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Therapeutic and orthotic effects of an adaptive functional electrical stimulation system on gait biomechanics in participants with stroke

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Abstract

Background: In recent years, functional electrical stimulation (FES) has become a common intervention for stroke survivors to correct foot drop and improve gait biomechanics. While the orthotic effects of adaptive FES systems were well-documented, the center of pressure (COP) symmetry has been largely neglected. Furthermore, the long-term therapeutic effects of adaptive FES systems on gait biomechanics have received less attention.

Methods This study applied a timing- and intensity-adaptive functional electrical stimulation system for evaluation and training tests to address these limitations. In the evaluation test, eight participants with chronic stroke walked under three FES conditions: no stimulation (NS), adaptive FES to the tibialis anterior (SA-ILC SCS), and hybrid adaptive FES to the tibialis anterior and the gastrocnemius (SA-ILC DCS). Nine healthy subjects walked under the NS condition as the control group. In the training test, two participants with stroke took part in a 21-day training session under the SA-ILC DCS condition.

Results: The results showed that the COP symmetry of participants with stroke in the SA-ILC SCS condition tended to improve compared to the NS condition, while the SA-ILC DCS condition showed significant improvement, approaching that of healthy subjects. After the 21-day treatment period, there was a tendency for improvement in the knee-ankle angle, anterior ground reaction force, and COP symmetry of both participants with stroke without assistance.

Conclusion: The observed improvements can be attributed to the hybrid adaptive FES targeting the tibialis anterior and gastrocnemius muscles. This study demonstrates that the adaptive FES system offers promising walking assistance capabilities and significant clinical therapeutic potential.

Trial registration Ethics Committee of Zhujiang Hospital, Southern Medical University, 2022-KY-149-01. Registered 29 September 2022.

Keywords Functional electrical stimulation, Stroke, Hemiplegic gait, Center of pressure, Gait symmetry, Orthotic effect, Therapeutic effect

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Background

Stroke is an acute cerebrovascular disease with a high mortality and disability rate, which poses a severe threat to human life and health [1]. Hemiplegic gait is a common sequela characterized by weakness or spasticity in the affected limb and a loss of muscle control [2]. At the ankle level, the most common manifestations of the injury are lack of foot clearance during the swing and reduced forward propulsion during late stance [3]. Furthermore, the damage to the ankle muscles can result in compensatory actions involving other parts of the body [4]. For instance, individuals may lean on the unaffected limb to maintain balance and facilitate forward movement [5]. These disturbances can decrease walking speed and stability, induce asymmetric gait, and elevate the risk of falls [6, 7]. Consequently, identifying appropriate intervention methods to correct and treat hemiplegic gait is vital.

Functional Electrical Stimulation (FES) is a common intervention technique to correct hemiplegic gait, which transmits control signals from external devices to the neuromuscular system to activate muscles [8]. In 1961, Liberson et al. first applied FES to increase dorsiflexion angle during the swing phase in participants with stroke [9]. Since then, numerous FES systems have been developed to assist participants with stroke by correcting foot drop [10], enhancing push-off at the terminal stance phase [11], and improving knee [12] or hip control [13]. To address the highly nonlinear and time-varying nature of the stimulated muscle, researchers have developed several closed-loop control strategies, including finite state machines [14], artificial neural networks [15], fuzzy logic [16], and Iterative Learning Control (ILC) [10]. Among these, ILC has gained widespread application due to its ability to improve system performance through repeated trials by learning from previous iterations [17]. In ILC, control inputs are updated based on the error between the actual output and the desired output from the previous iteration, enabling the system to progressively reduce errors with each cycle. Building on this iterative learning process, ILC offers fast convergence, stable tracking performance, and robustness to external disturbances, making it particularly effective for optimizing neuromuscular control. However, most of these studies concentrate on the immediate orthotic effects of FES, neglecting the neuromuscular system's capacity for enduring adaptation. Long-term use of FES can result in physiological changes, which may also affect motor performance in the absence of FES usage, and this carry-over effect is frequently termed the therapeutic effect [18]. Some studies recruited groups of participants with chronic stroke for more than four weeks of FES training, consistently observing improvements in gait performance [19–21]. FES has also been found to be an effective alternative to ankle foot orthosis for treating foot drop after stroke in other studies [22, 23]. Nonetheless, these studies often used basic open-loop FES systems with preset and fixed stimulus parameters, including pulse frequency, width, and current amplitude. These parameters cannot be dynamically adjusted to accommodate the physiological changes in participants with stroke after daily training, thus hindering the attainment of the optimal therapeutic effect. This makes the exploration of long-term training under closed-loop FES a worthwhile endeavor.

The effectiveness of FES systems in a clinical context can be assessed by analyzing various gait parameters. Regarding orthotic effects, researchers found that FES helped increase walking speed [24], reduce energy expenditure [25], increase knee-ankle angle [26], and change spatiotemporal characteristics [27]. In terms of therapeutic effects, many studies have demonstrated the effectiveness of FES in improving gait speed [20, 28]. FES also exhibited a positive therapeutic effect on additional activity-related parameters, including walking independence [19], walking distance [22], physiological cost index [20], and other variables. In addition to the above gait functions, after six weeks of FES training, Kesar et al. [21] found an improvement in gait biomechanics, including paretic propulsion and swing phase knee flexion. However, most of these studies focused on rehabilitating the affected limb to match the capabilities of non-disabled individuals, overlooking gait asymmetry caused by limb compensation. Center of pressure (COP) represents the cumulative neuromuscular response that controls the movement of the center of mass and is often utilized to evaluate balance control, gait deficits, and orthotic effect [29–31]. During the stance phase, the anteroposterior (AP) COP trajectory provides specific information that governs the forward progression of the center of mass. The medial-lateral (ML) COP movement mainly reflects the control process for regulating lateral stability during the single stance phase and the ability to shift weight between limbs during the double stance phase [29]. Nolan et al. [31] and Francis et al. [32] found that stimulating muscles like the tibialis anterior (TA) and gastrocnemius (GAS) could promote the anteroposterior movement of the center of pressure. Bamber et al. observed that stimulation of the peroneus longus muscle improved the lateral center of pressure during the stance phase [33]. Although applying functional electrical stimulation to ankle joint muscles can improve the center of pressure in previous studies, few of them considered the changes in symmetry after FES intervention.

In the previous research, we developed a hybrid adaptive functional electrical stimulation system [11]. Building upon this foundation, this study conducted extended evaluations. The orthotic effect of FES on COP symmetry, which is important for maintaining balance control while walking, was examined. Moreover, the therapeutic effect of the adaptive FES was studied by assessing improvements in gait biomechanics. We hypothesize that activating specific muscles in participants with stroke can facilitate the movement of the center of pressure on the hemiplegic side, improving gait symmetry. Furthermore, prolonged FES training might induce muscle strength and nerve excitability alterations, ultimately achieving therapeutic benefits.

Methods

Subjects

8 participants with chronic stroke (7 males and 1 female, Table 1) diagnosed with symptoms of foot drop were recruited for the study. Subject 1 and Subject 2 participated in a 21-day training session simultaneously. The inclusion criteria were as follows: (1) All participants with stroke were between 18 and 70 years of age, with a minimum stroke duration of 6 months. (2) The Fugl-Meyer motor assessment of lower extremity (FMA-LE) was conducted by physical therapists in the hospital, and the score was required to be $\geq$ 20 points. (3) The subjects possessed healthy nerves, neuromuscular junctions, muscle tissues, and a sufficient range of motion in dorsiflexion and plantarflexion. (4) The subjects could walk independently on a treadmill for at least 2 min without experiencing adverse reactions to FES. Meanwhile, 9 healthy subjects (3 males and 6 females), with an average age of 24 (±3.84) years, were recruited to serve as a control group. Before the experiment, all subjects were informed of the experimental protocol and signed an informed consent form. The Ethics Committee of Zhujiang Hospital, Southern Medical University, approved this study.

Experimental system

Figure 1 shows the experimental equipment in this study which includes a commercial treadmill (G6425-F3, Besterji Hermanos, Spain), a motion capture system (Optitrack, Natural Point, USA), four three-dimensional force sensors (Obatel Automation Equipment, Suzhou, China), a functional electrical stimulator (P2-9632, Fisco, China), and a plantar pressure sensor (B-201, Tekscan, USA). The three-dimensional force sensors measured ground reaction forces in three directions. At the same time, the motion capture system was utilized to quantify the instantaneous velocity of gait and joint angles. The plantar pressure sensor also detected heel state and segment gait cycles. A body weight support system and a safety strap were implemented to mitigate the risk of falls.

This study mainly involved three electrical stimulation modes: no stimulation (NS), adaptive FES applied to the TA during the swing phase (SA-ILC SCS), and hybrid adaptive FES applied to both the TA during the swing phase and the GAS during the stance phase (SA-ILC DCS). As in our previous study, the stimulation durations for both muscles were determined based on specific linear models and the current walking speed [34].

$$y_k(i) = \alpha_k v_i + \beta_k \tag{1}$$

where v_i represents the walking speed measured in real time, and k=1,2,3, the coefficients are defined as: $\alpha_1 = -286.8$, $\beta_1 = 541.6$, $\alpha_2 = -111.7$, $\beta_2 = 416.9$, $\alpha_3 = -213.2$, and $\beta_3 = 877.7$. When a heel-strike event occurs, the electrical stimulation of the GAS is triggered after a delay of $y_1(i)$, and the stimulation ceases once the toes leave the ground. When the heel-off event is detected, the delay $y_2(i)$ triggers the electrical stimulation of the TA, and the stimulation stops after the time interval $y_3(i)$. In contrast to the fixed-time stimulation,

Table 1 BASIC INFORMATION OF SUBJECTS AFTER STROKE

No.	Gender	Age	Lesion side	Months after stroke	FMA-LE	MCTS(km/h)
1*	M	62	R	23	20/34	2.0
2*	M	66	L	7	24/34	0.8
3	M	53	R	15	27/34	1.0
4	M	24	L	17	24/34	0.8
5	M	59	L	19	24/34	0.9
6	M	58	R	15	27/34	2.4
7	M	67	L	32	22/34	1.3
8	F	22	R	6	26/34	0.8
avg	–	51.5	–	16.8	24.3/34	1.225
std	–	18.2	–	8.4	2.4/34	0.587

M male, *F* female, *L* left, *R* right, *FMA-LE* Fugl-Meyer assessment for lower extremity, *MCTS* maximum comfortable treadmill speed

*represents long-term subjects

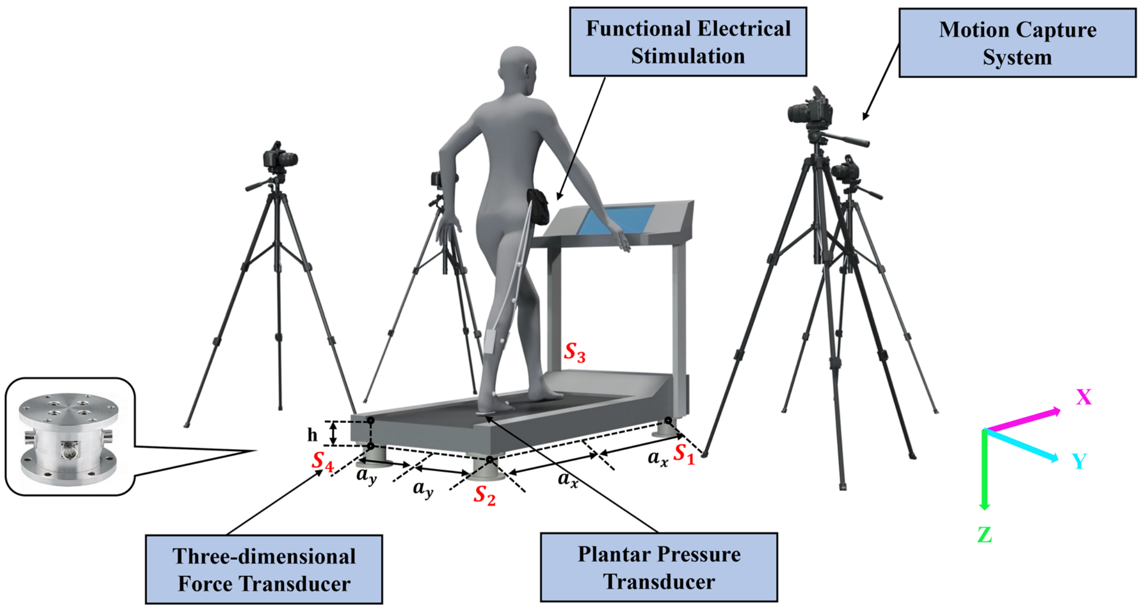

Fig. 1 The structure diagram of the adaptive FES system. The arrows indicate the positive directions of the three-dimensional force sensors, while S_i $(i = 1, 2, 3, 4)$ represents the *i*-th sensor

the speed-adaptive stimulation mode aligns more closely with the dynamic nature of muscles [34].

The iterative learning algorithm adjusted the stimulation intensity of the TA according to the maximum ankle dorsiflexion angle error observed during the previous swing phase, and the stimulation intensity of the GAS was adjusted iteratively based on the peak anterior ground reaction force error during the stance phase.

$$U_k(i) = T_k \cdot (U_k(i-1) + L_k \cdot e_k) \tag{2}$$

$$T_k = \begin{cases} \underline{I_k}, \ I < \underline{I_k}; \\ I, \ \ \underline{I_k} < I < \overline{I_k}; \\ \overline{I_k}, \ I > \overline{I_k}; \end{cases} \tag{3}$$

where $U_k(i)$ represents the controller's output stimulation intensity, e_k is the angle or force error of the previous gait cycle, and L_k denotes the learning parameter. $\overline{I_k}$ and $\underline{I_k}$ represent the upper and lower thresholds of stimulus intensity, respectively.

Experimental protocol

1) Evaluation test: The maximum comfortable treadmill speed (MCTS) was established as the fastest pace at which subjects could walk without assistance, following the method by Chaewon et al. [35]. Before the evaluation test, both stroke and healthy subjects walked on a treadmill for 5-7 min to determine the MCTS. Then, healthy subjects walked without any intervention, while participants with stroke were instructed to walk under NS, SA-ILC SCS, and SA-ILC DCS conditions. Each condition was performed three trials, with each trial lasting at least two minutes. The order of the trials was randomized. After each experiment, a 2-minute rest period was allowed to avoid muscle fatigue caused by electrical stimulation. Kinetic data were collected to calculate COP trajectories and evaluate the effect of different FES conditions on gait symmetry in participants with stroke.

2) Training test: The training protocol is shown in Fig. 2. The two participants with stroke completed a 21-day training program over four weeks. Prior to starting the long-term rehabilitation training, subjects underwent an initial assessment to determine their baseline MCTS. As training progressed, subjects' physical characteristics and muscle conditions changed, necessitating daily MCTS measurements [36]. Each day began with an assessment session, followed by an FES training session. During the assessment session, subjects walked at the daily MCTS without electrical stimulation, completing a total of three assessment trials, each lasting about two minutes. In the FES training session, subjects performed continuous walking exercises at the daily MCTS under the SA-ILC DCS condition, completing a total of three training trials, each lasting about four minutes. Kinematic and kinetic data from the assessment sessions were recorded to determine the overall improvement in gait following training.

AS Assessment session FTS FES training session

Stages of training	Pre-training Day0	Mid-training Day1 Day2 …Day19		Post-training Day20
Training sessions	AS	AS	FTS	AS

Fig. 2 Scheme of the training test

Data analysis

All data were imported into MATLAB (MathWorks, USA) for analysis. The kinematic data, measured by the motion capture system, were sampled at 100Hz and filtered using a second-order low-pass Butterworth filter with a cutoff frequency of 15Hz. The three-dimensional force sensors recorded the kinetic data at a sampling frequency of 1000Hz, and a sixth-order low-pass Butterworth filter with a cutoff frequency of 10Hz was applied to process the kinetic signals. Force data collected during unloaded treadmill running were subtracted to eliminate interference from treadmill weight and noise. The denoised data were then calibrated and summed to obtain the ground reaction forces in three directions, as described in the study by Belli et al. [37]. Finally, joint angles and the anterior ground reaction force were calculated, averaged over multiple consecutive steps in each experiment, and normalized to represent 100% of the gait cycle [11].

The center of pressure was determined using the formula proposed by Schmiedmayer et al. [38].

$$F_x = \sum_{i=1}^{4} F_{i,x}, \quad F_y = \sum_{i=1}^{4} F_{i,y}, \quad F_z = \sum_{i=1}^{4} F_{i,z} \tag{4}$$

$$x_{cop} = \frac{-F_x * h + a_x * (F_{z1} - F_{z2} + F_{z3} - F_{z4})}{F_z} \tag{5}$$

$$y_{cop} = \frac{-F_y * h - a_y * (-F_{z1} - F_{z2} + F_{z3} + F_{z4})}{F_z} \tag{6}$$

where $F_{i,j}$ $(i = 1, 2, 3, 4; j = x, y, z)$ represents the force components measured by the S_i sensor in the x, y, and z directions, as shown in Fig. 1. The resultant force, $\vec{F} = [F_x,\ F_y,\ F_z]$, represents the total ground reaction force obtained by combining the measurements from all four sensors. a_x and a_y indicate half of the distance between the sensors along the x- and y-axes, respectively, while h represents the vertical distance between the sensors and the running belt. The coordinate $\vec{r}_{cop} = [x_{cop},\ y_{cop},\ -h]$ indicates the location of the center of pressure on the treadmill.

In treadmill walking, the center of pressure trajectory of a healthy subject typically exhibits a characteristic butterfly-shaped pattern and shows highly reproducible spatiotemporal parameters [39]. Due to variations in foot position across different gait cycles, the center of the COP trajectory may shift. Therefore, spatial normalization is required to align the COP trajectories of individual gait cycles. Specifically, the method involves subtracting the mean of the entire sequence from each data point in the X and Y coordinates of the single-cycle COP data. Finally, the mean of multiple spatially normalized single-cycle COP trajectories was computed and time-normalized to 100% of the gait cycle, reflecting the overall motion characteristics of the subject throughout the cycle.

The symmetry indexes were calculated using the ratio method:

$$SI = V_{non-paretic} / V_{paretic} \tag{7}$$

where SI represents lateral symmetry (LS) or anteroposterior symmetry (APS), and V represents COP width or COP length. The calculation methods for COP width and COP length are illustrated in Fig. 3. The closer the symmetry ratio is to 1.0, the greater the degree of symmetry.

As in the study by Lee et al., the COP trajectories of hemiplegic subjects exhibit various asymmetry patterns [40]. For statistical analysis, Patterson et al. recommend that the numerator should always be the larger of the two values, irrespective of the side of paralysis, to avoid skewing the results by values less than 1.0 [41]. In the statistical analysis, this study focuses solely on the magnitude of asymmetry, without considering its direction.

Statistical analysis

The statistical analyses were performed using SPSS 19 (SPSS, Inc., Chicago, IL, USA). The significance level was set at 0.05.

1) Evaluation Test: We calculated the mean COP parameters across 15 continuous gait cycles for each of the 8 participants with stroke and 9 healthy controls. These mean values were then used in statistical analyses

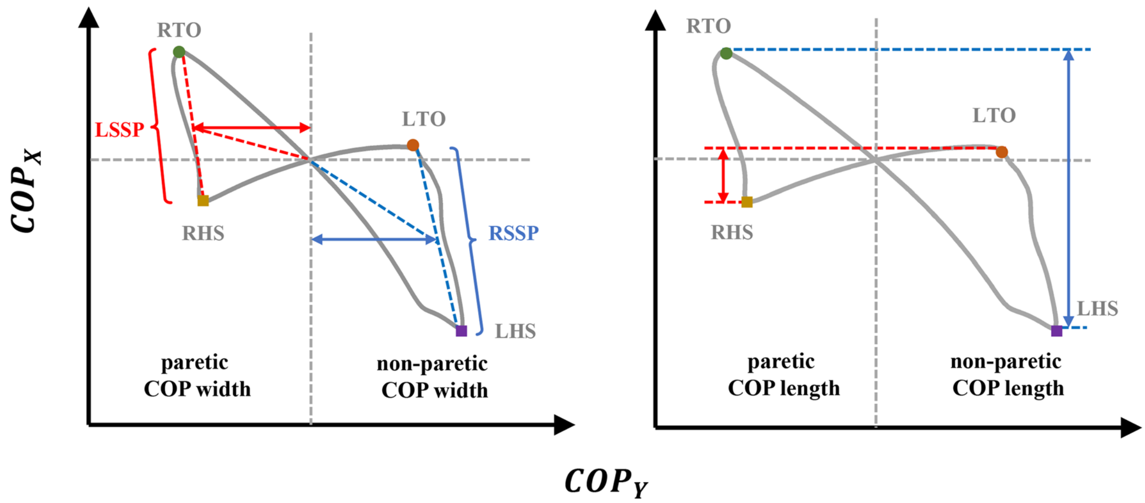

Fig. 3 Calculation method for COP parameters (left-side hemiplegia). The gray solid line represents the COP trajectory, with vertical segments indicating the single-support phase and diagonal segments representing the double-support phase. In the left panel, the red arrow shows the COP width on the paretic side, defined as the horizontal distance from the COP trajectory intersection to the midpoint of two consecutive gait events (toe-off to heel-strike of the same foot). The blue arrow indicates the COP width on the non-paretic side. In the right panel, the red arrow shows the COP length on the paretic side, defined as the vertical distance between two consecutive gait events (heel-strike to toe-off of the opposite foot). The blue arrow represents the COP length on the non-paretic side. *LHS* left heel-strike, *LTO* left toe-off; RHS: right heel-strike, *RTO* right toe-off, *LSSP* single-support phase of the left leg, *RSSP* single-support phase of the right leg

to assess group-level differences. The normality assumption for all data was assessed using Shapiro-Wilk tests. When normality was not satisfied, non-parametric tests were used. Specifically, the Friedman test was used within the stroke group to evaluate the main effect of different FES interventions on COP outcome variables. When a significant main effect was observed, post-hoc pairwise comparisons were conducted using Bonferroni-corrected multiple comparisons. Additionally, the Mann-Whitney U test was applied for pairwise comparisons between the stroke group (under different FES interventions) and the healthy control group to assess differences in COP outcome variables.

2) Training test: Statistical analyses were conducted separately for each subject, including 30–40 consecutive gait cycles per analysis. The normality assumption was evaluated using Shapiro-Wilk tests. When the normality assumption was met, Repeated Measures ANOVA was applied to compare the initial assessment (day 0) with subsequent sessions (days 5, 10, 15, and 20) to examine the main effect of training progress. When significant differences were found, post-hoc pairwise comparisons were conducted, with Bonferroni correction applied to control for multiple comparisons.

Results

Orthotic effect of FES in the evaluation test

Figure 4 shows the COP trajectories for three participants with stroke under three FES conditions, with healthy subjects serving as a control group. As shown in the figure, participants with stroke exhibit noticeable asymmetry without electrical stimulation. Under the SA-ILC SCS condition, gait asymmetry shows some improvement. Under the SA-ILC DCS condition, gait asymmetry demonstrates further improvement, with the COP trajectory of Subject 4 approaching that of the healthy control group.

Figure 5 illustrates the symmetry ratios of the COP trajectory for eight participants with stroke under three intervention conditions, with data from nine healthy controls. The results revealed significant differences in COP outcomes between different electrical stimulation conditions for stroke patients (LS, $\chi^2 = 9.000$, P = 0.011; APS, $\chi^2 = 7.750$, P = 0.021). Post-hoc pairwise comparisons showed that, compared to the NS condition, the SA-ILC SCS condition exhibited a trend towards improved lateral symmetry (LS) and anteroposterior symmetry (APS), although these improvements were not statistically significant (LS, P = 0.401; APS, P = 0.240). In contrast, the SA-ILC DCS condition significantly improved both LS and APS (LS, P = 0.008; APS, P = 0.018). Additionally, the stroke group under the NS condition showed significantly poorer LS and APS compared to the healthy control group (LS, U = 1.000, r = 0.816, P < 0.001; APS, U = 0.000, r = 0.840, P < 0.001). Under the SA-ILC SCS condition, the LS and APS of the stroke group remained significantly worse than those of the healthy control group (LS, U = 9.000, r = 0.630, P = 0.008; APS, U = 1.000, r

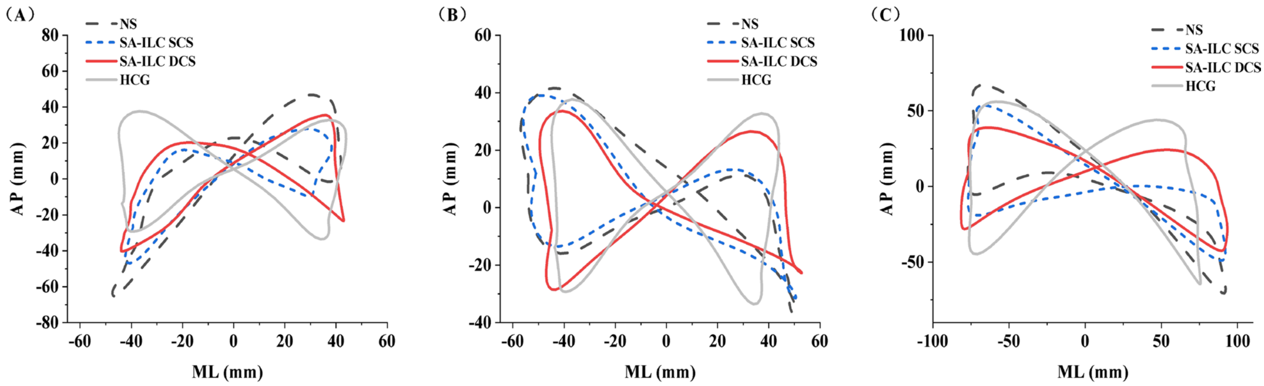

Fig. 4 Center of pressure trajectories for participants with stroke 3 (**A**), 4 (**B**), and 6 (**C**) under three FES conditions, compared with the healthy control (HCG)

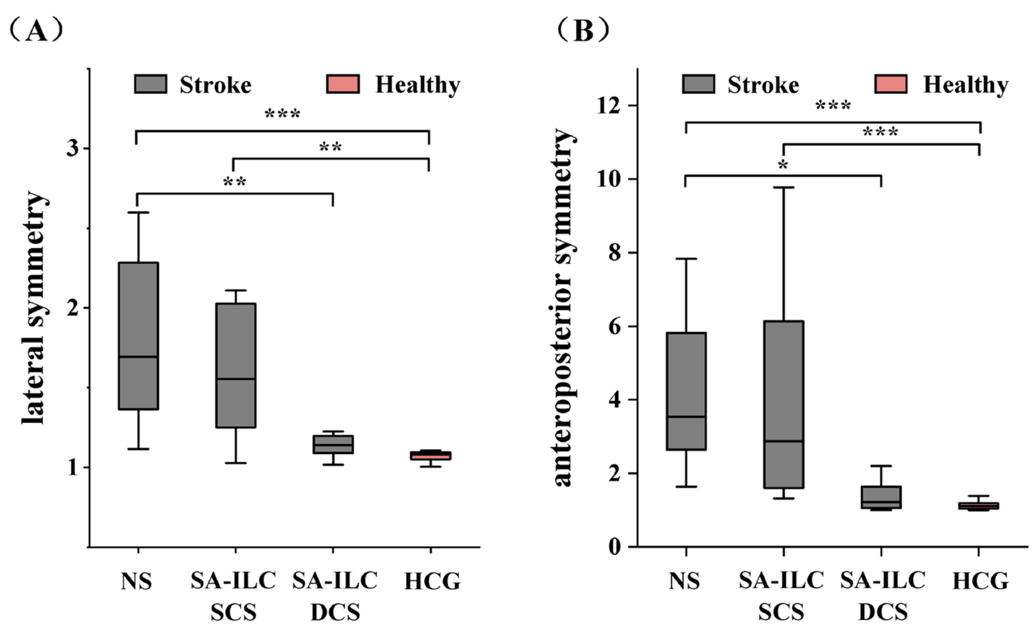

Fig. 5 Box plot of (**A**) lateral symmetry and (**B**) anteroposterior symmetry at different FES conditions. *HCG* healthy control group. Significant difference: *P <0.05, **P <0.01, ***P <0.001

= 0.815, P < 0.001). However, after applying the SA-ILC DCS condition, the symmetry ratios of the stroke group did not significantly differ from those of the healthy control group.

Therapeutic effect of FES in the training test

The therapeutic effects examined in this study were evaluated by comparing gait biomechanics across three stages: pre-training (day 0), mid-training (days 5, 10, 15), and post-training (day 20).

Figure 6 illustrates the improvements observed in post-training compared to pre-training without stimulation. For gait kinematics, Figs. 6A and 6B present the ankle and knee joint angles of Subject 1, while Figs. 6E and 6F show the corresponding angles for Subject 2. In terms of gait kinetics, anterior ground reaction force, normalized to body weight (BW), is depicted in Figs. 6C and 6G. Additionally, Figs. 6D and 6H demonstrate the changes in the COP trajectory for both subjects.

Figure 7 illustrates the changes in gait biomechanics of the two participants with stroke at different training stages. Figures 7A-7D show the trends in maximum ankle dorsiflexion during the swing phase, peak ankle plantarflexion, maximum knee flexion, and peak anterior ground reaction force. These gait parameters exhibited a consistent improvement trend in both subjects.

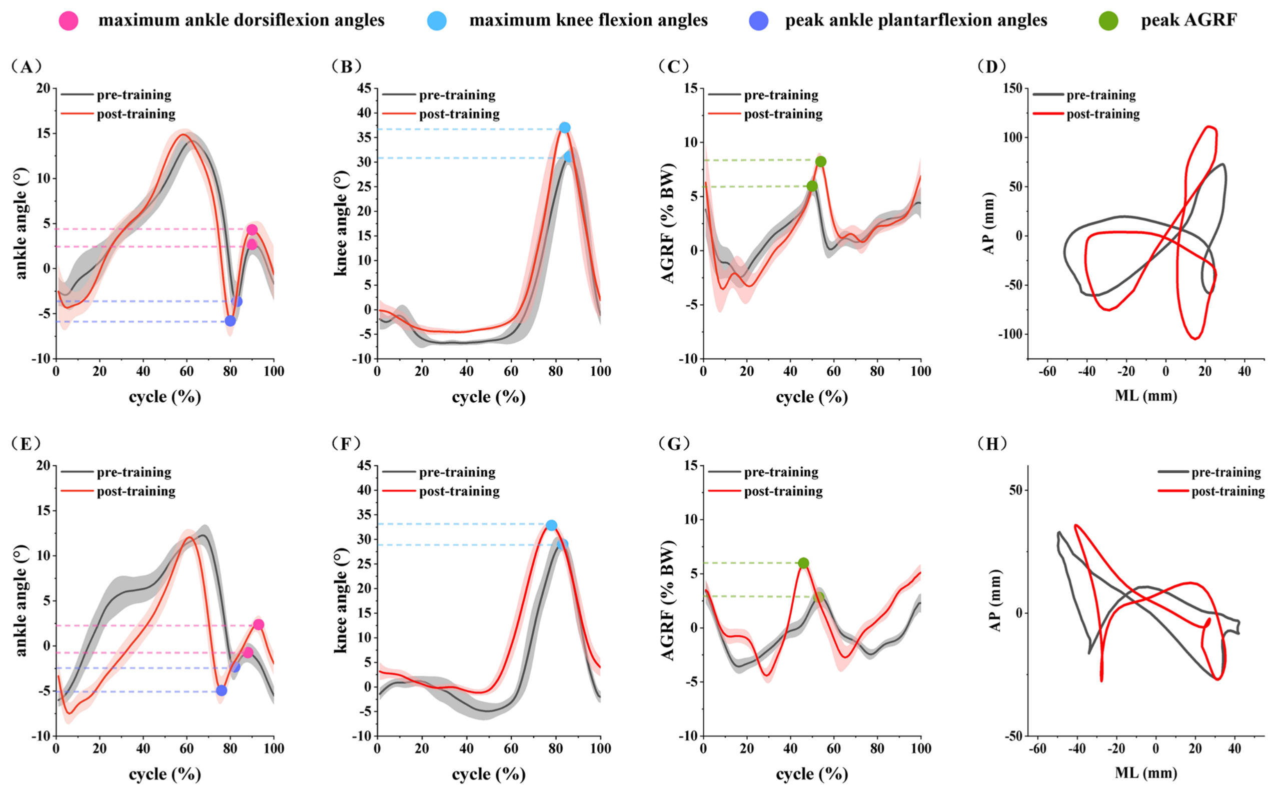

Fig. 6 Therapeutic effects from pre-training to post-training without FES: ankle angles (mean ± SD) for subject 1 (**A**) and subject 2 (**E**), knee angles (mean ± SD) for subject 1 (**B**) and subject 2 (**F**), anterior ground reaction force (mean ± SD) for subject 1 (**C**) and subject 2 (**G**), center of pressure (mean) for subject 1 (**D**) and subject 2 (**H**)

Figures 7E and 7F display the trends in lateral and anteroposterior symmetry, which gradually approached optimal levels following training with the adaptive FES system. These biomechanical changes align with the short-term orthotic effects observed.

Table 2 summarizes the changes in gait parameters from pre-training to post-training, along with the statistical significance and effect sizes (Cohen's *d*) of these changes. After 21 days of hybrid adaptive FES training, the two participants with stroke showed the following changes: the maximum ankle dorsiflexion increased by 1.61° and 3.04°, the peak ankle plantarflexion decreased by 1.89° and 2.52°, the maximum knee flexion increased by 6.07° and 3.94°, the peak anterior ground reaction force increased by 2.27% and 3.15%, lateral symmetry decreased by 1.22 and 0.65, and anteroposterior symmetry decreased by 0.51 and 2.09, respectively.

Discussion

This study aimed to evaluate the orthotic and therapeutic effects of an adaptive FES system on gait biomechanics in participants with stroke. Two significant findings were observed. The adaptive FES system can significantly enhance COP symmetry, assisting participants with stroke in better controlling their balance and enhancing stability when walking. Furthermore, the joint angles, anterior ground reaction force, and COP symmetry were improved through adaptive FES training, helping participants with stroke walk naturally without external assistance.

Orthotic effect of FES on COP symmetry

The COP trajectories of participants with stroke exhibited noticeable asymmetry compared to those of healthy subjects [40]. This may be attributed to lower limb sensorimotor impairment in participants with stroke [29]. Specifically, lateral asymmetry indicates challenges for participants with stroke in transferring weight between limbs [29]. Due to weakness in the limb on the hemiplegic side, participants with stroke rely more on the unaffected limb to compensate [42]. Anteroposterior asymmetry reflects the challenge of controlling the forward progression of the limb on the hemiplegic side, potentially stemming from weakness or spasticity in the ankle plantar flexors [32, 43]. Persistent asymmetric gait after stroke can easily lead to a reduction in walking activity level and an increase in the risk of falls, seriously affecting daily life.

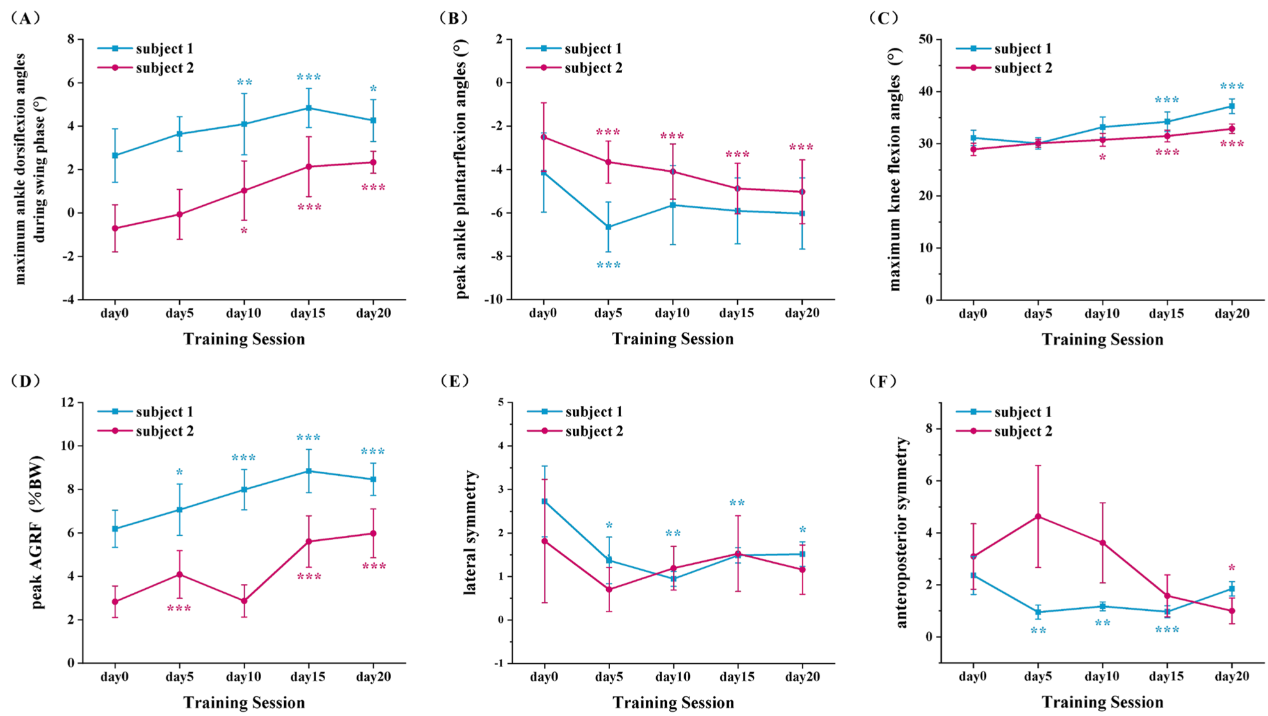

Fig. 7 Changes in gait parameters (mean ± SD) from pre-training to post-training without FES: **A** maximum ankle dorsiflexion angle during swing phase, **B** peak ankle plantarflexion angle, **C** maximum knee flexion angle, **D** peak AGRF, **E** lateral symmetry, and **F** anteroposterior symmetry. *denotes significant improvement in gait parameters at each training stage compared to pre-training. Significant difference: *P <0.05, **P <0.01, ***P < 0.001

Table 2 The therapeutic effects of gait training on subjects

Gait parameters	Subject	Pre-training	Post-training	P-value	Cohen's *d*
Maximum ankle dorsiflexion angles during swing phase (°)	1	2.65 ± 1.23	4.26 ± 0.97	0.01	1.45
	2	−0.70 ± 1.08	2.34 ± 0.51	<0.001	3.46
Peak ankle plantarflexion angles (°)	1	−4.14 ± 1.83	−6.03 ± 1.64	0.119	−1.09
	2	−2.51 ± 1.58	−5.03 ± 1.47	<0.001	−1.65
Maximum knee flexion angles (°)	1	31.13 ± 1.46	37.20 ± 1.41	<0.001	4.24
	2	28.93 ± 1.18	32.87 ± 0.91	<0.001	3.97
Peak AGRF (% BW)	1	6.19 ± 0.85	8.46 ± 0.75	<0.001	2.84
	2	2.83 ± 0.72	5.98 ± 1.12	<0.001	3.16
Lateral symmetry	1	2.73 ± 0.81	1.51 ± 0.28	0.032	-1.81
	2	1.81 ± 1.42	1.16 ± 0.57	0.504	-0.66
Anteroposterior symmetry	1	2.36 ± 0.73	1.85 ± 0.28	0.156	-0.81
	2	3.09 ± 1.26	1.00 ± 0.49	0.045	-2.48

In this study, a speed-adaptive strategy was employed to simulate the timing of ankle muscle activation during typical gait, alongside an iterative learning strategy to adjust electrical stimulation intensity based on gait performance adaptively. As the results show, stimulating the tibialis anterior muscle on the paretic side during the swing phase improves the spatial symmetry of COP trajectories in participants with stroke. This may be due to FES helping participants with stroke shift their weight onto the paretic limb, which provides a smoother progression of the COP [31]. While the contribution of the tibialis anterior is noteworthy, our study emphasizes the importance of coordinated activation of the TA and GAS. Previous research has found that a hybrid adaptive

FES system targeting two muscles helps increase the joint angle and provides anterior ground reaction force in the stance phase [11]. This study observed that the COP symmetry significantly improved under the SA-ILC DCS condition compared to the other conditions, approaching the level of healthy subjects. This observation could be due to the stimulation of the gastrocnemius during the stance phase, thereby promoting the forward advancement of the COP and enhancing leg stance [32]. In addition, the adaptive FES system can enhance neuromuscular control by adapting to changing muscle properties and mitigating external interference [44]. These improvements play an important role in maintaining balance control and enhancing gait symmetry, thus providing valuable biomechanical insights for optimizing interventions in stroke rehabilitation.

Therapeutic effect of FES on gait biomechanics

This study demonstrates the potential therapeutic effects of the hybrid adaptive FES system. After 21 days of training, significant improvements were observed in the knee and ankle angles, anterior ground reaction force, and COP symmetry. These improvements are crucial, as gait biomechanics are closely linked to walking function and safety post-stroke [45]. The observed changes in gait biomechanics could be partly attributed to the enhancement of muscle strength and range of motion (ROM) in the affected limbs [46]. Additionally, repetitive training involving ankle plantarflexion and dorsiflexion may promote motor learning [18]. The speed-adaptive FES system employed in this study mimicked the timing of normal muscle activation and delivered more biomimetic electrical stimulation, which may facilitate patients to learn correct muscle activation patterns. Studies have demonstrated that combining FES with voluntary contractions may strengthen spinal cord connections and activate cortical areas more effectively than FES alone [47, 48]. The ILC-based adaptive FES is believed to help enhance the patient's maximal voluntary contribution to task completion [10, 49]. Therefore, we speculate that long-term training with the adaptive FES system may promote better rehabilitation outcomes.

The P-value and effect size indicate that the improvements in gait biomechanics are statistically significant following long-term training. In terms of clinical significance, Guzik et al. proposed a minimal clinically important difference (MCID) of 8.48° for knee angle recovery on the affected side after stroke [50]. Our long-term training primarily targets the ankle joint, addressing issues such as foot drop and insufficient forward propulsion. Since FES does not directly target the knee joint, the observed improvement in knee function may be an indirect effect resulting from the enhanced plantarflexion torque during the push-off phase [21, 45, 51]. This may help explain why the maximum improvement in knee ROM observed in this study was smaller than the MCID. Kesar et al. reported that, after 6 weeks (18 sessions) of FES training, the participant with stroke's overground gait speed increased by 0.19 m/s [21]. This change in gait speed exceeded the MCID of 0.16 m/s for overground gait speed in stroke patients [52]. In addition, the increase in gait speed was accompanied by a 4.28° improvement in knee flexion during the swing phase. This finding suggests that, even though the knee angle improvement did not reach the MCID threshold, the observed changes in gait biomechanics may still have clinical relevance, particularly in enhancing overall functional mobility post-stroke.

Limitations and future work

Although FES demonstrates promising orthotic and therapeutic effects, this study has some limitations. Firstly, this study only evaluated the orthotic effect of FES based on the spatial symmetry of the COP. Subsequent studies could incorporate additional gait parameters, such as COP variability and temporal symmetry, as well as standardized functional walking tests like the 10 m Walk Test (10MWT) and the 6 min Walk Test (6MWT), to better evaluate gait improvement in participants with stroke. Secondly, the short-term study should encompass a larger cohort of participants with stroke and include age-matched healthy individuals as a control group. Finally, the long-term study was a pilot with only two participants with stroke. Although the findings from the training tests were promising, future studies with a larger number of participants with stroke should be conducted to ensure the generalizability of FES training.

Conclusions

This study aims to investigate the orthotic and therapeutic effects of the adaptive FES system on gait biomechanics in participants with stroke. FES can aid participants with stroke in improving COP symmetry during walking by stimulating the ankle dorsiflexion and plantarflexion muscles. Meanwhile, participants with stroke show improvement in knee and ankle angles, anterior ground reaction force, and COP symmetry without assistance after long-term training. This may be attributed to muscle function recovery, repetitive motor learning, or enhanced cortical excitability. These results indicate the extensive clinical application prospects of the lower limb adaptive functional electrical stimulation system and provide further groundwork for designing personalized rehabilitation programs in the future.

Abbreviations

FES: Functional electrical stimulation

COP:	Center of pressure
NS:	No stimulation
SA-ILC SCS:	Adaptive FES applied to the tibialis anterior during the swing phase
SA-ILC DCS:	Hybrid adaptive FES applied to both the tibialis anterior during the swing phase and the gastrocnemius during the stance phase
ILC:	Iterative learning control
TA:	Tibialis anterior
GAS:	Gastrocnemius
FMA-LE:	Fugl-Meyer motor assessment of lower extremity
MCTS:	Maximum comfortable treadmill speed
LS:	Lateral symmetry
APS:	Anteroposterior symmetry
HCG:	Healthy control group
BW:	Body weight
ROM:	Range of motion
MCID:	Minimal clinically important difference
10MWT:	10 m Walk Test
6MWT:	6 min Walk Test

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Author contributions
Project development and study design: RXH, YQD, RS. Data collection and pre-processing of the data: RXH, YQD, YL. Patient recruitment and clinical oversight: MXZ, SHP. Data analysis, statistical analysis: RXH, YQD. Drafting of the manuscript: RXH. Intellectual contribution: All remaining authors. All the authors approved the final version of the manuscript.

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Availability of data and materials
The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Before participating in the experiment, all subjects signed informed consent forms. The Ethics Committee of Zhujiang Hospital, Southern Medical University, approved this study.

Consent for publication
Subjects provided their consent to publish their data.

Competing interests
The authors declare that they have no Competing interests.

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