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Flexible Multi-Channel Electrical Stimulation System for Assisting Grasping in Patients with Hemiplegia

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***Abstract*— Stroke patients are unable to perform gripping actions effectively as normal individuals due to impaired hand function. Electrical stimulation is currently a relatively effective rehabilitation method, but there is still room for improvement in aspects such as grip control precision and grip posture selection. Therefore, we propose a multi-channel electrical stimulation system to achieve precise control of hand gripping in stroke patients and assist in hand function rehabilitation. The pressure-controlled constant current source electrical stimulation system is proposed and a flexible wearable 16-channel hand FPC electrical stimulation patch is designed according to the distribution of hand muscles. The MCU controls an external DAC chip to generate voltage to drive the pressure-controlled constant current source, thereby generating adjustable biphasic symmetrical stimulation pulse waveforms. The FPC transmits the generated stimulation pulses to the corresponding stimulation points to achieve precise electrical stimulation of specific points. Through three comparative experiments, the results indicate that precise control of finger movement angles has been achieved by adjusting the stimulation current and frequency. The flexible multi-channel hand electrical stimulation system offers a solution for restoring motor function in patients with hemiplegia.**

I. INTRODUCTION

Stroke, also known as cerebrovascular accident, refers to a disease characterized by the sudden interruption of blood supply to the brain or the rupture of cerebral blood vessels, resulting in functional impairment [1]. Stroke patients often suffer from impaired motilities and struggle with self-care [2]. Gripping is crucial for maintaining independent living as well as personal psychological well-being, as an essential skill in the daily life of an ordinary person. Consequently, various devices have gradually emerged worldwide to aid stroke patients in rehabilitation or enhance their grasping performance [3] [4].

Traditionally, gripping aids, like grasp balls, provide exercise tools or additional support for stroke patients [5] [6]. However, the usage of these purely physical tools presents challenges for patients, making the process tedious and carrying the risk of secondary injuries. Wearable devices have become a mainstream category that can exert their effects through forms, such as exoskeleton, gloves and watches, providing advantages such as implantability, real-time feedback, dynamic adjustment, and high adaptability [7]. As a relatively novel form of assistive technology, exoskeletons offer external forces or supports to finger joints through various sensors and actuators, substituting or enhancing the gripping capabilities of patients [8]. Notably, ETH's RElab tenoexo full-hand exoskeleton is representative in providing gripping assistance to those with hand movement disorders [9]. Nevertheless, issues such as bulkiness, lack of flexibility, short battery life, high cost, and low adaptability hinder the widespread adoption of exoskeletons [10]. Therefore, using wearable Flexible Printed Circui (FPC) electrical stimulation gloves as auxiliary tools bring bright futures for assisting and rebuilding gripping functions in stroke patients [11] [12].

Stroke patients struggle to perform gripping actions due to muscle numbness and atrophy. Functional Electrical Stimulation (FES) is a common tool used to activate muscles and rehabilitate hand functions [13]. FES utilizes low-frequency pulse currents with a certain intensity, stimulating predefined muscle groups to induce muscle movement or simulate normal voluntary movements, aiming to improve or restore stimulated muscle or muscle group functions [14] [15], and the FES works within the safe current range of the human body and has high safety.

Subtle-angle fingers movements such as gripping and pinching are commonplace in daily life. However, traditional FES methods involve stimulating muscles near target points with large electrodes, achieving only large-angle control movements like bending the arm or lifting the forearm [16] [17] [18]. It fails to accomplish fine gripping movements involving specific fingers, and further optimization is needed in addressing issues related to grip specificity and diversity

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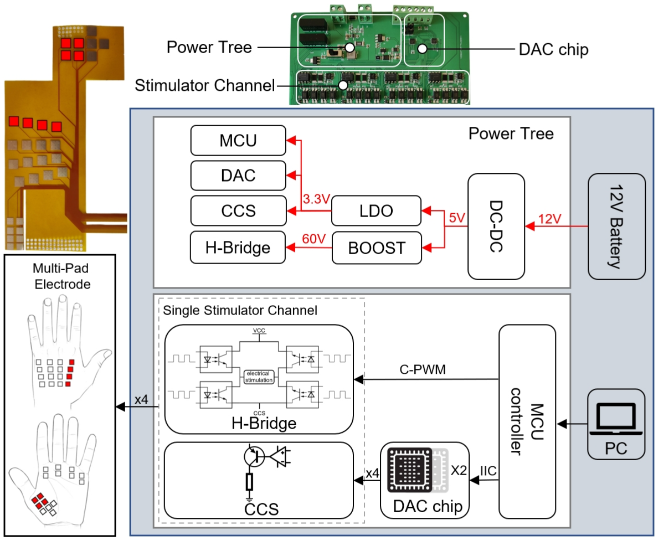

Fig. 1. Diagram of hand multichannel electrical stimulation system.

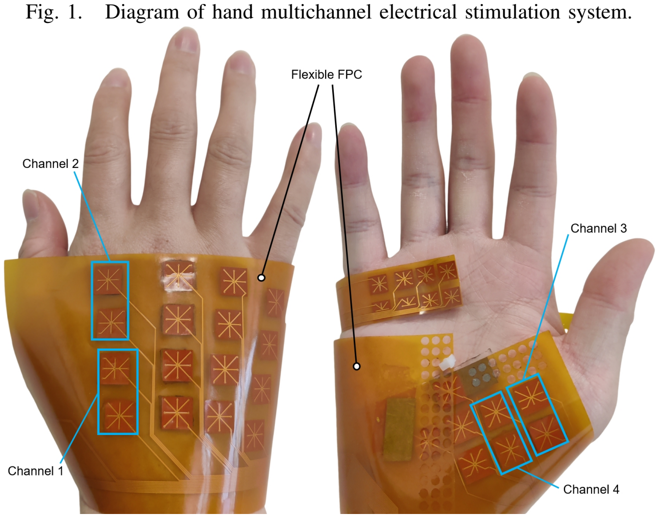

Fig. 2. FPC wearable location map.

[19] [20].

Therefore, we propose a multi-channel functional electrical stimulation system for the hand, achieving precise and subtle angle control of current and frequency through multi-channel coordinated control. This system ultimately aims to assist stroke patients in achieving precise and varied gripping gestures, effectively contributing to their rehabilitation.

II. Methods and Material

A. Electrical Stimulation System

Traditionally, electrical stimulators are implemented in two primary configurations: constant voltage and constant current modes. In the constant voltage mode, skin impedance is typically assumed to be a fixed value, and current passing through the skin is modulated by adjusting voltage [21]. However, this method yields stimulation currents based on assumptions, lacking precise control over stimulation intensity.

To address this limitation and facilitate effective multi-channel electrical stimulation of the hand, we introduce a multi-channel electrical stimulation system based on a constant current source. The system is composed of MCU, DAC chip, power tree, H-Bridge and voltage controlled constant current source. The specific composition is shown in Fig. 1, and the specific system parameters are shown in Table 1.

TABLE I
Electrical Stimulation Hardware System Configuration.

Parameter	Value
Supply voltage	12 V
Stimulating current range	$0-22$mA
Stimulus frequency adjustment step	1 Hz/Step
Stimulate pulse width adjustment step	10 us/Step
Number of channels	4

1) Power Tree: The power tree is responsible for supplying power to various components of the electrical stimulation system, including DC-DC (12 V to 5 V), DC-DC (5 V to ±5 V), LDO, and BOOST modules. The DC-DC (12 V to 5 V) buck converter, utilizing the MCP2315S power management chip, steps down the lithium battery supply voltage from 12 V to 5 V, providing power to the LDO, DC-DC (5 V to ±5 V), and BOOST modules, with a maximum output current of 3 A. The DC-DC (5 V to ±5 V) converter primarily converts a single 5 V power supply into dual ±5 V supplies, powering operational amplifiers in the circuit. The LDO regulator, employing the AMS1117-3.3 chip, offers advantages such as stability, rapid load response, and minimal output ripple, supplying a stable 3.3 V voltage to the MCU, DAC chip, and boost circuitry. The BOOST circuit, incorporating the MCP1650R chip, steps up 5 V to 60 V to provide voltage for electrical stimulation.

2) MCU Control: MCU control involves I2C, USART, and complementary PWM wave generation with dead-time. Complementary PWM waves with dead-time are generated by the MCU to drive the four optocouplers forming the H-Bridge, enabling biphasic electrical stimulation pulses. Dead-time is essential to prevent simultaneous conduction of the optocouplers, thereby preventing potential circuit damage due to their physical rise and fall times. Two TIM are employed to control the pulse width and frequency of the stimulation pulses. To regulate the stimulation current, the MCU communicates via I2C with an external 12-bit DAC chip, independently controlling the voltage of each stimulation channel. For system control, the MCU communicates via USART with a PC.

3) Voltage-Controlled Constant Current Source: The voltage-controlled constant current source comprises an operational amplifier and NPN transistor in a voltage-series negative feedback circuit. Under negative feedback conditions, the emitter voltage of the NPN transistor depends on the DAC voltage at the in-phase terminal, and the emitter current is determined by the DAC and sampling resistor. The sampling resistor is 150ohm, with the DAC voltage ranging from 0 to 3.3 V, resulting in an output current range of $0-22\,\mathrm{mA}$.

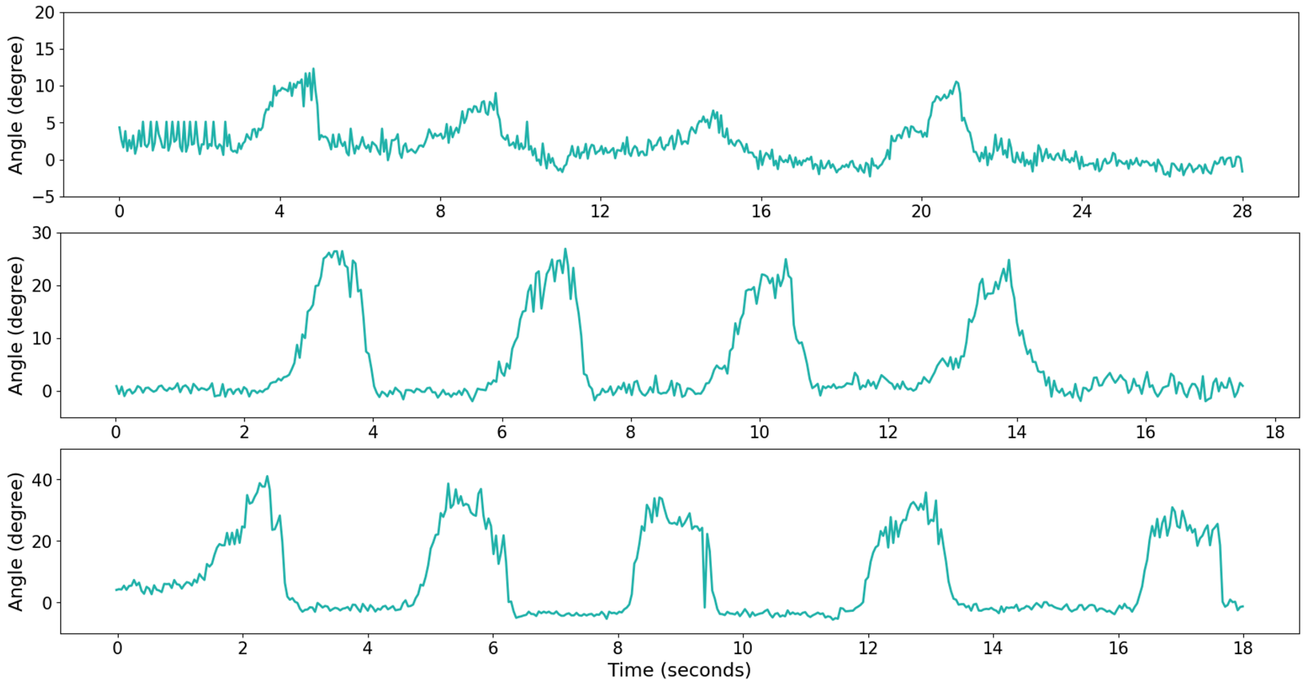

Fig. 3. Bending Angle of index finger varies with different current magnitudes at 60 Hz

B. Hand Electrical Stimulation FPC Design

The hand features a network structure formed by the ulnar, median and radial nerves, primarily responsible for muscle control and sensory transmission on the hand dorsum. The ulnar nerve controls the lateral aspect of the palm, including the muscles of the little finger, ring finger, and a portion of the palm. The median nerve controls the central and medial aspects of the palm, including the muscles of the thumb, index finger, middle finger, and part of the palm. The radial nerve controls most muscles on the dorsal aspect of the hand, including extensor carpi radialis longus, extensor digitorum, and extensor pollicis longus muscles.

1) FPC Point Design: According to the statistics of relevant institutions, the FPC size was designed based on the Average adult hand size. the electrical stimulation points were designed according to the distribution of nerves and muscles in the hand, The stimulation points cover most muscles controlling finger movement, with four channels selected, including those targeting the thenar eminence and the flexor digitorum superficialis muscle.The specific stimulation point position design and the way and position of wearing are shown in Fig. 2.

2) Wearable Design: To ensure a secure fit between the patch and the palm, a combination of self-adhesive conductive gel and positioning plastic studs was employed to firmly attach the FPC flex board to the hand.

C. Experimental Setup

To evaluate the coordinated control of the multi-channel electrical stimulation system and the effects of current and frequency on subtle finger movement angles, three comparative experiments were conducted: variations in finger movement angles under different stimulation currents, variations in finger movement angles under different stimulation frequencies, and tracking of finger movement angles with increasing current.

Conclusion based on [22], there are ten common grasping gestures used in daily life, including medium wrap, precision disk, lateral pinch, tripod, power sphere, and so on. The hand gesture chosen for the experiment was the lateral pinch gesture consisting of the thumb and index finger.

To avoid the need for additional wearable sensors, the experiment will use Mediapipe-based computer vision throughout to achieve non-intrusive detection of finger bending angles during electrical stimulation. Mediapipe was able to output 21 3D hand joint coordinates with an average accuracy of 95.7%, which was well in line with the requirements of the test.

1) Variations in Stimulation Currents: Maintaining constant stimulation frequency and pulse width, three sets of comparative experiments were conducted with stimulation currents of 12 mA, 15 mA, and 18 mA, respectively. At the beginning of each experiment, the fingers were in a relaxed state, with a single stimulation duration of 2 seconds, repeated 5 times.

2) Variations in Stimulation Frequencies: Maintaining constant stimulation current and pulse width, two sets of comparative experiments were conducted with stimulation frequencies of 30 Hz representing the low frequency and 90 Hz representing the middle and high frequency, respectively. At the beginning of each experiment, the fingers were in a relaxed state, with a single stimulation duration of 2 seconds, repeated 4 times.

3) Continuous Gesture Variation: The stimulation frequency was set to 90 Hz. At the beginning of each exper-

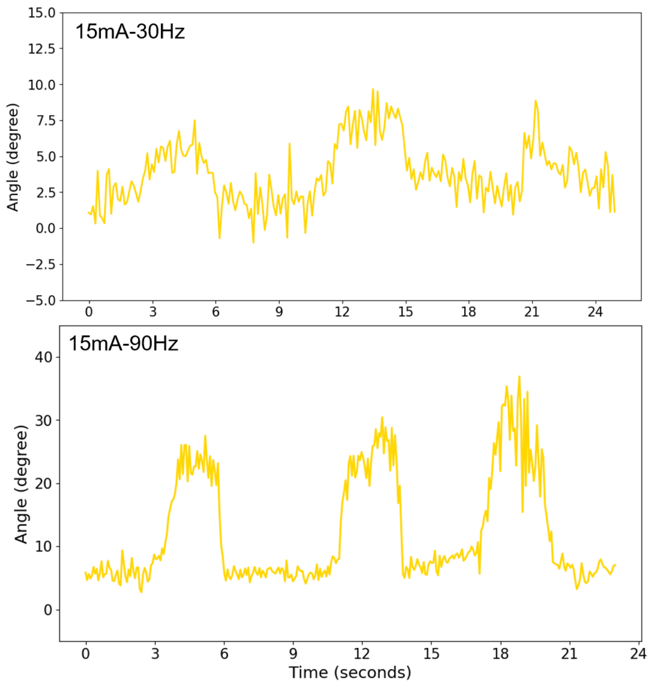

Fig. 4. Bending angle of index finger varies with different current frequencies at 15 mA

iment, the fingers were in a relaxed state, with the initial stimulation current set to 2 mA, increasing by 1 mA every 700 ms until reaching 18 mA.

III. Results

Due to the highly customized FPC, one subject participated in this experiment. The subject was male, 25 years old, 173 cm tall and 80 Kg in weight. The experimenter was right-handed and the experiment was tested on the right hand.

The participant had normal hand muscle movement and were right-handed. Prior to the experiment, all participants received written informed consent. The experimental protocol was approved and implemented under the supervision of the Medical Ethics Committee of the University of Southern Science and Technology(approval number: 20230226, date: 2023/12/25).

A. Current Correlation

According to Fig. 3, under the stimulation of 12 mA for 5 instances, four distinct finger movements were observed with a success rate of 80 %, and the angle of movement for the index finger was approximately 10°. Under the stimulation of 15 mA for 5 instances, again four evident finger movements were observed with an 80 % success rate, while the movement angle of the index finger ranged from 20°-25°. Under the stimulation of 18 mA for 5 instances, five noticeable finger movements were observed with a 100 % success rate, and the movement angle of the index finger was approximately 40°.

The experiment shows that the movement Angle of the index finger is obviously different under the stimulation of different currents. If the current can be more finely divided, it is expected to achieve more finely controlled Angle.

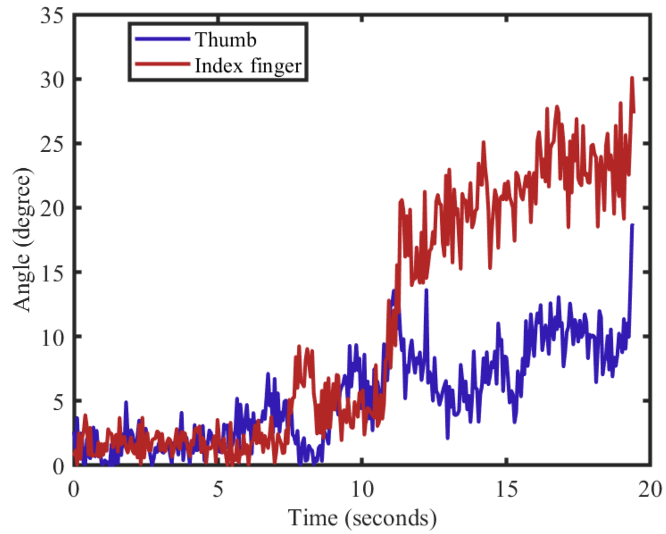

Fig. 5. Bending angle of thumb and index finger with current increasing evenly from 2 mA to 18 mA

B. Frequency Comparison

Fig. 4 illustrates a comparative analysis conducted on stimulation frequencies of 30 Hz and 90 Hz, while holding the stimulation current constant at 15 mA. The experiment was repeated four times at a frequency of 30 Hz, resulting in three distinct finger movements observed, with an 80 % success rate and an approximate finger movement angle of 6°. Likewise, the experiment was replicated four times at a frequency of 90 Hz, resulting in three significant finger movements, achieving an 80 % success rate, with a finger movement angle of about 30°.

The experiment shows that the movement Angle of index finger is obviously different under different frequency of stimulation while keeping the current unchanged. If the two conditions of fine current division and optimal stimulation frequency can be combined, it is expected to achieve accurate and rapid electrical stimulation.

C. Continuous Gesture Variation

Figure. 5 shows that the angle of movement for the thumb and index finger increases as the current increases. When the stimulation current exceeds 10 mA, the movement trend of both the thumb and index finger is significantly greater than when the current is below 10 mA. When the current is increased to 18 mA, the angle of movement for the index finger reaches 30°, and the angle of movement for the thumb reaches 15°.

This experiment shows that electrical stimulation in the hand can achieve better dynamic change ability of gestures, and if the control strategy of current is more targeted, it is expected to achieve flexible change of gestures, which is very important for restoring the grip of patients with hemiplegia.

IV. Conclusion

We introduce a FES-based system incorporating a multichannel electrical stimulator and a wearable 16-channel FPC patch to enable precise finger control. Initially, stimulation points are strategically distributed along the ulnar, median, and radial nerves, aligning with the respective finger muscle networks. A meticulously designed power tree efficiently allocates the $12\,\mathrm{V}$ supply voltage across the system. Utilizing an MCU to drive the H-Bridge and regulate a DAC chip, the system generates adjustable biphasic symmetrical stimulation pulses. These pulses are subsequently conveyed through the FPC to achieve precise electrical stimulation. Experimental findings demonstrate that under stable current frequency conditions, varying pulse currents of $12\,\mathrm{mA}$, $15\,\mathrm{mA}$ and $18\,\mathrm{mA}$ yield index finger bending angles of approximately $10°$, $28°$, and $40°$, respectively. Meanwhile, maintaining constant pulse currents at frequencies of $30\,\mathrm{Hz}$ and $90\,\mathrm{Hz}$ results in index finger bending angles of approximately $7.5°$and $30°$, respectively. Furthermore, a uniform increment in pulse current from $2\,\mathrm{mA}$ to $18\,\mathrm{mA}$ at a rate of $0.7\,\mathrm{mA}$ per second leads to approximately $18°$and $28°$bending angles for the thumb and index finger, respectively. Thus, the system exhibits effective precision finger control by modulating current intensity and frequency.

V. Discussion

Firstly, regarding the hardware system, currently, the flexibility and extensibility of the FPC patch material are not sufficient. It tends to slip during stimulating hand movements, affecting the precision of electrical stimulation and actual stimulation effects. In the future, we hope to improve the design of hand electrical stimulation patches by using more suitable materials. Moreover, finger movement joints are limited to the metacarpophalangeal joint (MCP), which poses limitations on flexible gestures. We will explore more different muscles to achieve controlling over the proximal interphalangeal joint (PIP) and distal interphalangeal joint (ABC), thus enabling more flexible gesture control. Secondly, we aim to enhance the software system by incorporating visual feedback using eye trackers or MR glasses. This will involve utilizing YOLOv8 for visual compensation feedback in grip control and employing a 6D grip posture generation model to automatically generate optimal initial grip postures, thereby enhancing the system's automation. In summary, the future focus will be on improving system accuracy, expanding system functionality, optimizing patient experience, and enhancing the effectiveness of rehabilitation assistance.

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