Article | Received 11 Feburary 2025; Accepted 22 May 2025; Published 2 June 2025
https://doi.org/10.55092/neuroelectronics20250005

FESGlove: a glove of functional electrical stimulation with good selectivity for finger motion control

Zeyu Cai[1], **Wenlong Zhang**[2], **Le Xie**[2] and **Dingguo Zhang**[1,*]

[1] Department of Electronic and Electrical Engineering, University of Bath, Bath, UK

[2] Institute of Medical Robotics, Shanghai Jiao Tong University, Shanghai, China

* Correspondence author; E-mail: dz492@bath.ac.uk.

Highlights:

- A portable FES glove enables independent finger motion control via Highly selective stimulation.
- Multi-channel system offers high selectivity with adjustable frequency, amplitude, and pulse width.
- Custom electrode glove integrates silver fiber and hydrogel for comfort and stability.
- Experiments on 8 subjects showed significant target finger movement with low coupling effects.
- Suitable for precise hand rehabilitation tasks requiring fine motor control.

Abstract: Functional electrical stimulation (FES) is an important rehabilitation technology for the recovery of motor function. This work developed a novel FES glove (FESGlove) with good selectivity for hand muscle stimulation. FESGlove aims to achieve independent finger motion control, which most available FES systems lack. The device is portable, multi-channel, and features adjustable stimulation parameters. FESGlove integrates a custom-designed electrode glove that combines silver-fiber fabric and hydrogel electrodes, enabling selective stimulation of hand muscles and nerves. Experiments were conducted on eight healthy participants to evaluate the system's performance in controlling target finger movements while minimizing non-target finger coupling. The results demonstrated that the FES system achieved high selectivity and repeatability in both flexion and extension modes, with target fingers exhibiting significantly greater movement amplitudes than non-target fingers. The system's adaptability to individual differences and comfortable user experience were also confirmed. This satisfactory performance demonstrates the potential of the system for hand rehabilitation or assistance for people with disabilities in the future.

Keywords: functional electrical stimulation; finger motion control; multi-channel stimulation; glove; hand motor function

1. Introduction

Millions of people with disabilities are suffering from hand dysfunction [1]. Hand functionality is critical for activities of daily living, such as eating, dressing, writing, and personal hygiene [2]. Limited hand function not only diminishes patients' ability to live independently but also severely reduces their quality of life, with some individuals becoming entirely dependent on caregivers [3].

Restoring hand motor function poses greater challenges compared to other body parts due to the intricate coordination required among multiple joints, muscles, and nerves [4]. Complex actions such as grasping, pinching, and tapping demand not only strength recovery but also precise motor control [5]. This highlights the need for highly specialized rehabilitation strategies that address the fine motor requirements of hand recovery. However, traditional rehabilitation approaches often do not meet the personalized demands of patients and show limited efficacy in improving hand function.

Functional electrical stimulation (FES) is a well-established neurorehabilitation technique that has been widely applied in the recovery of motor function following stroke [6]. Based on the principle of neuroplasticity, FES promotes functional recovery by directly stimulating target muscles and nerves [6, 7]. Existing FES devices for hand rehabilitation, such as the XFT-2003EA H2 [8], Bioness H200 Wireless [9], and ReGrasp [10], have demonstrated effectiveness in facilitating gross hand movements, such as grasping and extending. However, these systems face significant challenges in precisely controlling individual fingers. In particular, their limited number of stimulation channels restricts the ability to achieve highly selective stimulation, making it difficult to isolate the motion of a single finger. As a result, patients may be unable to perform intricate hand functions, such as picking up small objects or completing high-precision tasks, thereby hindering the achievement of comprehensive rehabilitation goals.

Beyond motor rehabilitation, electrical stimulation technologies, including the principles of FES, have been widely adopted in other domains of neural engineering. For instance, cochlear implants utilize reconfigurable neural stimulation circuits to restore hearing [11], retinal prostheses stimulate visual neurons to recover partial sight [12], and deep brain stimulation systems apply electrical pulses to alleviate symptoms in neurological disorders such as Parkinson's disease [13]. These applications reflect the technological versatility and growing impact of electrical stimulation in modern biomedicine.

To address the limitations of existing hand-focused FES devices, recent research has focused on enhancing the selectivity of stimulation techniques to improve single-finger control. Some studies have attempted to achieve finger flexion or extension by placing electrodes on the forearm to stimulate forearm muscles [14, 15]. Optimizing electrode placement and stimulation parameters has been shown to improve selectivity; however, the inherent multi-joint nature of forearm muscles and their tendons spanning multiple fingers frequently leads to unintended finger coupling, limiting the effectiveness of this approach [14, 16].

Advanced electrode designs and stimulation algorithms have also been proposed to improve control precision. For example, high-density electrode arrays with self-calibration mechanisms have been developed to enhance target finger selectivity [17]. Despite these advancements, challenges such as limited target finger movement amplitude, insufficient suppression of non-target finger motion, and suboptimal user comfort persist.

In addition, surface stimulation techniques targeting forearm muscles have demonstrated improvements in the accuracy of grasping and releasing movements [18]. However, these methods still struggle to provide precise, independent finger control, primarily due to shared anatomical structures, such as tendons and muscles.

Given these limitations, we developed FESGlove: a portable, multi-channel, and parameter-adjustable FES system tailored for hand rehabilitation. The system integrates a novel electrode glove that combines silver-fiber fabric with hydrogel electrodes. By capitalizing on the high selectivity afforded by multi-channel stimulation and the specialized glove design, FESGlove precisely targets small muscles and nerves in the hand to enable independent finger control. Compared to conventional devices, it provides greater channel diversity, adjustable stimulation parameters, and enhanced wearability. To evaluate its performance, we conducted experiments with eight healthy participants and monitored the movements of both target and non-target fingers. The study systematically assessed the system's effectiveness in facilitating independent finger control while minimizing unintended finger coupling.

To elucidate the physiological challenges of achieving independent finger movement, Figure **??** illustrates the comparative anatomy of the muscles and nerves in the forearm and hand. Previous studies have primarily targeted forearm muscles due to their accessibility and their critical role in gross motor functions of the fingers. For example, the flexor digitorum profundus and flexor digitorum superficialis muscles in the forearm control finger flexion, acting on the distal and middle phalanges, respectively [19, 20]. Similarly, finger extension is facilitated by the extensor digitorum, extensor indicis, and extensor digiti minimi muscles, which originate in the forearm and insert into the extensor hoods of the fingers [20]. However, these forearm muscles share tendon structures spanning multiple fingers, often leading to unintended coupling effects during electrical stimulation. In addition, their complex distribution (encompassing both superficial and deep layers) can activate non-target muscles simultaneously, resulting in unintended finger movements. This anatomical limitation restricts precise single-finger control. Furthermore, many forearm muscles span multiple joints and fingers, complicating the accurate localization of stimulation sites. The intricate branching of nerves, including the median, ulnar, and radial nerves, introduces yet another layer of complexity, making it difficult to selectively activate target muscles without inadvertently stimulating non-target ones. These factors collectively underscore the inherent challenges of relying on forearm-based stimulation for independent finger control in prior research.

In contrast, this study emphasizes localized stimulation of hand muscles and nerves that are directly involved in fine motor control. Specifically, for finger flexion, the stimulation targets branches of the flexor digitorum profundus and flexor digitorum superficialis corresponding to each finger, as well as the thenar muscles, hypothenar muscles, and branches of the median nerve within the hand. For finger extension, it focuses on the respective branches of the extensor digitorum, extensor pollicis longus, and the radial nerve [20]. By capitalizing on the hand's anatomy, this localized approach enables precise activation of individual fingers, markedly reducing unintended movements of non-target fingers and overcoming the tendon coupling limitations seen in forearm stimulation. Although intrinsic hand muscles produce less force than their forearm counterparts, targeting them allows for more selective and precise finger control. Therefore, this strategy avoids the challenges posed by the broader, more interconnected forearm muscles, effectively reducing unintended movements during single-finger flexion and extension tasks.

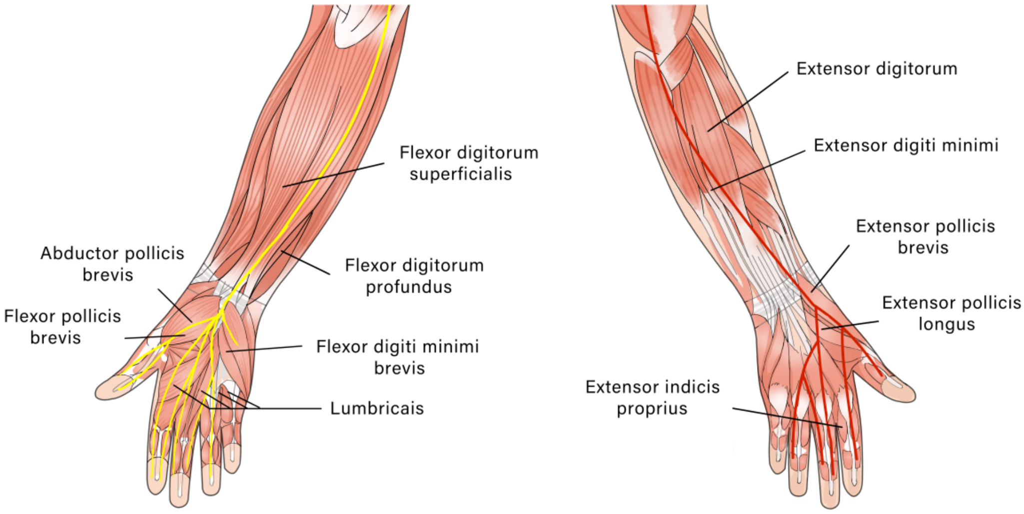

Figure 1. Anatomical diagram of forearm and hand muscles with associated nerves.

Figure 1 illustrates the primary muscles and nerves involved in finger flexion and extension. The left panel highlights the muscles and nerves responsible for finger flexion, while the right panel showcases those involved in finger extension. Conventional FES systems typically stimulate large muscles in the forearm, such as the flexor digitorum superficialis, flexor digitorum profundus and extensor digitorum *etc*. In contrast, the proposed FESGlove primarily stimulates localized muscles and nerves in the hand, such as the lumbricais, flexor pollicis brevis, abductor pollicis brevis, as well as branches of the median and ulnar nerves.

2. Methods

FESGlove aims to achieve better control of independent finger movements and is a multi-channel, parameter-adjustable FES system. FESGlove consists of three primary components: a software program, hardware circuits, and an electrode glove. These components were designed synergistically to deliver a highly integrated and flexible solution tailored to the precise motor rehabilitation needs of the hand.

To validate the effectiveness of FESGlove, experiments were conducted with eight healthy participants. During the experiments, inertial measurement unit (IMU) sensors were utilized to record finger motion data. These data were analyzed to evaluate the independent motion of the target finger and the coupling effects in non-target fingers. This section provides a detailed description of the system's design and components, the ethical review and participant recruitment process, the experimental protocol, the stimulation parameters, and the methods for motion monitoring and data analysis.

2.1. System design

FESGlove for hand rehabilitation consists of the following four components: Software Program: The software is responsible for generating control signals to adjust stimulation parameters and manage channel outputs. It operates on a microcontroller and enables user communication via a human-machine interface (HMI). Hardware System: Stimulation Circuit: Provides multi-channel constant-current outputs that generate electrical signals with adjustable frequency, amplitude, and pulse width to stimulate target muscles and nerves. Human-Machine Interaction System: Includes a 4 × 4 keypad and an LED screen for setting stimulation parameters (e.g., frequency, amplitude, pulse width), selecting output channels, and displaying the system status in real time. Electrode Glove: The glove integrates silver fiber fabric with hydrogel electrodes. Precisely arranged stimulation sites provide highly selective stimulation while ensuring user comfort and wearability.

FESGlove's overall architecture is depicted in Figure 2. By combining hardware circuits, software, and the electrode glove, the system effectively meets the complex demands of hand motor rehabilitation.

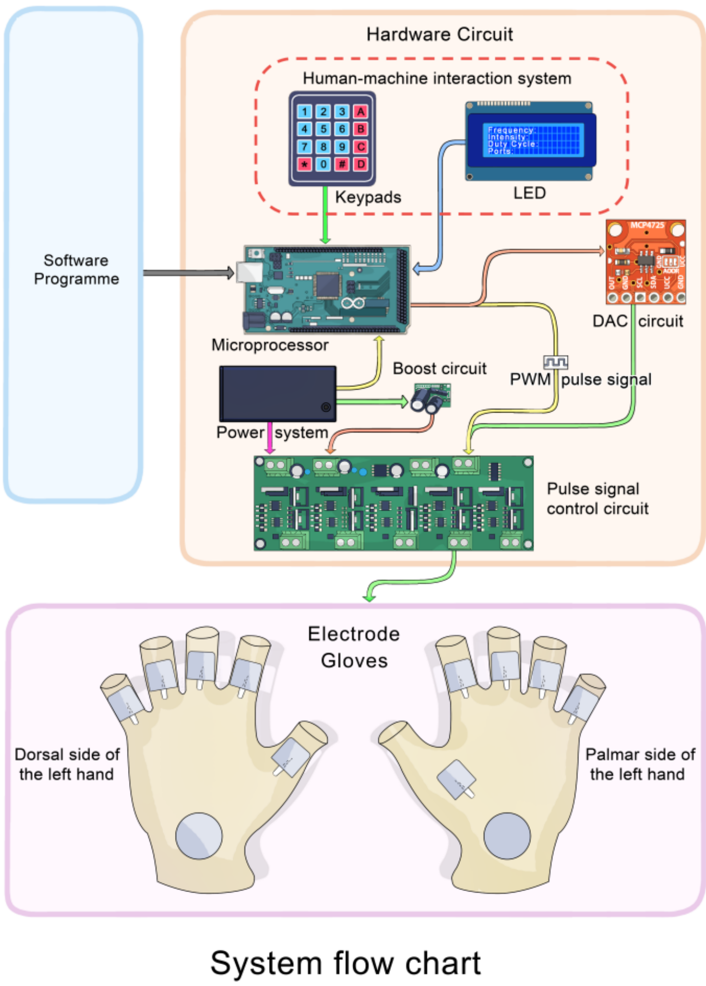

Figure 2. Schematic diagram of FESGlove system.

2.2. Stimulation circuit

The stimulation circuit supports 10 channels of constant-current output, with adjustable parameters including frequency (0–5000 Hz), amplitude (0–50 mA), and pulse width (100–2000 s). The circuit is controlled by an Arduino Mega 2560 microcontroller, and a digital-to-analog converter (DAC) module generates reference voltage signals. These signals are amplified by the pulse processing circuit and delivered to the electrode glove. The system is powered by a 9 V lithium battery, providing high portability and safety.

Figure 3 illustrates the workflow of the FESGlove hardware circuit system. The process begins with the microprocessor generating PWM signals at specific frequencies and pulse widths. These signals, referenced to the voltage output of the DAC circuit, are then amplified to a specified amplitude and stabilized within the pulse signal control circuit. The pulse signal control circuit comprises filtering, amplification, and a constant current source. Finally, stimulation currents with defined parameters are delivered to the electrodes of the FESGlove. This highly integrated structure ensures precise and stable signal transmission, which is essential for effective functional electrical stimulation.

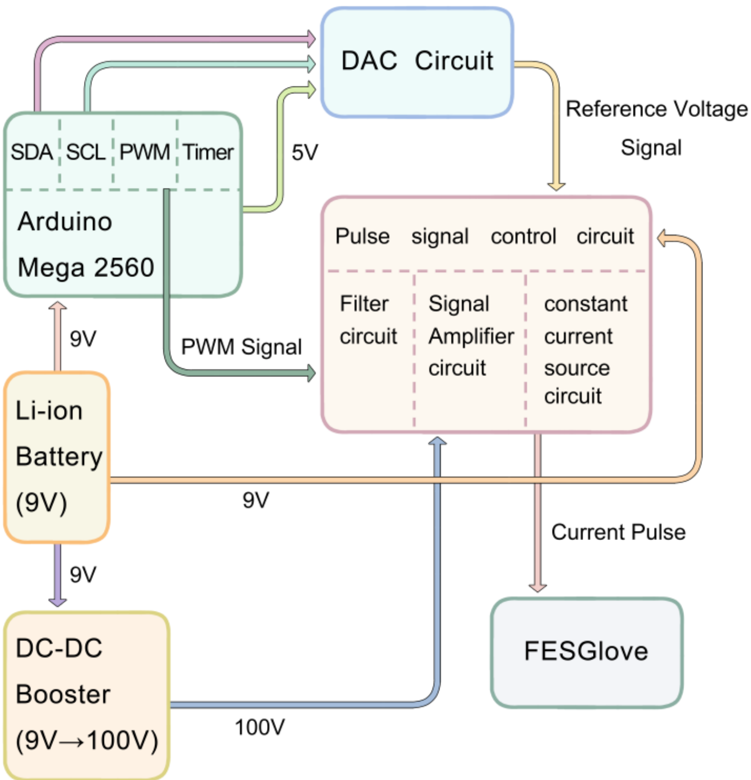

Figure 3. Hardware circuit workflow of the FESGlove.

The stimulation system's technical specifications are detailed in Table 1, providing a comprehensive overview of its capabilities and design features.

Table 1. Technical parameters of the FESGlove system.

Catgory	**Parameter**	**Value**	**Unit**	**Description**
Stimulation Parameters	Current Amplitude	0–50	mA	Range of stimulation intensity
	Pulse Width	100–2000	μs	Width of a single stimulation pulse
	Stimulation Frequency	0–5000	Hz	Repetition frequency of stimulation
	Waveform Type	Square Wave	-	Type of output waveform
Control Parameters	Number of Channels	10	-	Number of stimulation channels
	Voltage Range	0–100	V	Output voltage range
Mechanical Properties	Power Source	9V Lithium Battery	-	Power supply for the system
	Weight	296	g	Total weight (excluding battery)
Safety Parameters	Maximum Current Limit	50	mA	Maximum current for safety

In this study, the goal was to achieve independent control of single-finger movements by applying low-frequency functional electrical stimulation (FES) to localized muscles and nerves in the hand. Therefore, the required frequency range for this application is 1–100 Hz, and a frequency of 35 Hz was used during experiments. The pulse width was adjustable from 100 to 2000 μs, with 500 μs selected as the standard setting based on initial trials. The stimulation amplitude needed to be adjustable from 5 to 30 mA; during experiments, the current started at 5 mA and was gradually increased to elicit clear finger motion while remaining within the participant's comfort threshold.

To further verify the stability and accuracy of the FESGlove hardware circuit system, the output stimulation current was applied to a 1000-ohm load, with the target parameters set to a frequency of 35 Hz, a pulse width of 500 μs, and an amplitude of 10 mA. The choice of a 1000-ohm load was based on a common engineering approximation for the average impedance of the skin–electrode interface during transcutaneous electrical stimulation, particularly when using conductive gel electrodes [21]. The measured stimulation current signal was observed using an oscilloscope. As shown in Figure 4, the waveform demonstrates that the system is capable of generating stable stimulation signals that precisely match the pre-set parameters used in the human experiments of this study. These parameters include a frequency of 35 Hz, a pulse width of 510 μs, and a voltage amplitude of approximately 9.87 V, corresponding to a current amplitude of 9.87 mA. Hence, these findings confirm the system's reliability in generating stable and precise stimulation currents.

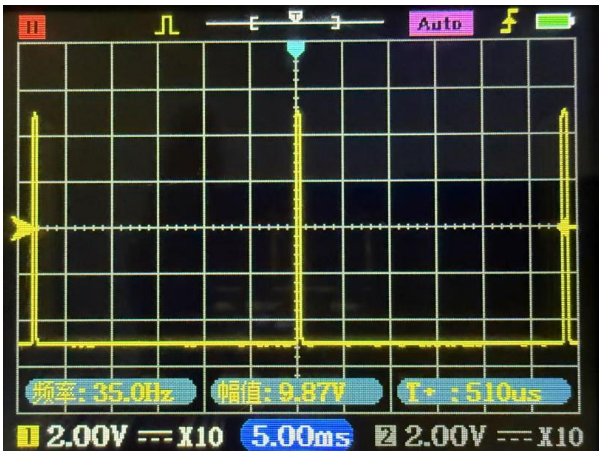

Figure 4. Oscilloscope observation of stimulation output waveform.

2.3. Electrode glove

The electrode glove was designed with considerations for ergonomics and electrical stimulation performance. Elastic fabric serves as the glove's base material, while silver fiber fabric and hydrogel electrodes are strategically positioned for effective stimulation. The specific design details of the electrode glove are illustrated in Figure 5.

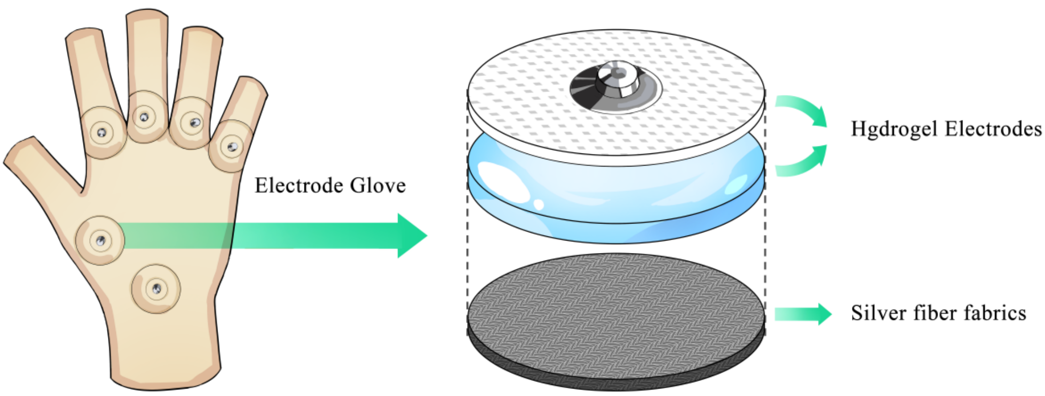

Figure 5. Schematic of the electrode glove design.

Electrode Placement: To identify consistent stimulation sites capable of eliciting isolated finger movements, pilot testing was conducted on three healthy subjects. A pulse current at 35 Hz was applied to various hand regions to test responses from different muscles and nerves, as shown in Figure 6. Based on the results, distinct electrode configurations were selected for finger flexion and extension tasks.

For finger extension, the stimulation electrodes (anodes) were placed on the dorsal side of each finger between the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints, while the reference electrode (cathode) was positioned on the dorsal base of the palm.

For finger flexion, the electrode placement varied between the thumb and other fingers. For the thumb, the stimulation electrode was placed over the central region of the thenar eminence. For the other fingers, the electrodes were positioned on the palmar side, also between the MCP and PIP joints. In both cases, the reference electrode was placed on the palmar base of the hand.

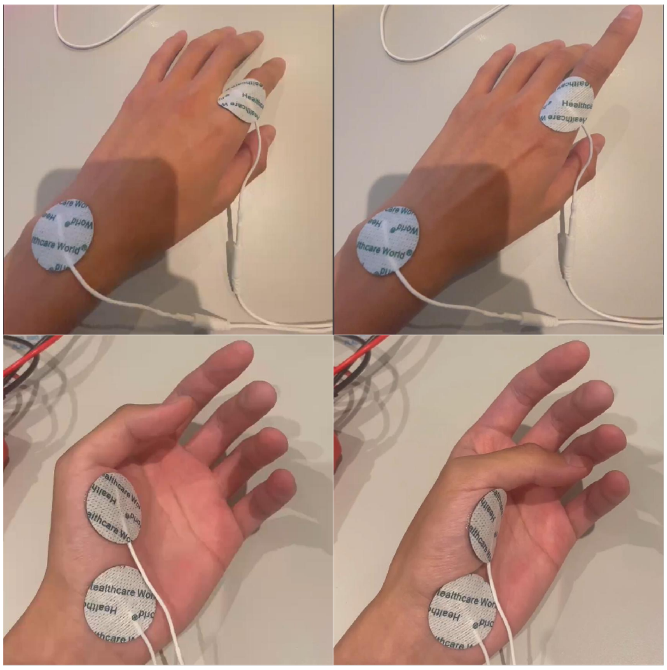

Figure 6. Photographs of a participant during pilot testing to determine optimal stimulation sites for inducing independent finger movements.

Electrode Dimensions: The reference electrode was a circular pad with a diameter of 2.2 cm. The stimulation electrodes varied in size, with a 1 × 1 cm square for the little finger and 1.5 × 2 cm rectangles for other fingers.

Material Properties: Silver fiber fabric, known for its softness and high conductivity, ensured close contact with the skin and efficient signal delivery [22, 23]. Combined with hydrogel electrodes, this design enhanced stability, comfort, and user experience during extended use [24].

This design achieves precise stimulation while ensuring ease of wear and long-term usability. Figure 7 shows the physical implementation of the complete hand functional electrical stimulation rehabilitation system.

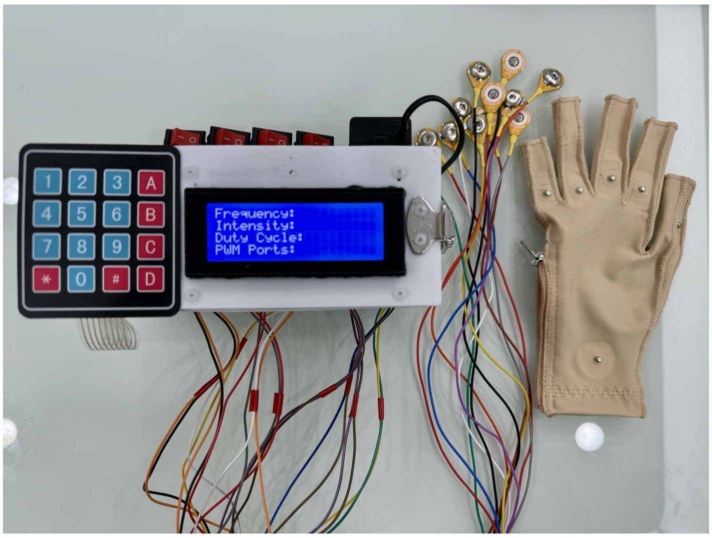

Figure 7. Physical diagram of the hand functional electrical stimulation rehabilitation system.

2.4. Experimental design

The study was conducted following ethical approval of University of Bath (Approval ID: 1117–4790). All participants provided written informed consent after being briefed on the experimental procedures and potential risks. Eight healthy volunteers (6 males and 2 females), aged 19–26 years (mean age: 22.5 ± 2.1 years), were recruited. All participants were right-handed and met the following inclusion criteria:

(1) No history of neurological, musculoskeletal, or other upper-limb impairments; (2) Healthy hand skin with no allergies or injuries; (3) No implanted electronic devices (e.g., pacemakers); (4) The palm circumference between 18 cm and 21 cm; (5) Good psychological condition without fear of electrical stimulation.

The experimental workflow, comprised three main phases:

Preparation: Participants wore the electrode glove, and initial stimulation parameters were configured using the HMI. Although the participants exhibited slight differences in hand size, all had palm circumferences between 18 cm and 21 cm, which fit well within the elastic range of the glove. The stretchable glove material enabled precise adjustment of the electrode positions to accommodate individual anatomical differences and ensure effective and selective stimulation. Prior to the formal trials, each electrode position was fine-tuned through brief calibration and then fixed to maintain consistency throughout the experiment.

Single-Finger Independent Control Test: Target fingers (thumb, index, middle, ring, little) were randomly stimulated to induce flexion or extension movements. Finger motion data were recorded to evaluate target finger movement amplitude and non-target finger coupling effects.

Collection and Analysis: Each stimulation task was repeated five times with a 10-second rest interval to prevent muscle fatigue. And each stimulation trial lasted no more than 5 seconds. All data were transmitted via Bluetooth to a computer for subsequent analysis.

To clarify the definition of finger angles in this study and to illustrate how the IMU sensor measures these angles, Figure 8 provides a schematic representation of the experimental setup. As shown in the figure, the initial angle (α_0) represents the finger's resting position at the start of the experiment. In the left panel of Figure 9, the finger naturally assumes either an extended or flexed posture, depending on the specific experiment. Specifically, in the finger flexion experiment, the finger begins in a naturally extended position, whereas in the finger extension experiment, it starts in a naturally flexed position. The subsequent angle (α_1) indicates the finger's position following stimulation-induced flexion or extension. The difference between these two angles ($|\alpha_1 - \alpha_0|$) quantifies the finger's movement during stimulation and serves as a key parameter for evaluating finger motion. These angles are calculated based on the IMU sensor's monitoring of the finger's relative orientation with respect to a horizontal reference plane. This standardized definition ensures consistency and accuracy in measuring finger motion across all experimental conditions.

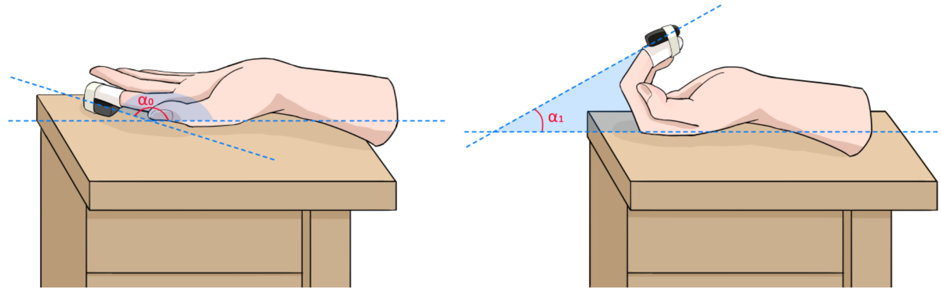

Figure 8. Schematic diagram of finger angle definition in the experiment.

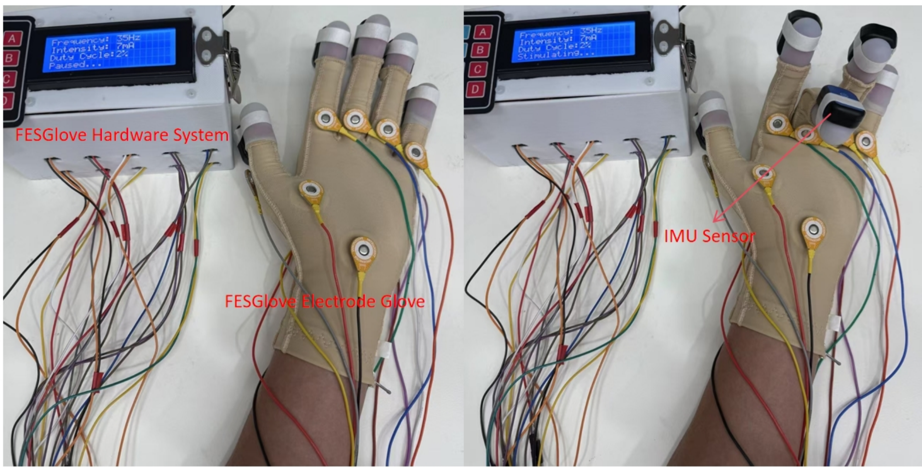

Figure 9. Experimental setup for independent single-finger control. It illustrates the experimental setup for evaluating middle finger flexion in one of the participants using the FESGlove system developed in this study.

2.5. *Stimulation parameters*

The following optimized stimulation parameters were employed to ensure safety and effectiveness:

Frequency: Set to 35 Hz to induce stable muscle contractions while minimizing fatigue caused by excessive frequencies [25, 26].

Amplitude: Because each subject had different motor and pain thresholds in response to functional electrical stimulation, the stimulation amplitude was individually adjusted. During the calibration phase, the initial current was set at 5 mA and increased in 1 mA increments. The threshold was identified when a clear movement of the target finger was observed. Then, the amplitude was further increased—within the subject's comfort limit—to achieve the largest possible flexion or extension angle without inducing discomfort or pain [27, 28].

Pulse Width: Fixed at 500 µs, which has been shown to effectively recruit muscles while reducing interference with non-target muscles [29, 30].

2.6. Motion monitoring and data analysis

Finger motion data were recorded using WT9011DCL IMU sensors. These sensors provide high-precision real-time motion data with an angular measurement accuracy of 0.2° [31]. The sensors were affixed to the fingertips using lightweight stabilizing fixtures, and data were sampled at a frequency of 200 Hz before being transmitted to a computer via Bluetooth.

Data Analysis: Target Finger Movement Amplitude: The maximum flexion or extension angle of the target finger during stimulation was recorded. Non-Target Finger Angle Changes: The movement of non-target fingers was quantified to assess coupling effects.

Statistical Analysis: One-tailed T-tests were used to evaluate the significance of the angle differences between target and non-target fingers, with the significance level set at $p < 0.05$ [32].

3. Results

This section provides a systematic analysis of the experimental data, focusing on the movement amplitude of target fingers under electrical stimulation, the coupling effects in non-target fingers, and the results of a one-tailed t-test. By examining the flexion and extension angles of the target fingers, this study evaluates the effectiveness and selectivity of the developed FES system in achieving independent single-finger control.

3.1. Target finger performance

As shown in Figure 8 , the IMU sensors recorded the inclination angle of each fingertip relative to a horizontal reference plane. The values presented in Figures 10–13 represent the change in this angle from the resting position to the peak position during stimulation, indicating the flexion or extension of the finger induced by FES.

The experimental data from eight participants were analyzed to assess the flexion and extension angles of the target fingers under selective stimulation. Figures 10 and 11 illustrate the average movement amplitudes of each target finger in flexion and extension modes, respectively. Key findings include:

Flexion Mode (Figure 10): Target fingers exhibited significant flexion movements when selectively stimulated. The thumb showed smaller flexion angles compared to other fingers, likely due to its unique anatomical structure and the relative independence of the muscles controlling its movement.

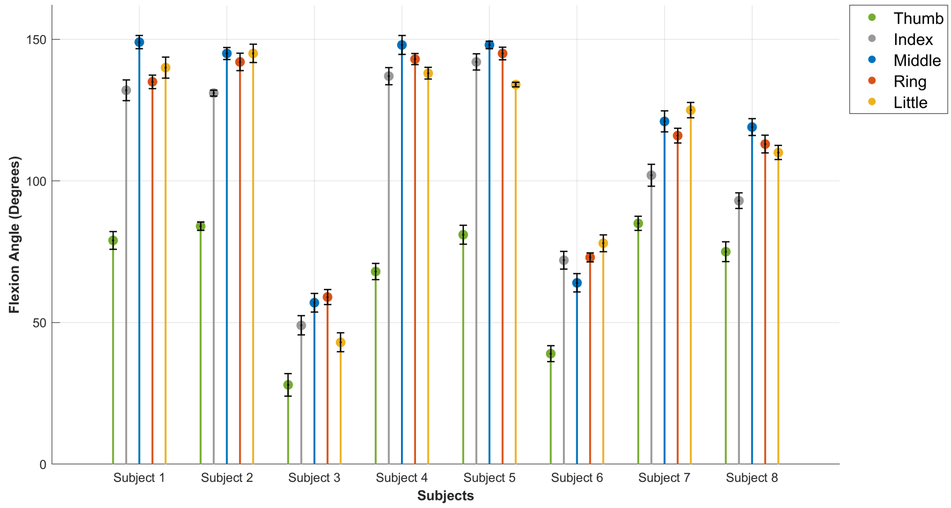

Figure 10. Target finger flexion angles for 8 subjects.

Extension Mode (Figure 11): In contrast to flexion, the extension angles of the target fingers were generally smaller, consistent with the physiological characteristics of hand muscles, where flexor muscles are typically more developed and capable of generating larger movement amplitudes.

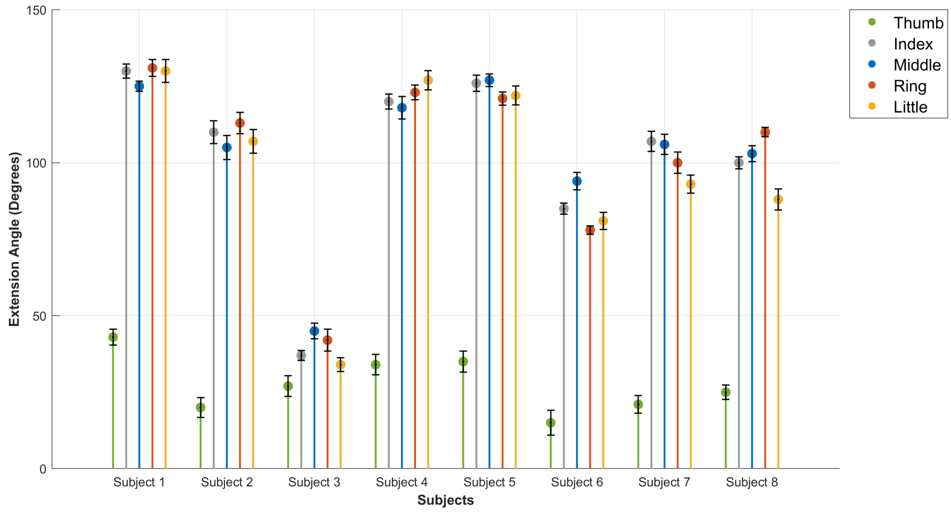

Figure 11. Target finger extension angles for 8 subjects.

Individual differences in target finger movement amplitudes were observed among participants, which may be attributed to variations in hand size, the fit of the electrode glove, and sensitivity to electrical stimulation. These findings underscore the importance of incorporating adjustable and personalized parameter settings in FES systems, which is consistent with the conclusions of previous studies [29, 33].

Although we did not conduct a dedicated parametric study, we observed that increasing the stimulation amplitude typically resulted in a larger range of finger flexion or extension, within the subject's comfort threshold. For example, in some participants, the middle finger flexion angle increased from approximately 30° at 6 mA to over 100° at 10 mA. This observation suggests a dose–response relationship between stimulation intensity and joint motion, consistent with previous findings in neuromuscular electrical stimulation research [34]. Throughout the experiment, no consistent decrease in the flexion or extension angles of the target fingers was observed over time. This suggests that the effect of neuromuscular adaptation was limited under the proposed stimulation protocol.

3.2. *Non-target finger coupling*

To evaluate the system's ability to suppress coupling effects in non-target fingers during independent finger control, the movement angles of non-target fingers were analyzed. Figures 12 and 13 present the average flexion and extension angles of all fingers when different target fingers were stimulated:

Flexion Mode (Figure 12): Occasionally, non-target fingers adjacent to the target finger exhibited slight coupling movements. This phenomenon was particularly evident between the middle and ring fingers, likely due to the shared tendons and anatomical connections of the hand [35].

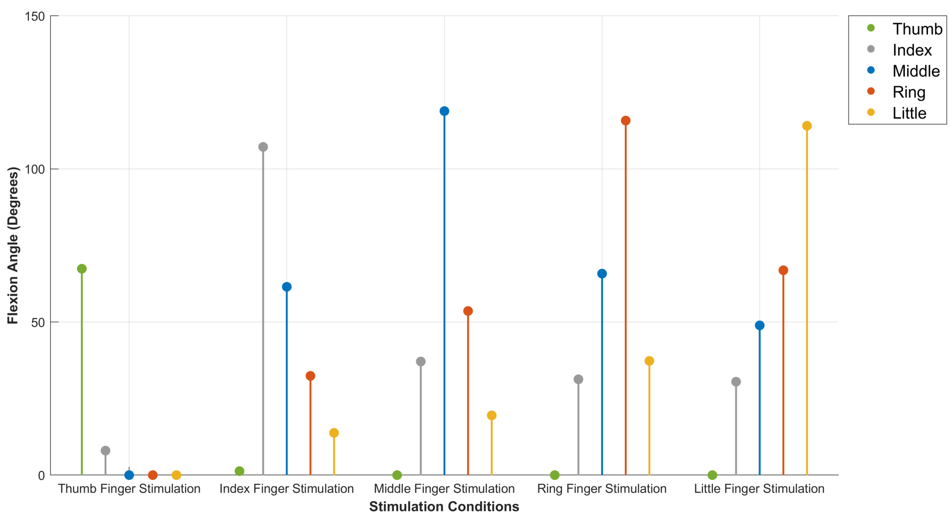

Figure 12. Flexion angles of each finger during stimulation of different target fingers.

Extension Mode (Figure 13): Coupling movements in non-target fingers were less pronounced compared to flexion mode but were still observed to a limited extent.

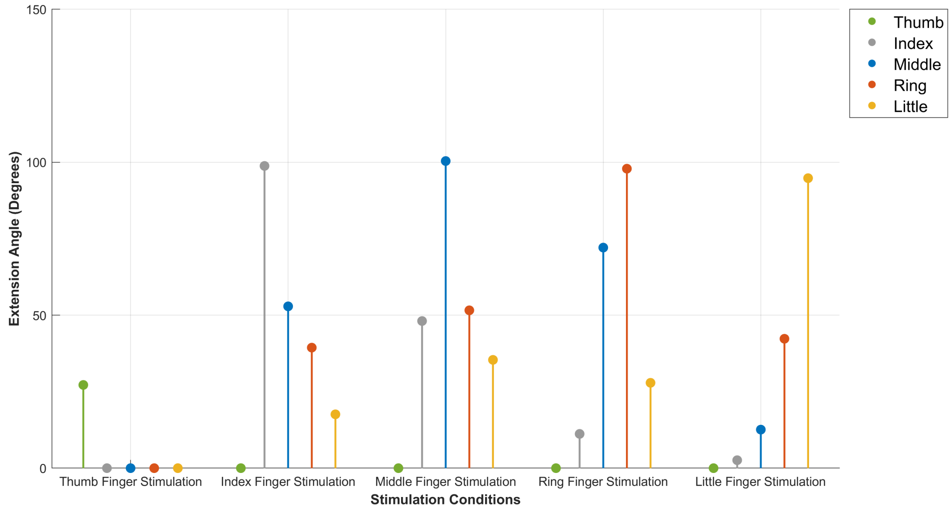

Figure 13. Extension angles of each finger during stimulation of different target fingers.

Although movements of adjacent fingers were occasionally observed during stimulation, their angular displacement was significantly smaller than that of the target finger and did not interfere with the intended motion. This level of coupling is considered acceptable, especially given the anatomical proximity of intrinsic hand muscles and tendons. Mechanical coupling between fingers is widely recognized as a limiting factor for fully independent finger movement [36]. Compared to conventional forearm-based stimulation methods, the FESGlove's multi-channel configuration and localized stimulation strategy substantially enhance finger selectivity and independence.

3.3. Statistical analysis

To further validate the differences in movement angles between target and non-target fingers, one-tailed T-tests were performed. The T-test was designed to assess whether the movement angles of the target fingers were significantly greater than those of non-target fingers. The hypotheses were defined as follows:

Null Hypothesis (H_0): The mean movement angle of the target finger is less than or equal to that of non-target fingers.

Alternative Hypothesis (H_1): The mean movement angle of the target finger is greater than that of non-target fingers.

The T-test formula used is as follows:

$$\mathrm{t} = \frac{\overline{\mathrm{X}}_\mathrm{t} - \overline{\mathrm{X}}_\mathrm{n}}{\sqrt{\frac{\mathrm{s}_\mathrm{t}^2}{\mathrm{n}_\mathrm{t}} + \frac{\mathrm{s}_\mathrm{n}^2}{\mathrm{n}_\mathrm{n}}}} \tag{1}$$

where: $\bar{X}_t$ = mean of the target finger samples, $\bar{X}_n$ = mean of the non-target finger samples, s_t^2, s_n^2 = variances of target and non-target samples, respectively, n_t, n_n = sample sizes of target and non-target fingers, respectively.

To calculate the one-tailed P-value, the cumulative distribution function (CDF) of the t-distribution was used:

$$\mathrm{P} = \mathrm{P}(\ \mathrm{T} \geq \mathrm{t}) = 1 - \mathrm{tcdf}(\mathrm{t}, \mathrm{df}) \tag{2}$$

where df represents the degrees of freedom, calculated as:

$$\mathrm{df} = \frac{\left(\frac{\mathrm{s}_\mathrm{t}^2}{\mathrm{n}_\mathrm{t}} + \frac{\mathrm{s}_\mathrm{n}^2}{\mathrm{n}_\mathrm{n}}\right)^2}{\frac{\left(\frac{s_\mathrm{t}^2}{\mathrm{n}_\mathrm{t}}\right)^2}{\mathrm{n}_\mathrm{t}-1} + \frac{\left(\frac{\mathrm{s}_\mathrm{n}^2}{n_n}\right)^2}{\mathrm{n}_\mathrm{n}-1}} \tag{3}$$

Statistical analysis revealed that the movement angles of all target fingers in both flexion and extension modes were significantly higher than those of non-target fingers ($p < 0.05$). Table 2 summarizes the T-test results, confirming the effectiveness of the system in achieving independent single-finger control.

Table 2. P-values for flexion and extension angles of stimulated fingers.

Stimulated Finger	**Flexion P-value**	**Extension P-value**
Thumb	2.0000e–05	NaN
Index Finger	0.0029	0.0029
Middle Finger	0.0014	0.0037
Ring Finger	0.0030	0.0072
Little Finger	0.0041	0.0012

3.4. Specific finger movement control

In addition to experiments on independent single-finger control, we evaluated the FESGlove's capability to stimulate multiple fingers simultaneously for more complex hand movements. Figure 14 illustrates the opposition movement achieved by the simultaneous flexion of the thumb and little finger, while Figure 15 shows a similar movement for the thumb and middle finger. These experiments were conducted on the same group of participants, using optimized stimulation parameters to elicit the targeted movements.

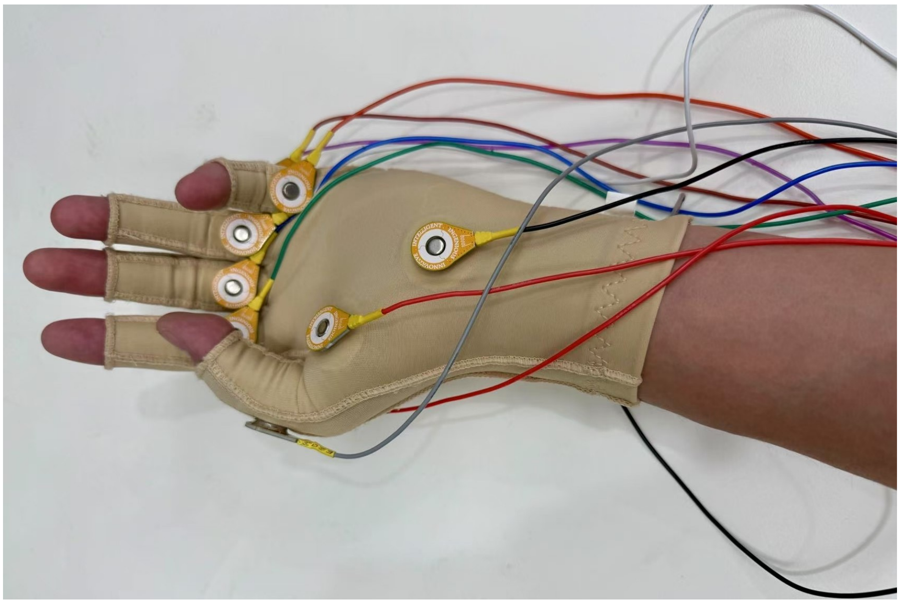

Figure 14. An image of a participant performing the thumb-to-little finger opposition movement.

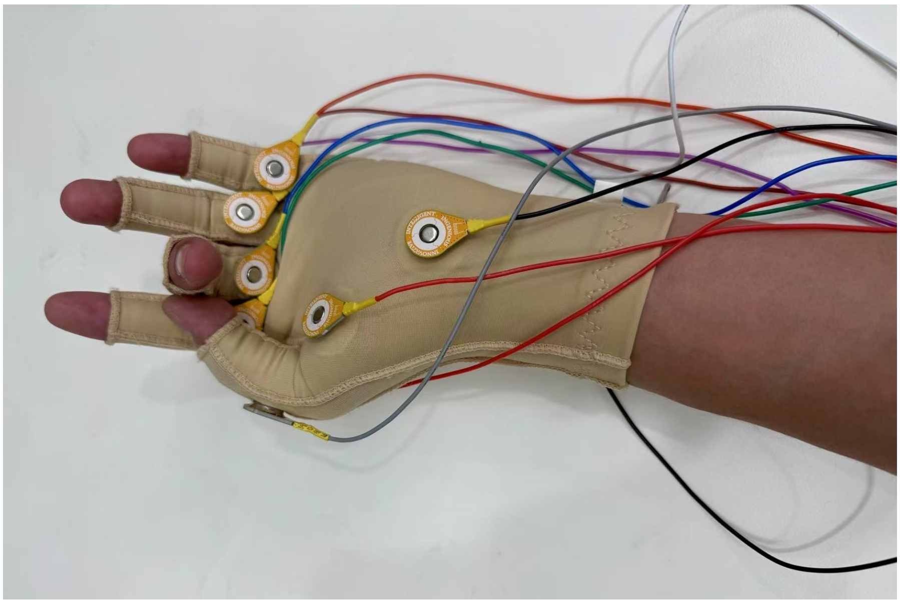

Figure 15. An image of a participant performing the thumb-to-middle finger opposition movement.

The experimental results demonstrate that FESGlove is capable of coordinating multi-finger movements, enabling users to perform functional and relatively complex specific hand gestures. These findings further validate the potential of FESGlove in hand rehabilitation and the restoration of fine motor skills.

3.5. Comprehensive evaluation of system performance

The experimental results demonstrate the following key features of the FESGlove's performance in controlling independent finger movements:

High Selectivity: The movement amplitudes of target fingers were significantly greater than those of non-target fingers in both flexion and extension modes (Figures 10–13). This is attributed to the precision of the multi-channel stimulation system and the optimized design of the electrode glove.

Adaptability to Individual Differences: Despite variations in hand anatomy and sensitivity to stimulation among participants, the system's adjustable parameters enabled effective adaptation to different users.

Comfort and Stability: All participants reported a comfortable experience during the stimulation process, with only one participant (Participant 4) noting mild pricking sensations.

Overall, the results validate the FESGlove's functionality and selectivity. Additionally, the findings provide valuable insights for further optimization of electrode design and stimulation algorithms.

4. Discussion

This study developed a portable, multi-channel, and parameter-adjustable functional electrical stimulation (FES) system, combined with a silver fiber-based electrode glove. The aim was to achieve precise, independent movement control of individual fingers by selectively stimulating the small muscles and nerves associated with hand and finger movements. This section provides an in-depth discussion of the study's findings, highlights the advantages and limitations of the proposed system, and outlines potential directions for future research.

4.1. Comparison with existing studies

To comprehensively assess the significance and advantages of the proposed multi-channel FES system, a comparison with existing research on FES-induced independent finger motion was conducted. Table 3 summarizes key methods and outcomes of related studies, highlighting their limitations, such as poor selectivity, limited control of individual fingers, and undesired finger coupling effects.

While previous studies demonstrated partial success in stimulating selective finger movements, issues such as finger coupling, inconsistent movement amplitudes, and poor adaptability to individual differences remain prevalent. In contrast, the proposed system, through its high-density electrode glove and adjustable stimulation parameters, achieves significantly improved selectivity and reduces unintended finger motion. This improvement is further validated by experimental results presented in Section 3, where target fingers exhibit consistently larger movement amplitudes compared to non-target fingers.

Table 3. Comparison of methods and results for FES-induced independent finger motion control.

Study Title	Methods for Stimulating Independent Finger Motion	Results and Limitations
FESleeve: A Functional Electrical Stimulation System with Multi-electrode Array for Finger Motion Control [37]	12 × 4 multi-electrode array with auto-calibration algorithm to enhance selectivity and target forearm muscles.	Achieved selective motion for most fingers, but finger coupling issues remain, especially for index and middle fingers.
Electrode Placement on the Forearm for Selective Stimulation of Finger Extension/Flexion [15]	Electrode positions tested across a 400-point grid system with monophasic pulses under varying forearm postures.	Selective stimulation achieved for most fingers; thumb and little finger demonstrated limited control.
A Functional Electrical Stimulation System of High-Density Electrodes With Auto-Calibration for Optimal Selectivity [17]	32-channel high-density electrode array with auto-calibration algorithm optimizing stimulation parameters.	Selective control achieved for at least three fingers; finger coupling issues persisted, particularly in stroke patients.
Selectivity and Resolution of Surface Electrical Stimulation for Grasp and Release [14]	Surface electrodes targeting EDC, FPL, and thenar muscles with selective range measurements.	Selective middle finger and thumb stimulation achieved; limited success for small fingers and high variability among subjects.
Voluntary and FES-Induced Finger Movement Estimation Using Muscle Deformation Features [38]	Forearm muscle deformation measured using A-mode ultrasound combined with FES stimulation.	Accurate estimation of FES-induced motion; finger coupling persists, limiting full independent control.
Selective Drive and Control of Index Finger Joint Using Multipoint Functional Electrical Stimulation [39]	Simultaneous multi-point stimulation with optimized voltage intensity and phase difference targeting finger flexor muscles.	Successfully achieved significant torque for independent index finger motion; however, precise parameter settings and electrode placement are critical for optimal performance.
FESGlove: A Glove of Functional Electrical Stimulation with Good Selectivity for Finger Motion Control	10 individually programmable channels delivering localized stimulation to intrinsic hand muscles via glove-integrated electrodes.	Experimental results indicate that the proposed FESGlove can achieve selective activation of individual fingers, despite some degree of coupling observed in adjacent fingers.

4.2. Advantages of the system

The FESGlove system offers significant advancements over existing functional electrical stimulation technologies, addressing critical challenges in selectivity, adaptability, and user experience for hand rehabilitation.

Efficient Independent Finger Control: Experimental results demonstrated the system's capability to selectively stimulate the target finger, yielding significantly higher movement angles than non-target fingers ($p < 0.05$ in t-tests). By optimizing the stimulation parameters and electrode placement, we enabled most participants to exhibit stable and precise flexion and extension movements of the target finger. This high level of selectivity was achieved through the system's multi-channel architecture and the precision of the silver fiber electrode glove.

Customizable Stimulation Parameters: The system supports user-specific adjustments of key parameters, including frequency, current amplitude, and pulse width, to accommodate individual differences in muscle and nerve response. Incremental increases in current amplitude during the experiments effectively minimized discomfort or pain caused by overstimulation. Through experimental validation, the combination of a fixed pulse width of 500 μs and a frequency of 35 Hz was found to be a suitable configuration for most participants, aligning closely with the parameter ranges reported in previous studies [40–42].

Silver Fiber-Based Electrode Glove: The custom-designed electrode glove integrates silver fiber fabric with hydrogel electrodes, offering superior wearability, comfort, and stimulation efficiency. The silver fiber fabric is both soft and highly conductive, ensuring close contact with the skin and efficient transmission of stimulation signals. The integration of silver fiber fabric into electrode designs, as supported by studies highlighting its superior conductivity, improved skin-electrode impedance, and enhanced user comfort compared to traditional electrodes, has been well-documented in recent research [43–45]. Furthermore, hydrogel electrodes can provide more stable stimulation currents. The combination of these two materials balances wearability, convenience, and effective stimulation, making the system more suitable for practical applications.

4.3. Limitations of the system

Despite its promising performance, the FESGlove system has several limitations that warrant further investigation and optimization to enhance its effectiveness and practicality.

Electrode-Skin Interface Issues: Due to the differences in hand size and proportions among participants, in some experiments, the flexible silver fiber electrodes showed inconsistent skin contact, resulting in uneven current distribution and suboptimal stimulation. This issue highlights the need for improved electrode materials and attachment methods. Additionally, designing electrode gloves in multiple sizes could better accommodate users with varying hand shapes and sizes, ensuring stable skin contact.

Non-Target Finger Coupling: Although the system effectively minimized unintended stimulation of non-target fingers, some participants exhibited finger coupling effects. This phenomenon is likely due to the inherent physiological and anatomical structure of the hand, where shared tendons and muscles contribute to finger interdependence.

Force Limitations Due to Small Muscle Stimulation: Another limitation of this study is that the force generated by stimulating finger movements is relatively small compared to previous studies. This is because earlier studies placed electrodes on the forearm to stimulate larger muscle groups, while our study focused on stimulating smaller intrinsic hand muscles, which inherently produce less force. While this approach enhances the selectivity of stimulation and reduces unintended finger coupling, it also limits the strength of the resulting finger movements, which may pose challenges for tasks requiring high grip or pinch force.

Individual Differences in Response: The considerable variability in participants' responses to electrical stimulation, including limited flexion or extension movements and reduced sensitivity to electrical current, aligns with findings that individual differences in cortical excitability, sensory thresholds, and body composition significantly influence the effectiveness of stimulation protocols [46, 47]. This highlights the need for further optimization of personalized stimulation parameters and electrode configurations to better accommodate individual differences.

4.4. Future research directions

The development of the FESGlove represents a significant step toward achieving precise, independent finger control for neurorehabilitation. However, the current system also highlights several areas for improvement and further exploration. Future research should aim to address the limitations identified in this study while expanding the system's functionality to meet broader clinical and practical needs. By integrating advanced technologies and tailoring the system to diverse patient populations, the FESGlove has the potential to become a comprehensive solution for hand motor function recovery. This section outlines key directions for future research and development.

Expanding to Multi-Finger Coordination Control: Building on the success of independent finger control, future studies could explore multi-finger coordination, enabling complex hand functions such as grasping and pinching. Achieving this goal will require not only optimized electrode designs but also the integration of more advanced control algorithms.

Closed-Loop Feedback Control: In future versions, closed-loop feedback mechanisms could be introduced to improve individual adaptability and stability of stimulation effects. Real-time sensing of finger joint movement using IMUs, flex sensors, or surface EMG could enable the system to dynamically adjust stimulation intensity based on actual motor response. Similar strategies have been successfully applied in gait rehabilitation, where sensory feedback-driven stimulation increased ankle control precision during walking [48]. Additionally, optimization of stimulation parameters has proven effective in other neuromuscular systems, such as ocular muscle control for strabismus treatment [34], and could be adapted to enhance fine motor rehabilitation in the hand. Such closed-loop control may significantly enhance the robustness and personalization of the FESGlove system.

Integration with Exoskeleton Systems: Combining the FES system with wearable exoskeleton devices could provide mechanical assistance during neurorehabilitation training, enabling patients to perform more stable and precise functional movements. At present, there have been several studies on hybrid systems combining FES and exoskeletons applied to the lower limbs, as well as the elbow and wrist joints of the upper limbs. However, research focusing on the hand is relatively scarce [49, 50]. This hybrid approach shows great potential for improving the recovery of hand motor function.

Integration with Brain-Computer Interfaces: Building upon the high selectivity and adaptability of the developed FES system, future research could explore its integration with brain-computer interfaces (BCIs) to create a closed-loop rehabilitation framework. BCIs decode neural activity to interpret the user's motor intentions, which can then be used to guide the timing, intensity and selective stimulation channels of FES stimulation. This integration has the potential to enhance neurorehabilitation outcomes by aligning electrical stimulation with the patient's voluntary motor efforts, thereby reinforcing neural pathways through neuroplasticity. The FES with BCIs systems has made significant progress in recent studies, highlighting the potential of closed-loop frameworks in promoting neuroplasticity and improving rehabilitation outcomes [6, 51].

Clinical Trials and Patient Feedback: Future research should focus on conducting clinical trials with patients suffering from stroke, spinal cord injuries, and other neurological disorders to evaluate the system's practical efficacy. Incorporating patient-reported outcomes and feedback mechanisms could further enhance user experience and therapeutic effects.

5. Conclusion

The proposed system FESGlove demonstrated good selectivity and stability in controlling independent finger movements. The combination of a multi-channel, customizable stimulator and a silver fiber-based electrode glove enabled precise stimulation on muscles and nerves of individual fingers. The performance of FESGlove was verified via experiments on some healthy subjects. Satisfactory results show that FESGlove is a promising tool for hand rehabilitation or assistance in future.

Acknowledgments

This work was supported by the Intergovernmental Key Program of the National Key Research and Development Plan of China under Grant No. 2024YFE0198200. The authors would like to express their gratitude to all participants and colleagues who contributed to the development and evaluation of the FESGlove system.

Author's contribution

Zeyu Cai (Z.C.): conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft, visualization. Z.C. led the design and development of the FESGlove system, conducted experiments, performed data analysis, and prepared the manuscript draft. Wenlong Zhang (W.Z.): software, validation, writing—review & editing. Le Xue (L.X.): supervision, writing—review & editing. Dingguo Zhang (D.Z.): supervision, funding acquisition, writing-—review & editing.

Conflicts of interests

The authors declare no conflict of interest.

Ethical statement

This study was conducted in accordance with the ethical guidelines outlined by the University of Bath. Approval for the study was obtained from the University of Bath Ethics Committee (Approval ID: 1117–4790).

References

[1] Lang CE, Bland MD, Bailey RR, Schaefer SY, Birkenmeier RL. Assessment of upper extremity impairment, function, and activity after stroke: foundations for clinical decision making. *J. Hand Ther.* 2013, 26(2):104–115.

[2] Liu Y, Jiang L, Liu H, Ming D. A systematic analysis of hand movement functionality: qualitative classification and quantitative investigation of hand grasp behavior. *Front. Neurorob.* 2021, 15:658075.

[3] Wolbrecht ET, Rowe JB, Chan V, Ingemanson ML, Cramer SC, *et al.* Finger strength, individuation, and their interaction: relationship to hand function and corticospinal tract injury after stroke. *Clin. Neurophysiol.* 2018, 129(4):797–808.

[4] Gu Y, Xu Y, Shen Y, Huang H, Liu T, *et al.* A review of hand function rehabilitation systems based on hand motion recognition devices and artificial intelligence. *Brain Sci.* 2022, 12(8):1079.

[5] Wang H, Arceo R, Chen S, Ding L, Jia J, *et al.* Effectiveness of interventions to improve hand motor function in individuals with moderate to severe stroke: a systematic review protocol. *BMJ open* 2019, 9(9):e032413.

[6] Khan MA, Fares H, Ghayvat H, Brunner IC, Puthusserypady S, *et al.* A systematic review on functional electrical stimulation based rehabilitation systems for upper limb post-stroke recovery. *Front. Neurol.* 2023, 14:1272992.

[7] Ting WKC, Fadul FAR, Fecteau S, Ethier C. Neurostimulation for stroke rehabilitation. *Front. Neurosci.* 2021, 15:649459.

[8] Shenzhen XFT Medical. XFT-2003EA H2 hand function rehabilitation device. Available: https://www.xft-china.com (accessed on 28 December 2024).

[9] Bioness Inc. H200 Wireless hand rehabilitation system. Available: https://www.bionessuniversity.com (accessed on 28 December 2024).

[10] Rehabtronics Inc. ReGrasp neurorehabilitation system. Available: https://www.rehabtronics.com (accessed on 28 December 2024).

[11] Ahn W, Kim D, Park J, Park JH, Lee T, *et al.* A reconfigurable neural stimulation IC with a high-resolution strength control and in-situ neural recording function for cochlear implant systems. *IEEE Solid-State Circuits Lett.* 2022, 5:162–165.

[12] Eom K, Park M, Lee HS, Ku SB, Kim N, *et al.* A low-stimulus-scattering pixel-sharing sub-retinal

prosthesis SoC with time-based photodiode sensing and per-pixel dynamic voltage scaling. *IEEE J. Solid-State Circuits* 2023, 58(11):2976–2989.

[13] Butz N, Kalita U, Manoli Y. Active charge balancer with adaptive 3.3 V to 38 V supply compliance for neural stimulators. *IEEE Trans. Circuits Syst. I Regul. Pap.* 2021, 68(10):4013–4024.

[14] Westerveld AJ, Schouten AC, Veltink PH, van der Kooij H. Selectivity and resolution of surface electrical stimulation for grasp and release. *IEEE Trans. Neural Syst. Rehabil. Eng.* 2011, 20(1):94–101.

[15] Bao X, Zhou Y, Wang Y, Zhang J, Lü X, *et al.* Electrode placement on the forearm for selective stimulation of finger extension/flexion. *PloS One* 2018, 13(1):e0190936.

[16] Muscolino JE. Muscles of the forearm and hand. In *Kinesiology: The Skeletal System and Muscle Function*, 3rd ed. St. Louis: Elsevier, 2017, pp. 181–236.

[17] Usman H, Zhou Y, Metcalfe B, Zhang D. A functional electrical stimulation system of high-density electrodes with auto-calibration for optimal selectivity. *IEEE Sens. J.* 2020, 20(15):8833–8843.

[18] Nathan R. FNS of the upper limb: targeting the forearm muscles for surface stimulation. *Med. Biol. Eng. Comput.* 1990, 28:249–256.

[19] Lung BE, Burns B. Anatomy, shoulder and upper limb, hand flexor digitorum profundus muscle. 2023. Available: https://www.ncbi.nlm.nih.gov/sites/books/NBK526046/ (accessed on 21 May 2025).

[20] Drake R, Vogl AW, Mitchell AW. *Gray's anatomy for students E-book*, 2nd ed. Amsterdam: Elsevier Health Sciences, 2009.

[21] Vargas Luna JL, Krenn M, Cortés Ramírez JA, Mayr W. Dynamic impedance model of the skin–electrode interface for transcutaneous electrical stimulation. *PLOS ONE* 2015, 10(5):e0125609.

[22] Huang C, Cai Y, Chen X, Ke Y. Silver-based nanocomposite for fabricating high performance value-added cotton. *Cellulose* 2022, 29(2):723–750.

[23] Liao S, Wang X, Hu Y, Zhu P, Sun R, *et al.* Flexible cellulose fibre/silver fabric for highly efficient and broadband EMI shielding via metal-organic decomposition approach. In *2023 24th International Conference on Electronic Packaging Technology (ICEPT)*, Shihezi City, China, August 08–11, 2023, pp. 1–4.

[24] Deng Z, Yu R, Guo B. Stimuli-responsive conductive hydrogels: design, properties, and applications. *Mater. Chem. Front.* 2021, 5(5):2092–2123.

[25] Marquez-Chin C, Popovic MR. Functional electrical stimulation therapy for restoration of motor function after spinal cord injury and stroke: a review. *Biomed. Eng. Online* 2020, 19(1):34.

[26] Sheffler LR, Chae J. Neuromuscular electrical stimulation in neurorehabilitation. *Muscle Nerve* 2007, 35(5):562–590.

[27] Popovic MR, Keller T, Papas I, Dietz V, Morari M. Surface-stimulation technology for grasping and walking neuroprostheses. *IEEE Eng. Med. Biol. Mag.* 2001, 20(1):82–93.

[28] Baker LL, Wederich C, Mcneal DR, Newsam CJ, Waters RL. *Neuro muscular electrical stimulation: a practical guide*, 4th ed. Downey: Los Amigos Research & Education Institute, 2000.

[29] Mayr W. Role of electrical parameters in functional electrical stimulation. In *Functional Electrical Stimulation in Neurorehabilitation: Synergy Effects of Technology and Therapy*,

1st ed. Cham: Springer, 2022, pp. 29–41.

[30] Baldwin ER, Klakowicz PM, Collins DF. Wide-pulse-width, high-frequency neuromuscular stimulation: implications for functional electrical stimulation. *J. Appl. Physiol.* 2006, 101(1):228–240.

[31] WitMotion Official Documentation. WT9011DCL Inertial Measurement Unit (IMU) sensor specification). Available: https://wit-motion.cn/proztwl/17.html (accessed on 8 January 2025).

[32] Pillemer DB. One-versus two-tailed hypothesis tests in contemporary educational research. *Educ. Res.* 1991, 20(9):13–17.

[33] Sun M, Smith C, Howard D, Kenney L, Luckie H, *et al.* FES-UPP: a flexible functional electrical stimulation system to support upper limb functional activity practice. *Front. Neurosci.* 2018, 12:449.

[34] Eom K, Lee HS, Park M, Yang SM, Choe JC, *et al.* Development of ocular muscle stimulation systems and optimization of electrical stimulus parameters for paralytic strabismus treatment. *IEEE Trans. Biomed. Eng.* 2025, 72(2):515–527.

[35] Lane JG, Gobbi A, Espregueira-Mendes J, Kaleka CC, Adachi N. *The Art of the Musculoskeletal Physical Exam*, 1st ed. Cham: Springer Nature, 2023.

[36] Lang CE, Schieber MH. Human finger independence: limitations due to passive mechanical coupling versus active neuromuscular control. *J. Neurophysiol.* 2004, 92(5):2802–2810.

[37] Shao T, Li X, Yokoi H, Zhang D. FESleeve: a functional electrical stimulation system with multi-electrode array for finger motion control. In *Intelligent Robotics and Applications: 9th International Conference, ICIRA 2016*, Tokyo, Japan, August 22–24, 2016, pp. 191–199.

[38] Zhou Y, Zeng J, Li K, Fang Y, Liu H. Voluntary and FES-induced finger movement estimation using muscle deformation features. *IEEE Trans. Ind. Electron.* 2019, 67(5):4002–4012.

[39] Hamana T, Kawashima M, Sakaino S, Tsuji T. Selective drive and control of index finger joint using multipoint functional electrical stimulation. *IEEE Access* 2022, 10:112444–112459.

[40] Moreira M, Bó APL. Muscle fatigue and the importance of electrical stimulation parameters on functional electrical stimulation. In *XXVI Brazilian Congress on Biomedical Engineering: CBEB 2018*, Armação de Buzios, Brazil, October 21–25, 2019 pp. 307–313.

[41] Gorgey AS, Mahoney E, Kendall T, Dudley GA. Effects of neuromuscular electrical stimulation parameters on specific tension. *Eur. J. Appl. Physiol.* 2006, 97:737–744.

[42] Bickel CS, Gregory CM, Dean JC. Motor unit recruitment during neuromuscular electrical stimulation: a critical appraisal. *Eur. J. Appl. Physiol.* 2011, 111:2399–2407.

[43] Song J, Zhang Y, Yang Y, Liu H, Zhou T, *et al.* Electrochemical modeling and evaluation for textile electrodes to skin. *Biomed. Eng. Online* 2020, 19:1–27.

[44] Hasan MM, Hossain MM. Nanomaterials-patterned flexible electrodes for wearable health monitoring: a review. *J. Mater. Sci.* 2021, 56(27):14900–14942.

[45] Zhou H, Lu Y, Chen W, Wu Z, Zou H, *et al.* Stimulating the comfort of textile electrodes in wearable neuromuscular electrical stimulation. *Sensors* 2015, 15(7):17241–17257.

[46] Witkoś J, Hartman-Petrycka M, Błażejewski G. The effects of sex, women's body composition and monthly cycle phases on the sensory threshold of upper limb to transcutaneous electrical nerve stimulation in healthy subjects. *Appl. Sci.* 2023, 13(14):8365.

[47] Krause B, Cohen Kadosh R. Not all brains are created equal: the relevance of individual differences in responsiveness to transcranial electrical stimulation. *Front. Syst. Neurosci.* 2014, 8:25.

[48] Shon A, Brakel K, Hook M, Park H. Closed-loop plantar cutaneous augmentation by electrical nerve stimulation increases ankle plantarflexion during treadmill walking. *IEEE Trans. Biomed. Eng.* 2021, 68(9):2798–2809.

[49] Gil-Castillo J, Herrera-Valenzuela D, Torricelli D, Gil-Agudo Á, Opisso E, *et al.* A new modular neuroprosthesis suitable for hybrid FES-robot applications and tailored assistance. *J. NeuroEng. Rehabil.* 2024, 21(1):153.

[50] Dunkelberger N, Berning J, Schearer EM, O'Malley MK. Hybrid FES-exoskeleton control: using MPC to distribute actuation for elbow and wrist movements. *Front. Neurorob.* 2023, 17:1127783.

[51] Brunner I, Lundquist CB, Pedersen AR, Spaich EG, Dosen S, *et al.* Brain computer interface training with motor imagery and functional electrical stimulation for patients with severe upper limb paresis after stroke: a randomized controlled pilot trial. *J. NeuroEng. Rehabil.* 2024, 21(1):10.