unified standard for full stacking and scale. The above algorithms are applied and applied in consideration of the different directions of the algorithm after the improvement of the standards and practical applications in the medical field. The improvement, the optimization of very specific features, has optimized the algorithm of FES applied to lower limb rehabilitation.

4 Conclusion

FES has been widely used from a few decades ago to its widespread use to-day, and its role from a single electrical stimulus makes it useful to be found to have stimulating nerves to rejuvenate muscles or limbs [Murphey and Palka (1974)]. The development of the system and the application of different algorithms are the most important links. Whether the development of the system from a single electrode-controller to a complete control system to the current brain-computer interface, or the improvement of the algorithm is corrected by transmitting data errors, asynchronous operation to improve muscle tolerance to lower limb modeling and use of nerves The improvement of network algorithms means that smart medical technology is developing rapidly in data processing and sensor collaborative operations. However, there are many problems that need to be overcome in the application of FES, such as how to solve the muscle fatigue problem caused by high-intensity stimulation, the early triggering of feedback state or the delay of triggering the urgently needed algorithm to improve the robustness of the brain, How to effectively and stably use the machine interface and how the collected patient data is applied to the intelligent medical industry through deep learning is an urgent problem to be solved. Now FANG's team has classified medical data such as electronic medical records through multi-label classification frame-work [Fang, Cai, Sun et al. (2018)]. The classified data solves the first problem of applying in-depth learning to intelligent medical field, that is, data preprocessing. Then, how to effectively learn data features and apply them to FES through in deep learning is an urgent problem to be solved.

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