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Optimization of a Combined Medium-Frequency Electrical Stimulation and Far-Infrared Therapy Protocol for Adhesive Capsulitis Based on the Taguchi Method and Genetic Algorithm

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Keywords: Adhesive capsulitis, Far-infrared therapy, Medium-Frequency Electrical Stimulation, Taguchi method, Genetic algorithm.

ABSTRACT

This study optimized therapeutic parameters for adhesive capsulitis (AC) using a hybrid method integrating medium-frequency electrical stimulation (MFES) and far-infrared rays (FIR). The Taguchi design analyzed three factors—FIR intensity, MFES mode, and treatment sequence—across nine parameter sets, evaluated by VAS, QD, RMS, and iEMG. Genetic algorithm (GA) optimization identified the optimal combination as FIR at medium–low intensity, MFES 6/6 square-wave mode, with FIR applied before MFES, achieving improved muscle relaxation, pain reduction, and functional recovery. The integrated Taguchi–GA framework demonstrated high optimization efficiency and provides a quantitative model for developing evidence-based physical therapy protocols for shoulder adhesive capsulitis.

INTRODUCTION

Adhesive Capsulitis

The shoulder joint, one of the most flexible joints in the human body, enables various movements such as lifting, rotation, and extension in daily life. However, with aging and prolonged poor posture, the shoulder joint is prone to degeneration and injury, which may lead to adhesive capsulitis(AC). This condition occurs more frequently in middle-aged and older adults over 40 years of age. In some patients with diabetes, the treatment process for AC is prolonged and challenging, seriously affecting quality of life and work performance (Baig, et al., 2025).

Treatment Approaches for Adhesive Capsulitis

Adhesive Capsulitis (AC), or frozen shoulder, is characterized by pain and restricted mobility. Treatments include injections, surgery, and physical therapy, each with specific benefits and limitations (Donatelli,, 2011, Fan, 2022).

Singh et al. (2025) found methylprednisolone injections relieve symptoms short term but pain may recur after six months; platelet-rich plasma offers longer relief but lacks dosage standardization, is costly, and shows variable responses. Boutefnouchet et al. (2019) reported capsular release surgery improves pain and motion, though recurrence is more likely in diabetics and post-multiple surgeries. Kanokvaleewong et al. (2025) showed physical therapy effectively reduces pain and improves mobility, regardless of stiffness severity. Overall, injections may provide lasting benefit but are costly and patient-dependent; surgery is effective for severe cases but may recur; physical therapy is safe and broadly applicable, with outcomes influenced by frequency and adherence. Cost-effective, convenient approaches could improve treatment uptake and outcomes.

Applications of Far-Infrared Therapy and Medium-Frequency Electrical Stimulation in Adhesive Capsulitis

Adhesive Capsulitis (AC), also known as frozen shoulder, is a common musculoskeletal disorder characterized by pain, inflammation, and progressive restriction of shoulder mobility. It significantly

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affects daily activities and quality of life. Standard treatments—such as corticosteroid or platelet-rich plasma injections, capsular release surgery, and physical therapy—have shown varying degrees of success but also present limitations. Injections can offer short-term relief but may lead to recurrence; surgery is invasive and costly with possible complications; while physical therapy is safe but requires long-term adherence and consistent participation. Therefore, developing non-invasive, cost-effective, and patient-friendly alternatives remains an important goal in AC management.

In recent years, non-invasive physical therapies have gained attention for AC management, particularly Far-Infrared Therapy (FIR) and Medium-Frequency Electrical Stimulation (MFES). FIR enhances blood circulation and soft tissue repair via deep thermal effects. Park et al. (2023) found FIR after arthroscopic rotator cuff repair reduced pain and improved outcomes, suggesting potential for managing chronic shoulder inflammation and stiffness. MFES modulates pain transmission and activates muscles. Morgan et al. (1996) showed MFES reduced procedural pain in frozen shoulder patients, while Lin et al. (2019) reported short-term pain and function improvement in chronic shoulder tendinitis. Its low cost and simplicity support broad clinical use.

Integrating FIR and MFES may offer complementary benefits—FIR promoting tissue healing and relaxation, and MFES enhancing muscle activation and pain modulation. Together, these mechanisms may help improve mobility, reduce pain, and accelerate recovery, making the combined approach a promising adjunct or alternative to conventional treatments for adhesive capsulitis.

Feasibility of Combining Far-Infrared Therapy and Medium-Frequency Electrical Stimulation for Adhesive Capsulitis

Adhesive Capsulitis (AC), commonly known as frozen shoulder, is characterized by pain and limited shoulder motion. Current treatments include corticosteroid or platelet-rich plasma injections, capsular release surgery, and physical therapy. Although these methods can reduce pain and improve mobility, each has limitations such as high cost, recurrence, or the need for long-term adherence.

Far-infrared (FIR) therapy and medium-frequency electrical stimulation (MFES) are non-invasive physical treatments that promote circulation, relieve pain, and enhance tissue recovery through different mechanisms. FIR provides deep thermal effects that improve blood flow and tissue repair, while MFES reduces pain and activates deep muscles through electrical stimulation. Combining both treatments in one session may produce synergistic effects—relaxing tissues, controlling pain, and accelerating recovery—while being more convenient and cost-effective.

However, limited evidence exists comparing this combined approach with standard treatments. This study investigates the feasibility and potential effectiveness of integrating FIR and MFES for managing adhesive capsulitis, aiming to identify optimal parameters for clinical application.

Research Purpose

This study aims to investigate the feasibility and effectiveness of applying Far-Infrared Therapy (FIR) and Medium-Frequency Electrical Stimulation (MFES) simultaneously in the management of Adhesive Capsulitis (AC). Most existing studies focus on a single therapy: FIR improves blood circulation, relieves soft tissue tightness, and alleviates chronic pain, while MFES modulates neural pain pathways and activates deep muscle groups to aid functional recovery. However, evidence on their combined use remains limited. In clinical practice, physical therapists typically operate one device at a time, and there are no clear guidelines for the synergistic effects or workflow of multi-device application.

This study will establish a parameter combination for the combined use of FIR and MFES, evaluating its effects on pain relief, range of motion, and functional recovery. The findings are expected to fill the current research gap and provide a new non-invasive treatment strategy for AC.

- Objectives: To (1) identify the optimal treatment parameters for the combined FIR–MFES approach, and (2) compare its effectiveness with conventional single-modality interventions in improving shoulder pain and mobility.
- Hypotheses: (1) The combined FIR–MFES therapy will produce greater improvements in pain reduction and range of motion than either therapy alone; and (2) this combined approach will demonstrate high feasibility and patient tolerance in clinical application.

LITERATURE REVIEW

Far-Infrared Therapy

Far-Infrared Therapy (FIR), a non-invasive intervention, has shown potential in relieving musculoskeletal pain, enhancing circulation, and promoting tissue repair. Kyselovic et al. (2023) noted that FIR (3–1000 μm) reduces inflammation and supports tissue recovery through cellular and molecular interactions. Barolet et al. (2016) further reported that proper FIR doses stimulate antioxidant production and collagen synthesis, slowing tissue

degeneration in chronic shoulder disorders. Moreover, Tashani, O. (2028) found FIR combined with exercise alleviates chronic muscle pain and improves quality of life. Collectively, FIR provides evidence-based benefits for pain relief and tissue repair, both relevant to AC.

Medium-Frequency Electrical Stimulation

Medium-Frequency Electrical Stimulation (MFES) is a non-invasive electrotherapy using two medium-frequency currents(approximately 4,000 Hz) that intersect to produce a low-frequency modulated current (1–100 Hz), enabling deeper tissue stimulation to reduce pain and muscle spasm. Taylor et al. (2015) reported that neuromuscular electrical stimulation can lessen exercise-induced muscle damage and soreness while enhancing performance. A systematic review by DeJesus et al. (2023) found that medium-frequency stimulation shows moderate to high efficacy in chronic musculoskeletal pain management, reducing both resting and movement-related pain. Overall, MFES alleviates pain and improves tissue function by enhancing blood flow, reducing inflammation, and modulating neural transmission, making it promising for chronic conditions such as AC.

Taguchi Method

The Taguchi method is a statistical optimization technique that uses orthogonal arrays to evaluate multiple factors with minimal trials (Riyanto, et al., 2024), identify optimal parameter combinations, and reduce variation (Rao, et al., 2008). Though widely applied in engineering, its medical use faces challenges such as individual variability and nonlinear interactions (Shiou, et al., 2025). Nonetheless, its systematic design and signal-to-noise ratio analysis emphasize robustness against interference (Liao, et al., 2025). Medical studies have applied it successfully in process improvement (Taner, & Antony, 2006), biomechanical design (Ke, 2010), ergonomics (Tsrng, 2019) gait classification (Sakeran, 2019), and medical imaging optimization (Tseng, 2022). Given this study's mix of subjective pain assessment, physiological data, and complex factor interactions, the Taguchi method offers a structured foundation for parameter optimization and variation control, making it suitable for preliminary analysis.

Genetic Algorithm

Since its introduction by Holland in 1975, the Genetic Algorithm (GA) has been widely applied in engineering, machine learning (Lee, et al., 2025, Peng, et al., 2025, Wang, et al., 2024, Li, et al., 2024), and medical optimization. GA simulates biological evolution through selection, crossover, and mutation, iteratively searching for a global optimum. In medicine, it is well-suited for nonlinear problems with multiple interacting factors, such as patient variability and complex treatment parameters. Although small sample sizes may affect stability, integrating GA with fitness function design and simulation can mitigate these issues (Holland, 1992). Recent studies highlight GA's value in healthcare, including cancer gene feature selection with only eight samples (Wang, et al., 2023), pediatric trial design (Tsuchiwata, 2023) personalized rehabilitation robots (Martinez-Pascual, et al., 2024), stroke rehabilitation allocation (Yan, et al., 2022), and spinal cord stimulation optimization (Gilbert, et al., 2022). GA has also optimized deep learning architectures and neuromuscular stimulation parameters, enhancing recognition and treatment tolerability. These findings underscore GA's robust optimization capacity for small-sample, multi-variable, and complex medical problems.

Combined Application of the Taguchi Method and Genetic Algorithm in Medicine

The Taguchi method and GA are key techniques for experimental design and global optimization, respectively—Taguchi systematically identifies critical factors via orthogonal arrays, while GA simulates natural evolution to solve nonlinear, multi-objective problems. With the rise of data-driven medical decision-making, combining these methods has become an effective strategy. Roy (2010) applied the Taguchi method to refine GA for breast cancer gene signature discovery, successfully identifying stable risk combinations in small, high-dimensional datasets. More recently, Phadke (1995) integrated Taguchi with GA to optimize neural network hyperparameters for cardiovascular disease prediction, enhancing both accuracy and generalization. In summary, Taguchi supports systematic factor screening, while GA enhances optimization and stability. Given the multiple intervention factors and patient variability in this study, a hybrid Taguchi–GA approach is both rational and feasible for healthcare parameter optimization.

APPLICATION OF TAGUCHI METHOD TO ANALYZE THE OPTIMAL PARAMETER COMBINATION FOR THE TREATMENT OF ADHESIVE CAPSULITIS OF THE SHOULDER USING MEDIUM-FREQUENCY ELECTRICAL STIMULATION AND FAR-INFRARED RAY COMBINATION TECHNOLOGY

The experiment investigated the effects of MFES and FIR on AC by varying treatment mode, intensity, and sequence. Experimental design and analysis followed the Taguchi method, with GA optimization to improve efficiency and identify the optimal parameter set.

Research Methods

(1). Definition of the Taguchi Optimization Problem

The study aimed to optimize procedural combinations for maximizing muscle relaxation and pain relief. Three factors were considered: FIR intensity, MFES mode, and treatment sequence. Outcomes includet aled four indicators: pain (VAS), muscle activity (RMS and iEMG), and upper limb function (QD). This definition established the basis for the Taguchi design and subsequent health promotion strategies.

(2). Selection of Factors and Levels

In the Taguchi method, the selection of key control factors and their levels is crucial, as these factors determine the system's response and directly influence the optimization outcome. In this experiment, three primary factors and their corresponding levels were selected based on their potential impact on therapeutic effectiveness. Factor 1 was the intensity of far-infrared radiation (FIR), with two levels: medium–low temperature and medium–high temperature. Factor 2 was the mode of medium-frequency electrical stimulation (MFES), including CONST mode and 6/6 square-wave mode. Factor 3 was the treatment sequence, consisting of three levels: FIR applied before MFES, MFES applied before FIR, and simultaneous application of FIR and MFES. These factors were considered essential for identifying the optimal combination that maximizes pain relief and muscle relaxation in patients with adhesive capsulitis.

(3). Selection of an Appropriate Orthogonal Array

This study adopted the Taguchi mixed-level design $L_8(3^1 \times 2^2)$ orthogonal array (Table1). The L_8 array was selected because it allows efficient experimental design with a small number of runs while maintaining balanced and systematic representation of factor-level combinations. This structure minimizes experimental cost and time without compromising analytical accuracy, making it suitable for studies involving multiple factors with mixed levels. To further validate parameter combinations absent in the original design, one additional supplementary trial was included beyond the initial eight runs, thereby improving the inferential strength of the results. After assigning all factors and levels into the array, Table 1 was generated to present the factor coding and treatment sequence group codes.

(4). Experimental Procedure and Analysis Workflow

Nine participants over 20 years old, all diagnosed with AC in the freezing stage and experiencing significant pain, were randomly assigned to nine groups. Each received two sessions per week for four weeks (eight sessions total). sEMG and VAS were measured before and after each session, while the QD was completed weekly and post-treatment. Recorded signals were filtered, transformed, and processed; questionnaire scores were statistically analyzed. Finally, Taguchi S/N Ratio analysis was conducted and optimized using a GA.

L_8 ($3^1 \times 2^2$)	Factor 1	Factor 2	Factor 3	Group
	FIR intensity (Code:a)	MFES mode (Code:b)	Treatment sequence	
1	1(medium–low temperature)	1(CONST)	1(ab)	A1
2	1(medium–low temperature)	1(CONST)	2(ba)	B1
3	1(medium–low temperature)	2(6/6 square-wave)	3(ab Both)	C1
4	2(medium–high temperature)	2(6/6 square-wave)	1(ab)	A2
5	2(medium–high temperature)	2(6/6 square-wave)	2(ba)	B2
6	2(medium–high temperature)	1(CONST)	3(ab Both)	C2
7	1(medium–low temperature)	2(6/6 square-wave)	1(ab)	A3
8	1(medium–low temperature)	2(6/6 square-wave)	2(ba)	B3
9	1(medium–low temperature)	1(CONST)	3(ab Both)	C3

Table 1 $L_8(3^1 \times 2^2)$orthogonal array

Analysis Results

This study adopted the S/N ratio from the Taguchi method as the evaluation criterion. Depending on the desired outcome, the S/N ratio can be classified into nominal-the-best (NTB), larger-the-better(LTB), and smaller-the-better(STB)characteristics. In this experiment, only the NTB characteristic was applied. The calculation formula is as follows (Maghsoodloo, 2001)：

$$\eta_{NTB} = 10 \cdot log_{10}\left(\frac{m^2}{\frac{1}{n}\sum_{i=1}^{n}(y_i - m)^2}\right) \quad \text{(Eq. 3.1)}$$

η_{NTB} = nominal-the-best characteristic, y_i = value of the i-th experimental sample, n = total number of samples, m = target value.

(1). RMS

The RMS value reflects the level of muscle activation and tension. A decrease indicates muscle relaxation, with a greater reduction representing a stronger relaxation effect. Since variations can be both positive and negative, the conventional one-sided S/N ratio is unsuitable; instead, the NTB characteristic was applied, with a target value of -2000. The S/N ratio main effects plot is shown in Figure 1. The optimal RMS S/N ratio combination was: FIR medium–low temperature intensity, MFES CONST mode, and simultaneous application.

(2). iEMG

The iEMG represents the cumulative muscle activity. A downward trend indicates effective relaxation. Since variations can be both positive and negative, the NTB characteristic was applied, with a

target value of -300,000. The S/N ratio main effects plot is shown in Figure 2. The optimal iEMG S/N ratio combination was: FIR medium–low temperature intensity, MFES 6/6 square-wave mode, and MFES first followed by FIR.

Fig 1 RMS main effects plot

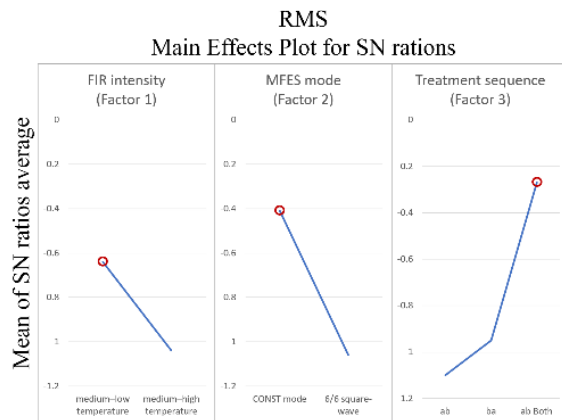
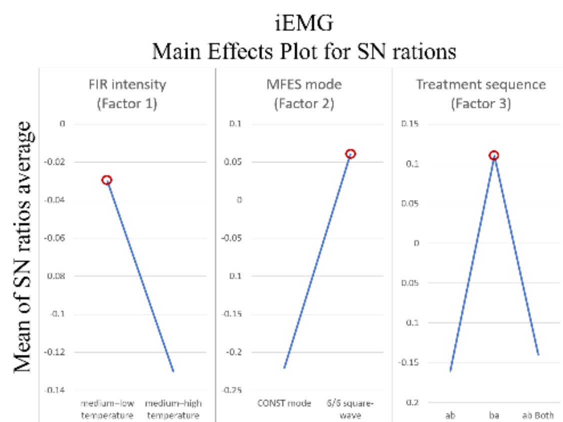


Fig 2 iEMG main effects plot



(3). VAS

The VAS is used to assess pain intensity, with a greater reduction indicating a more significant decrease in perceived pain. Since variations can be both positive and negative, the NTB characteristic was applied, with a target value of -100. The S/N ratio main effects plot is shown in Figure 3. The optimal VAS S/N ratio combination was: FIR medium–high temperature intensity, MFES 6/6 square-wave mode, and MFES first followed by FIR.

(4). QD

The QD records the extent to which shoulder and arm discomfort affects daily life, with the goal of maximizing score reduction. Since variations can be both positive and negative, the NTB characteristic was applied, with a target value of -30. The S/N ratio main effects plot is shown in Figure 4. The optimal QD S/N ratio combination was: FIR medium–low temperature intensity, MFES CONST mode, and FIR first followed by MFES.

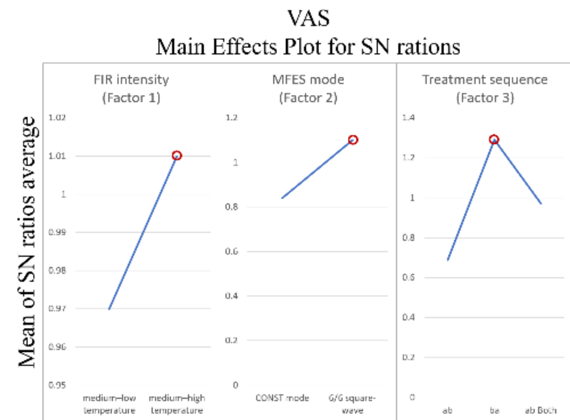


Fig 3 VAS main effects plot

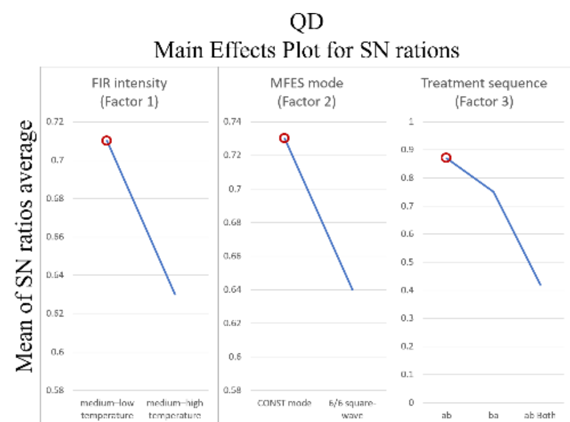


Fig 4 QD main effects plot

Discussion

Comprehensive S/N ratio analysis showed differing optimal combinations across indicators. For RMS, the best was FIR medium–low intensity with MFES CONST in simultaneous application; for iEMG, FIR medium–low intensity with MFES 6/6 square-wave applied before FIR; for VAS, FIR medium–high intensity with MFES 6/6 square-wave applied before FIR; and for QD, FIR medium–low intensity with MFES CONST applied before MFES. Overall, medium–low FIR was generally superior, both MFES modes were similarly effective, and applying MFES before FIR favored relaxation and pain relief. Variations among indicators reflected their nature: RMS and iEMG are objective physiological measures, whereas VAS and QD are subjective assessments influenced by perception and emotion.

RESULTS OF THE OPTIMAL PARAMETER COMBINATION OBTAINED BY OPTIMIZING TAGUCHI'S METHOD USING GENETIC ALGORITHMS

Research Methods

A multiple linear regression model with LOOCV was used to construct prediction models. Global optimization via GA, with repeated computations and averaging, reduced overfitting and improved parameter reliability. LOOCV predictions for RMS, iEMG, VAS, and QD are shown in Eq. (4.1)–(4.4) (Han, et al. 2006, Montgomery, et al., 2021), and fitness function definitions in Eq. (4.5)–(4.8) (Shao, 1993, Haupt, 2004), where AvgLoss denotes average error and ε a random perturbation term.

$$Y_{-i}^{RMS} = -(0.6887 - 0.2626x_1 - 0.2286x_2 + 0.0374x_3) \quad \text{(Eq. 4.1)}$$

$$Y_{-i}^{iEMG} = -(0.7380 - 0.3220x_1 - 0.1513x_2 - 0.0629x_3) \quad \text{(Eq. 4.2)}$$

$$Y_{-i}^{VAS} = -(0.6869 + 0.1019x_1 - 0.1301x_2 - 0.0986x_3) \quad \text{(Eq. 4.3)}$$

$$Y_{-i}^{QD} = -(-0.0534 - 0.0392x_1 + 0.2505x_2 + 0.2099x_3) \quad \text{(Eq. 4.4)}$$

$$Fitness_{RMS} = -(AvgLoss_{RMS} + \varepsilon) \quad \text{(Eq. 4.5)}$$

$$Fitness_{iEMG} = -(AvgLoss_{iEMG} + \varepsilon) \quad \text{(Eq. 4.6)}$$

$$Fitness_{VAS} = -(AvgLoss_{VAS} + \varepsilon) \quad \text{(Eq. 4.7)}$$

$$Fitness_{QD} = -(AvgLoss_{QD} + \varepsilon) \quad \text{(Eq. 4.8)}$$

The explanatory power of GA models was assessed using the coefficient of determination (R^2), with formulas provided in Eq. (4.9)–(4.12)[37] for RMS, iEMG, VAS, and QD. Here, the mean normalized S/N ratios of each indicator are denoted as $\overline{RMS_{norm}}$ 、 $\overline{iEMG_{norm}}$ 、 $\overline{VAS_{norm}}$ and $\overline{QD_{norm}}$. An R^2 close to 1 indicates strong predictive power, while values near 0 reflect weak performance.

$$R_{RMS}^2 = 1 - \frac{\sum_{i=1}^{n}(RMS_{norm,i} - Y_{-i}^{RMS})^2}{\sum_{i=1}^{n}(RMS_{norm,i} - \overline{RMS_{norm}})^2} \quad \text{(Eq. 4.9)}$$

$$R_{iEMG}^2 = 1 - \frac{\sum_{i=1}^{n}(iEMG_{norm,i} - Y_{-i}^{iEMG})^2}{\sum_{i=1}^{n}(iEMG_{norm,i} - \overline{iEMG_{norm}})^2} \quad \text{(Eq. 4.10)}$$

$$R_{VAS}^2 = 1 - \frac{\sum_{i=1}^{n}(VAS_{norm,i} - Y_{-i}^{VAS})^2}{\sum_{i=1}^{n}(VAS_{norm,i} - \overline{VAS_{norm}})^2} \quad \text{(Eq. 4.11)}$$

$$R_{QD}^2 = 1 - \frac{\sum_{i=1}^{n}(QD_{norm,i} - Y_{-i}^{QD})^2}{\sum_{i=1}^{n}(QD_{norm,i} - \overline{QD_{norm}})^2} \quad \text{(Eq. 4.12)}$$

Analysis Results

(1). RMS

The GA optimized the RMS performance value to 0.0533 at the 673rd iteration (Figure 5), corresponding to the optimal wellness parameter combination of FIR medium–low temperature intensity, MFES 6/6 square-wave mode, with FIR applied before MFES. The coefficient of determination R^2 was 0.1187, indicating that the model explained 11.87% of the variation in RMS S/N ratio.

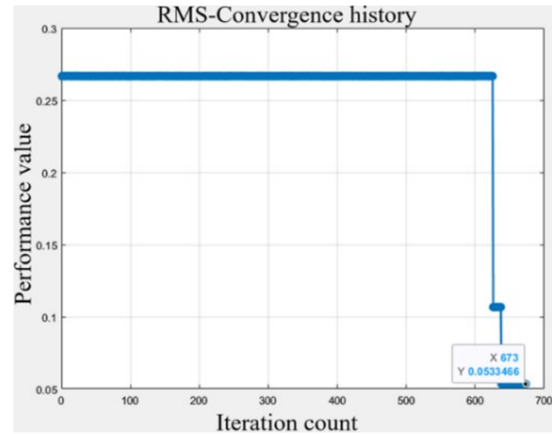


Fig 5 RMS-Convergence history

(2). iEMG

The GA optimized the iEMG performance value to 0.0494 at the 649th iteration (Figure 6), corresponding to the optimal wellness parameter combination of FIR medium–low temperature intensity, MFES 6/6 square-wave mode, with FIR applied before MFES. The coefficient of determination R^2 was 0.0938, indicating that the model explained 9.38% of the variation in iEMG S/N ratio.

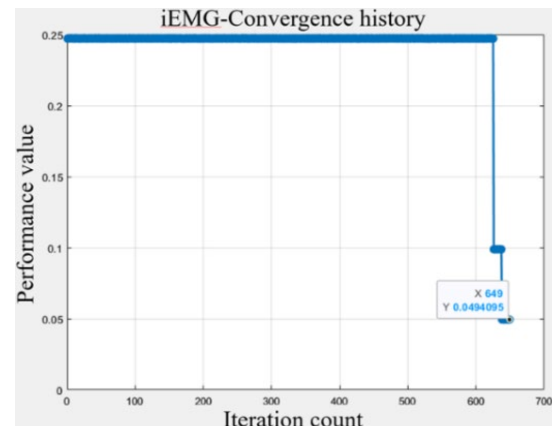


Fig 6 iEMG-Convergence history

(3). VAS

The GA optimized the VAS performance value to 0.0555 at the 661st iteration (Figure 7), corresponding to the optimal wellness parameter combination of FIR medium–high temperature intensity, MFES CONST mode, applied simultaneously. The coefficient of determination R^2 was 0.1666, indicating that the model explained 16.66% of the variation in VAS S/N ratio.

(4). QD

The GA optimized the QD performance value to 0.0327 at the 649th iteration (Figure 8), corresponding to the optimal wellness parameter combination of FIR medium–low temperature intensity, MFES 6/6 square-wave mode, with FIR applied before MFES. The coefficient of determination R^2 was 0.3340, indicating that the model explained 33.40% of the variation in QD S/N ratio.

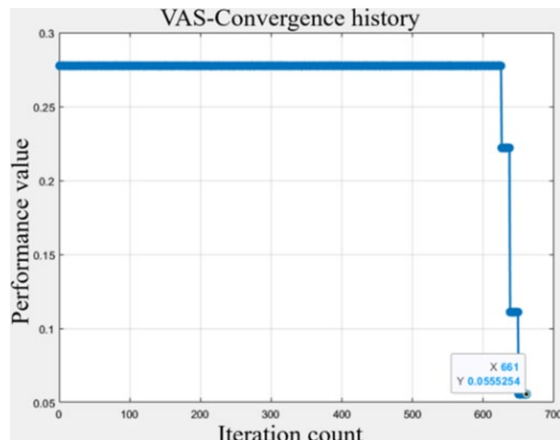


Fig 7 VAS-Convergence history

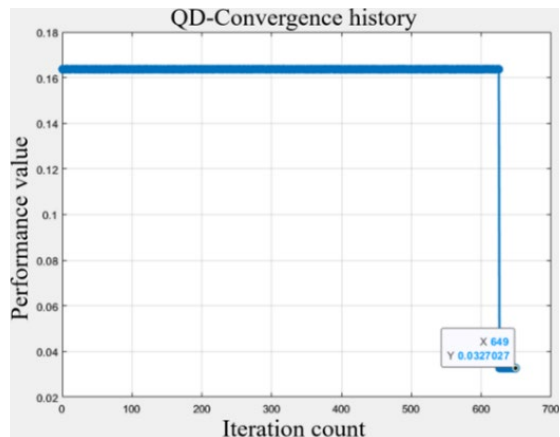


Fig 8 QD-Convergence history

Discussion

GA optimization indicated that the optimal combination for RMS, iEMG, and QD was FIR medium–low intensity with MFES 6/6 square-wave applied after FIR (R^2= 0.1187, 0.0938, 0.3340). For VAS, the best was FIR medium–high intensity with MFES CONST in simultaneous application (R^2= 0.1666). Except for VAS, results were consistent, suggesting potential benefits for muscle relaxation and functional improvement, with notable interaction effects between MFES mode and application sequence.

CONCLUSIONS AND FUTURE PERSPECTIVES

Conclusions

This study applied the Taguchi method combined with Genetic Algorithm (GA) optimization to determine the optimal parameter combination of far-infrared ray (FIR) intensity, medium-frequency electrical stimulation (MFES) mode, and treatment sequence for patients with adhesive capsulitis. The Taguchi analysis revealed that FIR at medium–low intensity generally produced superior outcomes across most indicators. Specifically, the optimal combinations were:

- **RMS:** FIR medium–low intensity, MFES CONST mode, and simultaneous application.
- **iEMG:** FIR medium–low intensity, MFES 6/6 square-wave mode, with MFES applied before FIR.
- **VAS:** FIR medium–high intensity, MFES 6/6 square-wave mode, with MFES applied before FIR.
- **QD:** FIR medium–low intensity, MFES CONST mode, with FIR applied before MFES.

GA optimization further refined these results. The optimal RMS, iEMG, and QD performance values were 0.0533, 0.0494, and 0.0327, respectively, achieved at the 649th–673rd iterations. The corresponding coefficients of determination (R^2) were 0.1187, 0.0938, and 0.3340, indicating reasonable model stability. For VAS, the best performance value (0.0555) and R^2 = 0.1666 were obtained under FIR medium–high intensity with MFES CONST mode applied simultaneously.

Overall, these findings indicate that the combination of medium–low FIR intensity and MFES 6/6 square-wave mode applied sequentially (FIR after MFES) can effectively enhance muscle relaxation and upper limb function, while medium–high FIR intensity with CONST mode is preferable for pain reduction. The results demonstrate that Taguchi–GA hybrid optimization can efficiently identify effective treatment parameter sets even with small sample sizes, supporting its potential use in clinical rehabilitation for adhesive capsulitis.

Future Perspectives

To enhance the performance of the model and its clinical value, the following improvements are recommended :

- **Expand input samples:** Increase sample size and incorporate diverse features such as age, sex, pain duration, and occupational patterns to derive more personalized and adaptive parameter combinations.
- **Upgrade algorithm models:** Based on the current multiple linear regression with LOOCV framework, introduce nonlinear models such as deep learning to improve the fitting and predictive capabilities for highly variable and

subjective indicators(e.g., VAS).

- **Long-term follow-up:** Assess the persistence of pain relief, muscle relaxation, and functional improvement after wellness interventions to verify clinical stability.
- **Intelligent modularization:** Modularize the model and develop an interface to rapidly provide optimal wellness parameter combinations based on input conditions.

In conclusion, the model developed in this study, integrating the Taguchi method with a genetic algorithm, holds potential for continuous optimization and practical application.

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