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Closed-loop Functional Electrical Stimulation (FES) – cycling rehabilitation with phase control Fuzzy Logic for fatigue reduction control strategies for stroke patients

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Abstract
Functional Electrical Stimulation (FES) cycling, or FES-Cycling, holds great therapeutic potential for individuals with paralysis, such as those with Spinal Cord Injury (SCI), traumatic brain injury, or stroke, aiming to restore mobility. However, the nonlinear nature of the musculoskeletal system poses a significant challenge in controlling FES-Cycling. To address this, an integrated closed-loop phase angle fuzzy-based system was developed. This system offers real-time control by adjusting stimulation intensity (pulse width) within the range of 50 to 200µs while maintaining a constant frequency of 35Hz, thereby ensuring precise pedaling trajectory and cadence patterns. An experimental study involved three healthy individuals (Cases A, B, and C) and one individual with hemiplegia stroke (Case D). Results showed that the proposed system consistently reduced average angle trajectory errors for Cases A, B, and C, with values of 2.6945, 3.2958, and 2.9922 degrees, respectively. Case D, affected by hemiplegia stroke, faced greater challenges and exhibited a higher error of 3.4562 degrees. Fatigue resistance, evaluated through fatigue indices, showed promising results for Cases A, B, and C with values of 0.10778, 0.06866, and 0.04603, respectively. However, Case D experienced higher fatigue (0.2304) due to the unique challenges of hemiplegia stroke. These findings highlight the effectiveness of the proposed control system in optimizing FES-Cycling, particularly for healthy individuals. For individuals with paralysis, like Case D, further research is needed to adapt the system to their specific conditions and cycling patterns. This system holds the potential for enhancing FES-Cycling as a therapeutic strategy and warrants additional investigation and customization for different patient populations.

Keywords:
Functional Electrical Stimulation (FES);
Fuzzy Logic Controller (FLC);
Phase angle shift;
Pulse Width (PW);
Spinal Cord Injury (SCI);

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INTRODUCTION

Stroke is a significant contributor to death, paralysis, and disability on a global scale [1]. According to National Stroke Association of Malaysia (NASAM), 40,000 Malaysians suffer from a stroke annually and six new cases are reported every hour. The impact of a stroke varies depending on the affected brain area and the severity of the damage, causing symptoms such as weakness, balance problems, language difficulties, vision problems, and cognitive issues. Rehabilitation and therapy, including Functional Electrical Stimulation (FES), can help stroke patients recover abilities and improve their quality of life by stimulating muscle strength, movement, and function. FES is also used for other conditions that affect muscle control, and has shown benefits in preventing incontinence, strengthening the immune system, reducing spasticity, regulating heart rhythm, wound healing, reducing muscle atrophy, improving blood flow, improving gait, reducing osteoporosis, enhancing Range of Motion (ROM), gaining muscle mass, and improving mental health [1].

There is significant research interest in lower limb paralysis models, such as paraplegia, monoplegia, diplegia, tetraplegia, and hemiplegia, which is explored through exoskeletons, rehabilitation exercises, robotics, wheelchairs, and activities such as cycling and rowing [2]. FES has been proven to be effective in rehabilitation exercises including cycling and rowing. In recent years, there has been rapid growth in FES engineering and human motor control, and FES-cycling has received increased attention as an efficient way of transportation and a means of improving quality of life [3]. The FES-cycling system is highly recommended for its immunological benefits, convenience, and improved physiological and emotional benefits, as shown by clinical studies [2]. FES-cycling has been proven to be a useful tool for developing, assisting, improving, and regaining cardiovascular parameters [2][3].

One of the potential problems with FES cycling is phase control, which involves the timing and order of muscle contractions. Proper phase control is crucial for effective and efficient movement, and if muscles contract in an incorrect sequence, it can result in poor cycling performance and reduced functional benefits. Factors such as electrical stimulation intensity, electrode placement, muscle strength, and coordination can impact phase control during FES cycling. To ensure optimal results, it is crucial to consult with a physical therapist or physician to customize the treatment to the individual's needs and address phase control issues. In conclusion, FES cycling can be a valuable form of physical therapy, but it is important to be mindful of phase control issues to maximize the benefits of the treatment.

Hence, a new control method was devised and tested in an experimental environment using an upgraded Fuzzy Logic Controller (FLC) based on phase shift control strategy with real-time system. The previous FLC was unable to control phase angle differences and identify lead or lag phase conditions. This new control strategy was tested on AB and stroke patients to verify its efficiency. It can serve as a FES control system for stroke patients undergoing rehabilitation, such as hemiplegic patients, to speed up their recovery. The phase-optimized fuzzy logic control is used in this approach to regulate the electrical stimulation, reducing the tracking error and minimizing the electrical stimulation to reduce muscle fatigue and prolong the duration of cycling exercise.

State of the Art: Stroke Rehabilitation

The effects of a stroke can lead to a loss of function and many interventions have been developed to address impairments [4, 5, 6]. This review of stroke rehabilitation examines various approaches for improving upper and lower limb function and balance, such as robotics and bilateral arm training, walking aids and gait training, and therapies for urinary incontinence. The review also discusses mobility therapy which combines upper and lower limb function and balance [2, 6, 7, 8]. The focus of the research is on Electro-stimulation intervention as a method for stroke rehabilitation.

FES for Hemiplegia Stroke Rehabilitation

FES has a long history of helping to regain muscle function lost due to Spinal Cord Injury (SCI), Hemiplegia stroke and other spinal cord-related injuries, since the 1960s. As a result, many studies have focused on lower-limb paralysis, such as paraplegia, monoplegia, diplegia, tetraplegia and hemiplegia, exploring various methods such as exoskeletons, gait exercise, robotics, wheelchairs, cycling, rowing, etc. [2].

FES has been a focus of extensive research and development, particularly for treatment of lower limb paralysis [3]. Many studies have been conducted globally, and FES has been widely adopted as a therapeutic tool for this type of paralysis. FES has numerous physiological benefits for individuals with SCI, strokes, and other conditions affecting the central nervous system. These benefits include preventing bladder/bowel incontinence, boosting immunity, reducing spasticity, regulating heart rhythm, promoting wound healing, reducing muscle atrophy, improving limb blood circulation, aiding gait control, reducing osteoporosis, enhancing ROM, building muscle mass, and positively impacting mental health. These benefits are achieved by properly administering current and pulses to the muscle [3, 8, 9].

FES therapy has been shown to improve muscle strength, generate force, enhance voluntary movement, and increase functional capacity in therapy and rehabilitation [2, 10, 11]. It has been found to be effective when combined with rehabilitation exercises such as cycling and rowing. Research into FES engineering and human motor control has grown in recent years, highlighting FES cycling to improve quality of life. FES cycling is widely used, with studies showing its positive impact on cardiovascular health and providing immunological, physiological, and emotional benefits [2]. FES cycling is usually done on stationary bikes and is particularly effective in stimulating the hamstrings, glutes, and quadriceps. According to [10] and [12], FES cycling is recommended due to its immunological effectiveness, ease of use, and improved physiological and emotional benefits [2]. Clinically, FES cycling has been proven to be a valuable tool for developing, supporting, improving, and regaining cardiovascular function [3].

FES Muscle Control

In recent years, there has been a surge of interest in the field of FES for muscle control, attracting attention from control and system engineers. Various advanced control techniques have been explored to address the complex challenges associated with FES, including the control of activities such as standing up [13, 14, 15], cycling [2, 14, 15, 16], and knee joint movement [1][7]. While these techniques have shown promise, they come with their own strengths and limitations, and it is essential to critically evaluate their effectiveness and potential shortcomings.

Fuzzy Logic Control (FLC)

FLC is one of the commonly used and promising techniques in FES applications. It offers the advantage of handling complex, nonlinear systems effectively. FLC is particularly useful for its simplicity and adaptability to real-world scenarios. However, it may lack the precision of more sophisticated control methods and may require fine-tuning to achieve optimal results.

Neural Network Control

Neural network control systems have been explored for activities like cycling and knee joint movement [18]. These systems offer the potential to adapt and learn from data, making them suitable for personalized control. However, the complexity of neural networks can make them computationally intensive and challenging to implement in real-time applications.

Proportional Integral Derivative (PID) Control

PID control is a well-established method used for leg swinging, knee joint movement, cycling, and sit-to-stand activities [19]. It provides a systematic approach to control and has been successfully employed in various applications. Nevertheless, PID control may struggle with handling complex, time-varying systems and may require manual tuning for optimal performance.

Model Reference Control

Model reference control is a robust technique that can be applied to knee joint movement [20]. It offers precise tracking of reference models and can adapt to changing conditions. However, the accuracy of the control largely depends on the fidelity of the reference model, and errors in modeling can lead to suboptimal results.

Model Predictive Control, Adaptive Control, and Optimal Control

These advanced control techniques are known for their ability to optimize control based on prediction and adapt to changing conditions [21]. They can be effective for handling nonlinearities and uncertainties. However, the computational complexity and tuning requirements for these methods can be significant challenges.

Machine Learning for Locomotion

Machine learning techniques have gained popularity for locomotion control, offering adaptability and the potential to discover control strategies from data [22]. While they show promise, they may require large datasets and extensive training, making them less feasible for some applications.

Gaps in Knowledge and Contribution of the Current Study

Despite the strengths of these advanced control techniques, there is a conspicuous gap in the existing literature, namely the lack of a control strategy aimed at optimizing fatigue level during FES activities. Prior research has emphasized accuracy, real-time performance, and adaptability, neglecting the efficient utilization of electrical stimulation to reduce fatigue.

The current study seeks to address this knowledge gap by introducing a closed-loop phase angle fuzzy-based control system, focusing on optimizing fatigue level during FES-cycling. This approach aims to make FES therapy more sustainable and cost-effective while enhancing muscle movement control.

By adopting a structured approach and addressing phase control issues during FES-cycling, the study lays the foundation for more effective stroke rehabilitation using FES. Furthermore, the utilization of single muscle activation and closed-loop control has the potential to extend therapy durations and minimize fatigue, which can be particularly beneficial for patients recovering from strokes.

Muscle Activation Properties

Additionally, this research acknowledges the complexities related to electrical stimulation's nonlinear and changing properties, including muscle fatigue, spasticity, and daily variations [2, 23, 24]. It recognizes the need for model and controller design to tackle issues related to fatigue during FES-cycling, which is vital for the efficacy of rehabilitation in individuals with SCI.

This study aligns with the recommendation to explore variable frequency trains to enhance power output, particularly in the fatigued state of FES-stimulated muscles. Although it may not fully restore function in lower limbs, this approach can help build muscular endurance and strength over time through longer, more robust FES-evoked exercises.

METHOD

The flowchart Figure 1 illustrates the key steps and components of our control system, which focuses on optimizing fatigue levels during FES cycling for stroke rehabilitation. The development of this research starts with data collection from experimental tests utilizing FES for electrical stimulation tests, followed by pendulum testing for knee joint experimental data using a Goniometer. The data parameter of lower limb characteristics is gathered from anthropometric data. The following experimental setup provides an overview of the hardware implementations, including the suggested system applications and architectures.

FES-Cycling experiment setup

The focus of this study is on using a computer-based closed-loop control method for FES-Cycling as a post-stroke rehabilitation treatment. The controller focuses on the activation of a single muscle group in the lower extremities (quadriceps) to provide adequate pulse production, allowing for longer rehabilitation sessions.

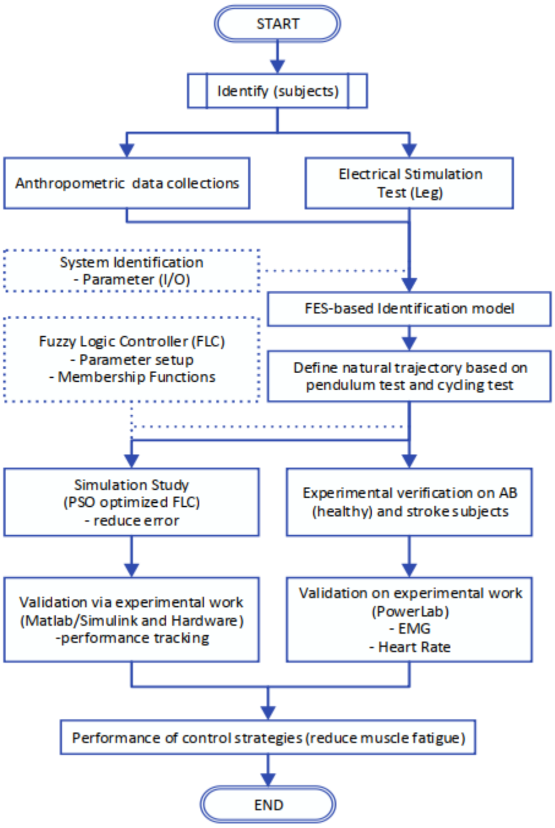

Figure 1. Flowchart of general process

This study enrolled 3 healthy subjects and 1 post-stroke patient in a knee extension exercise using FES while seated on a custom wheelchair and cycling ergometer. The subjects wore a lower limb suit with a zipper to hide electrodes on their quadriceps muscles, and were seated on a comfortable, adjustable wheelchair for easy cycling and data collection as depicted in Figure 2. The wheelchair was 60 cm tall, with a seating area of 48x48 cm^2 and 40 cm between the center of the ergometer crank with a variance of ±10 cm. The phase angle data was acquired during the cycling sessions with the help of an electro-goniometer acting as a digital converter. The surface electrodes were placed on the quadriceps muscles and collected by a system that connected to a personal computer to give real-time feedback and control of the FES-cycling pace.

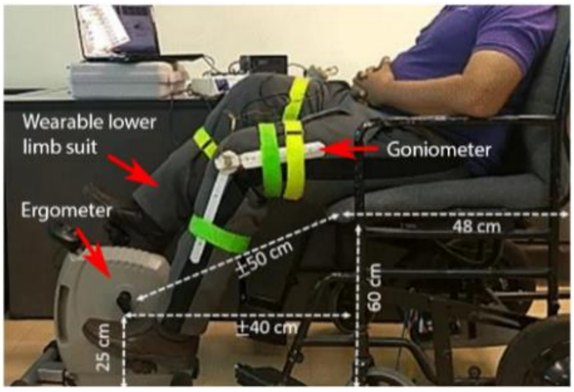

Figure 2. Pre-setup wheelchair FES-Cycling cadence

To address the potential interference of voluntary muscle contractions by the subjects with the contractions induced by FES, several steps were taken to control the subject behavior and enhance replicability. These steps include:

1. Subject Training: Subjects underwent training sessions to familiarize themselves with the FES-cycling setup and the desired pedaling pace. The training ensured that subjects understood the required cycling pattern and were less likely to engage in voluntary muscle contractions that could interfere with the FES-induced contractions.
2. Real-time Monitoring: A closed-loop control system was employed to monitor the subjects' performance and muscle fatigue. This monitoring allowed for immediate adjustments in the FES-cycling pace to maintain the desired pattern and mitigate the impact of any voluntary contractions.
3. Fatigue Assessment: Muscle fatigue was continuously assessed using lead-and-lag phase angle and FLC fuzzification. If signs of fatigue were detected, the session's duration was adjusted accordingly, minimizing the likelihood of interference from voluntary contractions.
4. Closed-Loop Control: The FLC-controlled FES system adjusted the stimulation parameters based on real-time feedback, ensuring that the FES-induced contractions remained synchronized with the desired cycling motion.

By implementing these strategies, this study aimed to reduce the potential impact of voluntary muscle contractions on the FES-induced contractions, thus enhancing the replicability and reliability of the experiment. These steps were taken to ensure that the experimental results accurately reflected the effectiveness of the FES-cycling system in post-stroke rehabilitation.

A HASOMED stimulator was used to activate the quadriceps muscles with a rectangular biphasic current. The pulse width ranged from 0-300μS with a fixed frequency of 35 Hz and current intensity from 30-90mA. The duration and amplitude of stimulation were adjusted based on pedaling frequency and the muscle group targeted. Surface electrodes were placed on the left or right quadriceps muscle with anode and cathode, positioned with a gap of ±15cm and in a position to achieve the best muscular response, as measured by the results of the cycling trajectory and fatigue during exercise.

The study aimed to stimulate the quadriceps muscles at the right time during the 360-degree crank cycle motion to ensure smooth and effective cycling. The muscle stimulation was triggered by the angle from the electro-goniometer, resulting in a continuous cycling pattern for both legs at a constant pace of 20 rpm per session. Each session lasted 1 minute, and the duration was adjusted based on muscle fatigue, which was monitored through lead-and-lag phase angle and FLC fuzzification. The FES-cycling test aimed to evaluate how long each participant could sustain the cycling pattern without muscle fatigue, using a closed-loop control system for real-time monitoring of performance and fatigue.

Control Strategies using Phase Angle Shift

This study involves a closed-loop control system for FES using fuzzy logic, sufficient to control the phase angle effectively and determine the patient's fatigue. As a result, a new control system based on real-time phase shift control with FLC was developed and tested on healthy and post-stroke subjects. The objective was to study the relationship between the input (reference angle, θ_{ref}) and the output (actual knee angular position, θ_{act}) by analyzing the phase difference between them, which were sine waves, as shown in Figure 3. The two sine wave signals are referred to as the intended reference (displayed in red) and the experimental result (displayed in blue) of the FES cycling movement to study the FES cycling trajectory's response to the input signal.

Closed Loop System of FES-Cycling

The block diagram in Figure 4 shows how the overall FES cycling closed-loop system was created using MATLAB. The reference angle, θ_{ref}, representing the expected angle for the subject to follow with minimal error, and the actual knee angular position, θ_{act}, were used to control the stimulation. The FLC provided the required pulse width to the FES stimulator interface based on a phase angle fuzzification mechanism passed to the Hasomed FES stimulator. The surface electrodes were used to stimulate the quadriceps muscle through the FES output, and the actual trajectory was measured in real-time by an electro-goniometer and sent to a computer for analysis using MATLAB/Simulink via an Arduino Mega.

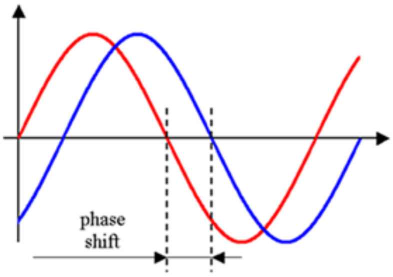

Figure 3. Phase shift angle

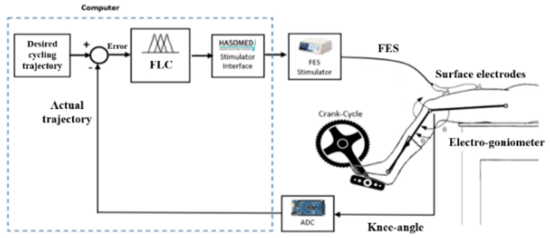

Figure 4. Block diagram for closed-loop control system with left-right stationary cycling

Knee Extension

The process of using the FES device in rest mode starts with the knee angle being set at 100 degrees. The angle remains at 100 degrees until a stimulus charge is applied to the quadriceps muscles by the FES device. This stimulus charge contracts the muscle and causes a knee extension movement. The actual angle produced by the limb's movement, θ_{act}, is used as feedback for the FLC to determine the required Pulse Width (PW) that needs to be adjusted during stimulation. The difference between the reference angle, θ_{ref}, and the actual angle, θ_{act}, is referred to as the Error, ε. The difference between the current error and the previous error is referred to as the Change in Error, Δε, and is defined in (1) and (2).

$$Error, \varepsilon \ = \ Reference\ angle, \theta_{ref} - Actual\ angle, \theta_{act} \qquad (1)$$

$$Change\ in\ Error, \Delta\varepsilon \ = Current\ error, \varepsilon - Previous\ error, \epsilon_{last} \qquad (2)$$

The FLC takes the input data of error (ε) and change in error (Δε) to determine the necessary PW to achieve the desired angle (θ_{ref}). If the error is positive, it means the applied charge is not enough, so the PW will be increased. If the error is negative, it means there is overstimulation, so the PW will be decreased until the error reaches zero, meaning the target angle has been met.

Fuzzy Logic Controller (FLC)

The control of knee extension in the closed-loop FES system in this study was accomplished using FLC instead of a mathematical formula, as FLC can handle complex, nonlinear systems effectively. The FLC system has five sub-modules: Fuzzy Error Conversion, Fuzzification, Rule base, Fuzzy Inference, and Defuzzification, as seen in Figure 5. The Fuzzy Error Conversion sub-module converts the measured knee position (θ_{act}) into error (ε) and change in error (Δε). These inputs were then scaled to 8-bit data from 0 to 255 for digital implementation.

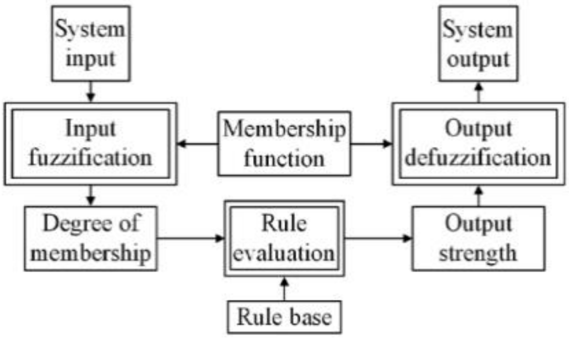

Figure 5. Overall structure of FLC

The Fuzzification sub-module transforms the crisp inputs (ε and Δε) into a range of 0 to 1 using Membership Function (MF), which categorize inputs into fuzzy sets. The Rule-Base sub-module stores knowledge in the form of rules that dictate the actions of the FLC based on inputs. The Fuzzy Inference sub-module makes control decisions based on the MF, fuzzy set, and fuzzy rule. The two most used fuzzy inference methods are Mamdani and Takagi–Sugeno. The Mamdani system, which uses the Center of Gravity (COG) technique for defuzzification, is easy to understand and well-suited for expert system applications. The Sugeno system, which uses a weighted average, does not have output MF. The main difference between Mamdani, Tsukamoto, and Sugeno FIS is the way they convert fuzzy inputs into crisp outputs, with Mamdani using COG and the other two using Weighted Average.

Design and Modelling of FLC for Knee Extension

For the study, Trapezoidal MF were chosen for both inputs and outputs. The parameter values were plotted on the x-axis and the degree of the MF on the y-axis, as demonstrated in Figure 6.

Fuzzification

The MFs with varying widths were used for the two inputs due to its simple arithmetic operation algorithm and easy interpretation. Three linguistic terms, Positive (P), Medium (M), and Negative (N), were created for the error input MFs with a range of [-100 100] as shown in Figure 7(a).

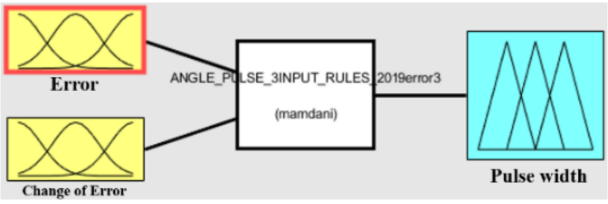

Figure 6. Mamdani type of FIS

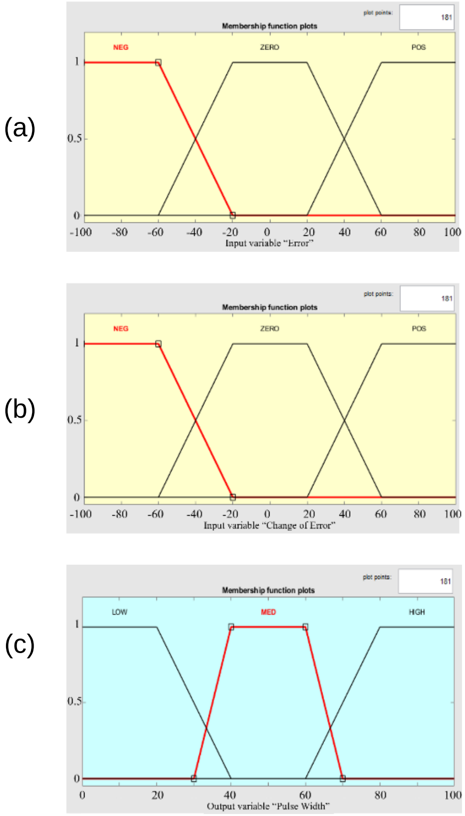

Figure 7. Trapezoidal MF that was used to define the (a) input variable error (b) input variable change of error and (c) output variable PW

For the change of error (Δε), three terms Positive (P), Zero (Z), and Negative (N) were used with MFs in the range of [-100 100] as shown in Figure 7(b). If inputs fall outside the parameters, the algorithm employs saturation to bring them back inside the acceptable range and sends them to the defuzzification system, where they are tuned to produce PW output values. The 7 linguistic terms for the output were High (H), Low (L), and Medium (M) with MFs in the range of [0 100] as shown in Figure 7(c).

The success of phase shift control in a fuzzy system is determined by the characteristics of the system being controlled and the control goals. Typically, phase shift control is employed to enhance the system's dynamic response and stability, and to minimize overshoot and oscillation in the control output. This is useful when a straightforward on/off control approach is insufficient to meet desired performance.

Rule base

The FLC system relied on a set of fuzzy rules (Rule Base) to make decisions based on the degree of MF. The number of rules was determined by the number of MFs for each input and was determined by understanding the control process and the relationship between knee trajectory response and the applied stimulation charge. Since the FLC had two inputs (ε and Δε) with 3 MF each (NB, NS, ZE, PS, PB), 9 rules (3 x 3 = 9) were generated, as shown in Table 1. Any combination of two linguistic terms activated at least one rule.

Table 1. Phase angle rule

Error, ε Delta_error, Δε	**N**	**Z**	**P**
P	M	L	L
Z	H	M	L
N	H	H	M

The inference rules presented in Table 1 can be read as follows: For example, IF the error, ε is Medium AND the Delta_error, Δε is Medium THEN output, $u(z)$ will be Zero (Z).

The Rule Base was used to determine the right level of electrical stimulation to be given to the patient's muscles based on inputs like electrical stimulation intensity and muscle activity. Using a Rule Base in FES allowed for the representation of vague or uncertain ideas and the creation of more flexible and secure control rules, to enhance the control system's effectiveness and efficiency. The aim is to reduce the difference between the reference and experimental signals. For instance, if the experimental signal angle is slower than the reference trajectory, the system should provide higher PW, which in turn aligns the pedaling output with the reference angle, resulting in faster pedal speed. When the output system leads, meaning the experimental signal is faster than the reference, the PW is higher and the pedal goes faster than intended. The system then reduces the PW from FES to make the pedaling slower and align with the reference signal. Lastly, when the experimental knee angle is the same as the desired angle, there's no change in the system. This means the observations and tests won't have any impact.

Defuzzification

The next step after finding the output level for each rule in the MF was to combine these levels into a single value, which would then be used as the PW signal to control the muscle's charge. In this study, the closed-loop FES system was designed to operate at different reference angles for each case, and the sets of MF output levels were optimized to match these reference angle settings as shown in Table 1. This was usually done using techniques like the centroid of the signal's overall distribution or the mean-of-maximum method.

In the final step, the output was calculated using the COG method for intervals a and b. The COG method was preferred because it reduced computational complexity and produced a fast output [25]. It was implemented by multiplying the fuzzy output from each rule's evaluation with its corresponding value, then dividing the sum of these values by the sum of all fuzzy outputs from the rules' evaluations, as described in (3).

$$z^* = \frac{\sum_a^b Fuzzy\ output,u(z) \times output,z}{\sum_a^b Fuzzy\ output,u(z)} \qquad (3)$$

Where z^* represents the crisps output, $u(z)$ corresponds to membership function and z is the output variable. In fuzzy control systems, the output from the systems often consisted of several different control parameters as shown in Figure 8.

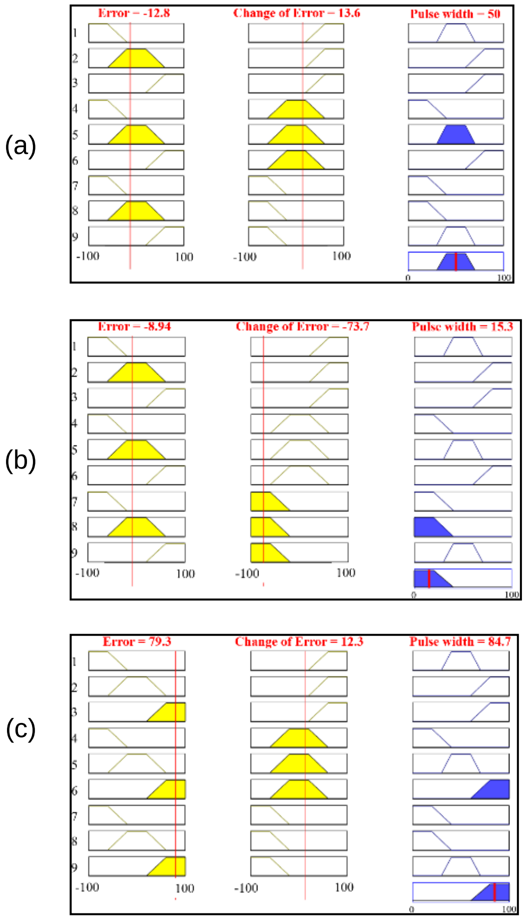

Figure 8. Graphical application of the fuzzy rules using the COG method for output (a) Medium PW, (b) Low PW and (c) High PW

The subsystem model creates the necessary PW value that is sent to the HASOMED simulator to regulate the voltage input of the electrode, as depicted in Figure 4.

Fatigue index

The calculated contraction error during stimulation was used to determine Fatigue Indices (FI) based on average error, $\varepsilon_{average}$ and the first 5 errors, $\varepsilon_{init,}$ of each session, as shown in (4). FI indicates the degree of fatigue resistance, with FI = 1 representing complete muscle exhaustion (higher error), and FI = 0 indicating no fatigue. Each leg was treated as a separate sample.

$$FI = \frac{\varepsilon_{average}}{\varepsilon_{init}} \mathrm{FI} = \frac{\varepsilon_{\mathrm{average}}}{\varepsilon_{\mathrm{init}}} \qquad (4)$$

RESULTS AND DISCUSSION

Test case

The designed FLC was tested on both healthy and Hemiplegia stroke individuals to verify its ability to produce the calculated PW output. It enables the presentation of the FIS output value for all combinations of two input variables in a 3-D format, as shown in Figure 9.

Figure 10(a) illustrates that the feedback signal was ahead of the input signal when the error and derivative signals alternated between positive and negative values. This resulted in a phase shift when the error fluctuated. This occurred as the feedback attempted to align with the reference value by slowing down and reducing the error over time. However, when both signals were in phase (no phase shift), the error was zero.

Figure 10(b) depicts that the feedback signal is lagging the input signal when both the error and derivative signals are alternating in positive and negative values, causing phase shift as the error fluctuates.

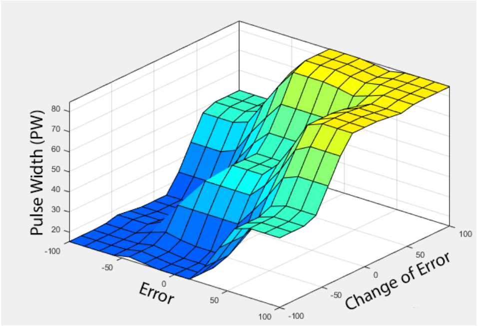

Figure 9. Surface viewer of PW for Fuzzy Inference System (FIS) in FLC

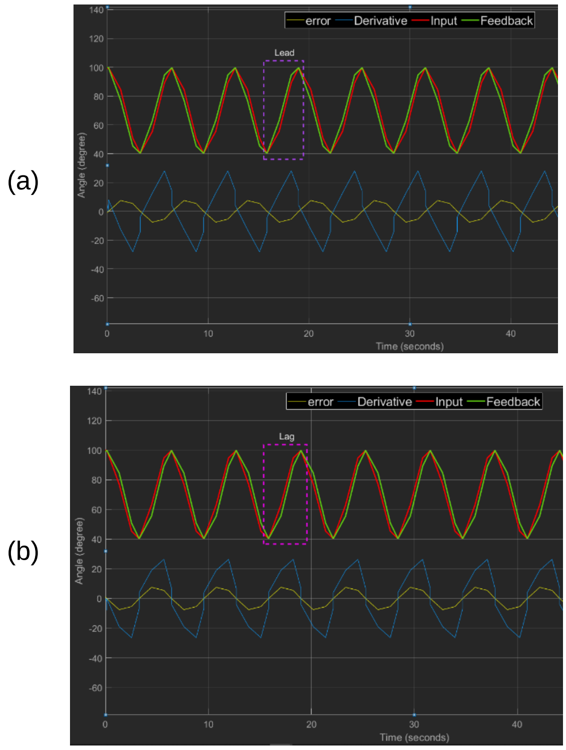

Figure 10. (a) feedback angle lead compared to input signal, and (b) Feedback angle lag compared to input signal

This occurs as the feedback tries to match the reference by increasing speed, resulting in a decrease in error over time. At the point where both signals are in phase (no phase shift), the error is zero.

Comparison between simple rule base FLC and proposed phase angle fuzzy based system

The experiment considered the demographics of subjects, which were shown in Table 2. Each subject underwent a single experiment, which involved a study of cycling movement with FES for single muscle contraction. Three AB subjects were used to compare the results of a simple FLC and a phase angle shift fuzzy system. One Hemiplegia stroke subject was included to evaluate its fatigue.

Subject A

The proposed signal in Figure 11(b) from FLC of subject A was compared with simple rule base signal as shown in Figure 11(a). It had the smallest average angle trajectory error with minimum 2.6945 compared to simple rule base method which is 3.42997.

Table 2. Demography of subjects for Case A, B, C and D

Case	Age	Height (Cm)	Weight (Kg)	Health Condition	Injury History
A	34	168	98	Excellent	No
B	33	175	92	Excellent	No
C	31	170	87	Excellent	No
D	75	165	55	Hemiplegia (Stroke)	2010

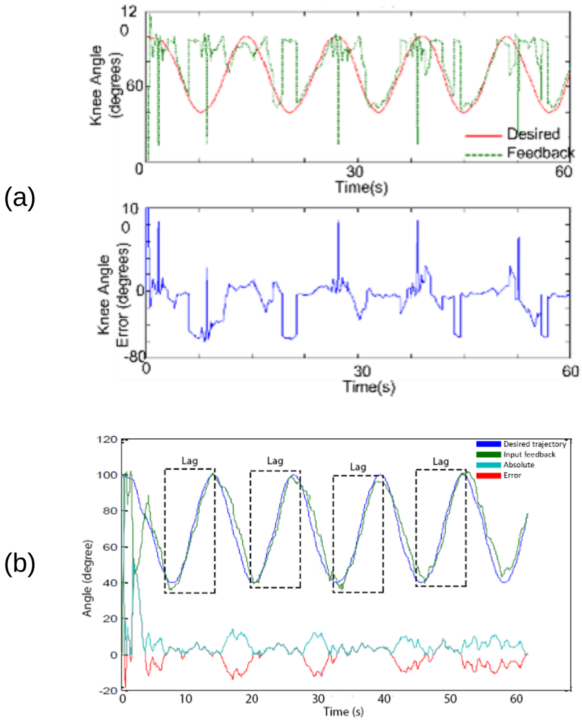

Figure 11. Feedback vs desired angle trajectory of subject A for (a) simple rule base (b) Proposed FLC

Subject B

In Figure 12, the comparison between the feedback signals for subject B in two different control strategies: a simple rule-based FLC represented in Figure 12(a), and proposed Phase Angle Fuzzy-Based System depicted in Figure 12(b) was presented. Figure 12(b) had the smallest average angle trajectory error with minimum 3.29584 compared to Figure 12(a) with 3.43301. The feedback signal is represented by the green line in both figures, and it reflects the lead and lag status of the system. This feedback signal plays a crucial role in calculating the fatigue index by using the error generated value.

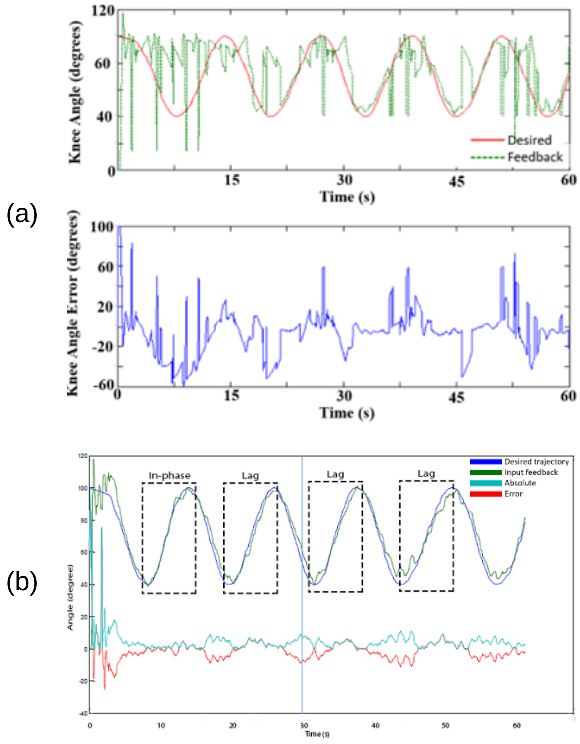

Figure 12. Feedback vs desired angle trajectory of subject B for (a) simple rule base (b) Proposed FLC

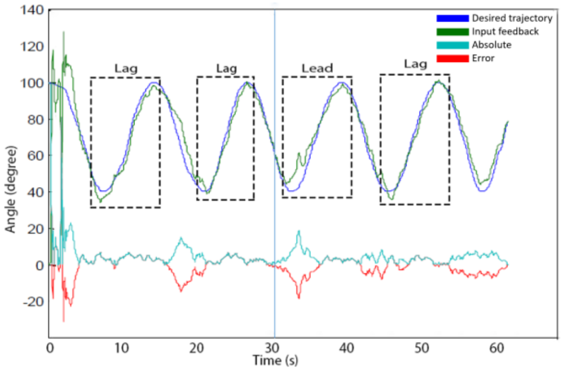

Figure 13. Feedback vs desired angle trajectory of subject D for Proposed FLC

Table 3. Average error of angle trajectory and Fatigue Index

Subject	Angle trajectory error (degree)	Fatigue Index (FI)
Case A	2.6945	0.10778
Case B	3.2958	0.06866
Case C	2.9922	0.04603
Case D	3.4562	0.2304

Statistical analysis

The proposed signal in Figure 13 from FLC of subject D was compared with simple rule base signal. The average angle trajectory error was 3.4562 which was the highest due to the person was having difficult time to catch up with the reference signal. The result of average error angle trajectory was tabulated in Table 3 across each subject. Its respective FI was calculated within the specified time.

The results showed that in three of the four subjects, there was less fatigue during distributed stimulation, as indicated by the low error and consistent period in the test sessions for subjects A, B, and C. However, only one subject had a higher fatigue index with distributed stimulation, which was due to their Hemiplegia condition and different cycling pattern.

CONCLUSION

This research has demonstrated a control strategy for real-time FES-Cycling using a single muscle with FLC. By using FLC with phase angle fuzzification, it was found to be more effective than a simple FLC method in minimizing errors and increasing exercise time for subjects. The strategy was tested on both AB and Hemiplegia stroke subjects and was found to effectively induce muscle movement to follow a desired cycling pattern with less fatigue. The goal of the research was to reduce error, increase workload while maintaining a healthy lifestyle. The results showed that the system is suitable for both AB and Hemiplegia stroke patients, especially for indoor exercise and rehabilitation. Overall, the system is considered helpful and valuable for therapy and daily life to improve lower limb of disabled people.

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