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Research Article

Feasibility of Neuro Prosthetic Functional Electrical Stimulation for Chronic Hemiplegia

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ABSTRACT

Purpose: To determine whether the optimal frequency of Neuro Prosthetic Functional Electrical Stimulation (NP-FES) to reawaken awareness of paralyzed hand movement for the purpose of disuse prevention in persons with chronic hemiplegia left with a paralyzed limb differs from that in the acute phase.

Design: Intervention study.

Setting: Japanese nursing home day care and community residents.

Participants: Eleven Elderly persons with hemiplegia aged 50-90 years.

Interventions: NP-FES (Neuro Prosthetic Functional Electrical Stimulator) applies 70 Hz and 120 Hz.

Control: NP-FES applies 35 Hz.

Main outcome measures: Interviewing whether the patient was again aware of the movement of the paralyzed hand, wrist extension angle, Body Mass Index (BMI) and pain.

Results: Awareness of the movement of the paralyzed hand again was answered positively in nine of the eleven participants. The wrist extension angle was stabilized and less pain was observed in five subjects at 70 Hz and in three subjects at 120 Hz.

Conclusion: Initial stimulation parameters for NP-FES to reawaken awareness of paralyzed hand movements in persons with chronic hemiplegia suggested different parameters than in the acute phase.

Keywords: Electrical stimulation; Disuse prevention; Body image; Chronic disease; Patients

INTRODUCTION

Chronic persons with hemiplegia face the fundamental problem of disuse functional decline of the paralyzed limb owing to physical resigned indifference. Physical resigned indifference is a term used to encompass various stroke sequelae such as visual-spatial resigned indifference, learned non-use and afferent sensory impairment. In rehabilitation treatment settings, although efforts are made to promote the use of the paralyzed limb, it is not easy for persons to naturally use the paralyzed limb in daily life.

Neuromuscular Electrical Stimulation (NMES) can improve spasticity, range of motion and upper extremity function and has been used as an effective tool for persons with hemiplegia [1-3]. Therefore, in many cases, the conditions for electrical stimulation by studies with the goal of restoring paralysis in the acute or rehabilitation phase and the pre-set conditions for the device are used. However, in many cases, the conditions for electrical stimulation are based on studies aimed at restoring paralysis during the acute or rehabilitation phase and these pre-set conditions for the device are commonly used. As a result, the conditions of electrical stimulation used in previous studies may not be optimal for individuals with chronic hemiplegia, who often experience the effects of disuse. In such cases, difficulty with voluntary movement frequently leads to a disused hand. In addition, malnutrition causes wasting of muscle and adipose tissues, which exacerbates sarcopenia [4]. Muscle atrophy also reduces the number of mobilized motor units [5]. As a result, it may require a higher frequency than in healthy muscles. Additionally, decreased muscle metabolism can lead to glucose depletion, which may reduce the maximum joint angle during repetitive motion [6]. Furthermore, it has been shown that as the thickness of subcutaneous fat increases, the stimulation current required to activate muscle also increases [7]. Therefore, higher frequencies than those used in the electrical stimulation parameters for acute hemiplegic persons may be necessary to maintain the reproducibility of joint movements [8]. This reduces dispersion on the skin and allows the current to flow

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more effectively towards the target muscle. This compensates for the reduction in current due to the increased impedance. Despite these concerns, most clinical settings use NMES devices at the same doses as persons in recovery and the underlying problem is a lack of evidence due to a lack of data. The paucity of clinical trials is also due to the lack of cost-effectiveness of investigational efforts. To solve this problem, quasi-randomized trials or other alternatives to clinical trials must be conducted while maintaining interest in the subject population.

The development of methods that maintain the interest of persons with chronic hemiplegia is eagerly awaited. Interest is closely related to making the paralyzed hand aware again of its movements. It has been reported that electric current stimulation has the effect of making persons aware again of the movement of this paralyzed hand, but in order to accumulate the number of cases that can contribute to the establishment of evidence through observational studies rather than clinical trials, it is essential to present a treatment method that attracts their interest. In particular, reducing pain during electrical stimulation can help decrease the patient's aversion and resistance to the treatment. In this study, we focused on NP-FES. This method allows persons to freely perform electrical stimulation themselves.

Movements are induced on the non-paralyzed side and the timing of electrical stimulation on the paralyzed side can be controlled by the patient's own will. This active involvement contributes to the generation of voluntary movements and decreases resistance to electrical stimulation. With repeated practice of this active control, the patient's interest in their paralyzed hand increases and they can expect an increased awareness and willingness to use their paralyzed limb. However, this is important to avoid fear or rejection of the pain of electrical stimulation, even in conventional NMES. In the acute phase, sensory nerves may be impaired together, which may make it difficult to feel pain. It is possible that adequate research cooperation could have been obtained without considering the motivation to use electrical stimulation on a daily basis.

Therefore, we focus on the use of a NP-FES. Regarding optimal conditions for electrical stimulation, Sentandreu-Mano et al., reported that 35 Hz was effective [8]. However, this study was conducted on persons in the acute phase. While this condition may be movement-creating in the acute setting, there are limited reports of this condition being equally effective in chronic persons due to the presence of peripheral neuropathy in the paralyzed hand, muscle degeneration and limited range of motion in the joints. Sasaki et al., have shown that electrical stimulation at 35 Hz is effective in persons with chronic conditions, while Gorgey et al., have described the effectiveness of low frequency based on its effect on reducing muscle fatigue [8,9]. On the other hand, in a study comparing high-frequency (100 Hz) and low-frequency (50 Hz) Transcutaneous Electrical Nerve Stimulation (TENS), Chen et al., reported greater comfort with high frequency [10]. In other words, high frequency may be more practical than low frequency, which is associated with strong pain. However, in these discussions, there has been no examination of optimal conditions using the improvement in reawaken awareness of paralyzed hand movement as a criterion. Clarification of these conditions would play an effective role in generating evidence.

Currently, there is no established consensus in national and international literature on the most effective method of functional electrical stimulation to create stable movements in persons with hemiplegia. "Stable movements" are defined as those with range of motion variability within one Standard Deviation (1 SD) and high reproducibility of the maximum extension movement. Therefore, we decided to use 35 Hz, a frequency widely used in NMES therapy, based on the report by Sentandreu-Mano et al. [8]. In addition, greater metabolic and mechanical stress to the muscle is necessary to initiate the processes that ultimately lead to muscle protein synthesis [11]. Therefore, it has been reported that high frequency (60 Hz) activates signaling pathways that promote muscle protein synthesis better than low frequency (20 Hz) [12]. Furthermore, it has been reported that high frequency (100 Hz) produces stronger torque than low frequency (20 Hz) when a stimulus with a wide pulse width (1 ms) is used [13]. This suggests that higher frequencies may result in greater joint motion. These findings suggest that high-frequency stimulation may have a higher therapeutic effect than low-frequency stimulation.

The reason it is important to reduce rejection of electrical stimulation is to motivate persons to become aware of their body's disuse and to actively use the hand on the paralyzed side. This innovative approach allows persons to determine the conditions of electrical stimulation themselves. This could replace traditional therapist-directed methods. It also allows for treatment planning that can help generate new evidence in clinical observational studies. The device is inexpensive and is expected to reduce economic barriers to providing treatment to a wide range of persons. In addition, allowing persons to administer their own treatments may facilitate future improvements in independence and Quality of Life (QOL) at a reasonable cost. In this study, persons with hemiplegia who had been paralyzed for more than one year were included. We then examined the effect of the NP-FES to make them aware again of the movements of the paralyzed hand. First, eligible chronic hemiplegic persons were recruited and listed. Next, we assessed the disuse status of the hand. After educating the persons on the use of the device and confirming the accuracy of the current stimulation, an experiment was conducted. Responses at different frequencies were recorded and procedures were followed.

MATERIALS AND METHODS

Participants were selected from those who met the inclusion criteria and responded to the call for participation. The study was conducted in a suburban area of Japan with a local government area population of 370,000 and an aging rate of 28% [14]. The subjects were persons with hemiplegia who regularly attended day rehabilitation services at a nursing home two to four times a week were included. Subjects were recruited who responded to the call to participate in the study. Inclusion criteria for hemiplegic group were a history of cerebrovascular disease for at least one year and an age range of 50-90 years. Both hemorrhagic and ischemic stroke persons were included, without focusing on specific brain regions. However, most persons had a history of ischemic stroke and exhibited pyramidal tract impairment. Participants with hemiplegia should present with a Brunnstrom stage at least two for hemiplegia of the hand in order to be included in the study. Exclusion criteria included peripheral neuropathy, Mini-Mental State Examination (MMSE) score of 10 or less, sensory loss and visual spatial resigned indifference that prevented recognition of the condition of both upper limbs. Prior to the study, participants received a comprehensive written and verbal description of the study and their willingness to participate was confirmed by a signed informed consent form. During the entry phase, recruitment was conducted by displaying a poster in the facility, indicating the nature of the experiment and verbally confirming willingness

to participate. If the selection criteria were met, the prospective participants were given a full written and oral explanation of the study purpose and ethical considerations and only those who agreed to participate were enrolled. This study was approved by the Gunma PAZ University Ethical Review Committee (PAZ21-17). The study was registered in the UMIN Clinical Trials Registry, number UMIN000051267.

The assessment items included differentiation of whether or not the patient was again aware of the movement of the paralyzed hand, which reflected body part resigned indifference. The incidence of positive expressions was assessed by recording the two values of "cannot move" and "can move" after the intervention.

Body weight, BMI, body fat percentage and skeletal muscle mass were measured using the in body dial (In Body Japan Corporation, Republic of Korea). Pain was assessed using a Numerical Rating Scale (NRS: 0=no pain at all to 10=unbearable pain).

The specific experimental procedure first involved postural control. The subjects were seated in a chair with a (Japanese Industrial Standards) JIS standard backrest based on a standard human skeletal specimen and their forearms were placed on a table at 30° of shoulder flexion and 60° of elbow flexion. An input electrode was affixed to the dorsal surface of the healthy forearm to perform the timing of the switch by itself for electrical stimulation and two stimulation electrodes were affixed to the dorsal surface of the forearm of the paralyzed hand. The NP-FES was attached in such a way that the input and output devices formed a circuit in the same individual (Figure 1).

We modified the ARDUINO program to create a clone that outputs based on the frequency conditions of the TENS3000 when the input-side electromyography signal exceeds the threshold through BPIO (Bi-directional Parallel Input/Output).

Movement measurements were made using an EXLIM EX-FH20 (CASIO) with a resolution of 1280 × 720 pixels and 30 frames per second (fps). We evaluated the maximum wrist joint angle achieved through muscle contraction induced by electrical stimulation. Since the persons were not actively try to move the joint themselves, the movements generated by electrical stimulation was considered passive range of motion. To accurately assess these movements, we analyzed video recordings taken from the sagittal plane to determine the maximum extension angle of the wrist joint. The movement created by NP-FES was measured in terms of the extension angle of the wrist joint.

Video images during the experiment were processed using PV-studio 2Dver2 (OA Science Corporation, Japan), a software program for analyzing the trajectory coordinates of target landmarks on video images. The wrist extension angle was calculated using the lateral humeral epicondyle, styloid process of ulna and fifth metacarpal head as landmarks.

The functional electrical stimulation exercise intervention method was as follows: Low-frequency, biphasic square waves were administered using a Backyard Brains (USA) Human-Human interface. The input electrode, which performs the timing of the switch for electrical stimulation itself, was affixed to the dorsal forearm of the non-paralyzed side and two stimulation electrodes were affixed to the dorsal forearm of the paralyzed hand. When the patient tried to move the paralyzed hand Themselves, they contracted the muscles on the non-paralyzed side. The device used an Arduino-based microcomputer to detect when the myopotential threshold reached 9 to 15 mV and to switch on and off the electrical stimulation on the paralyzed side at its own will and timing. Specifically, 2-inch square electrodes were placed 1.2 inches apart along the extensor digitorum muscle in the middle half of the dorsal forearm and electrical stimulation was administered accordingly. This produced wrist extension and some extension of the fingers was obtained. This creates a new non-invasive, self-contained external nerve conduction circuit.

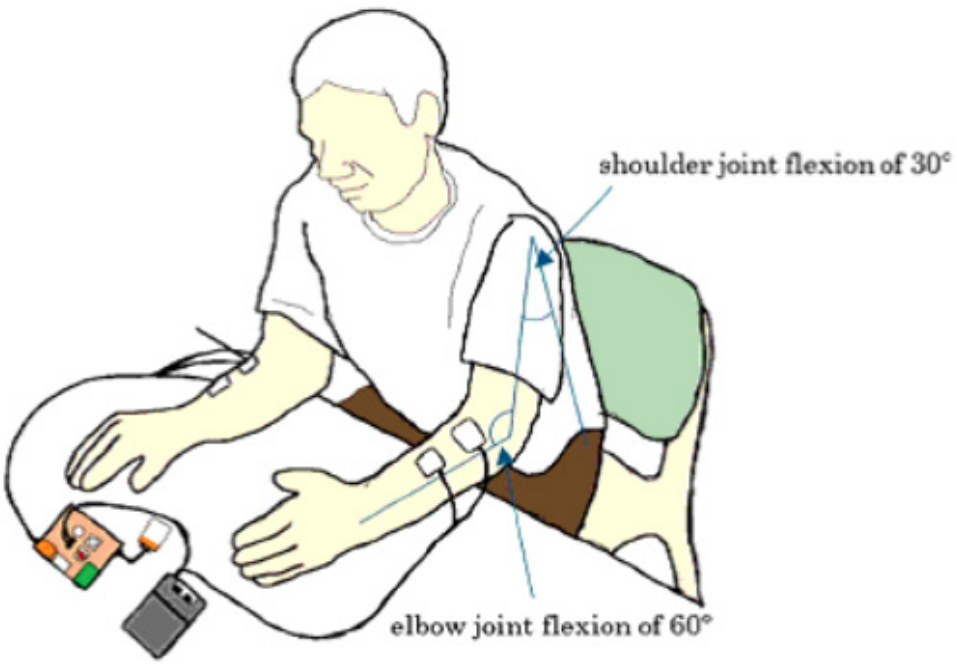

Figure 1: Usage scenario of the Neuro Prosthetic Functional Electrical Stimulation (NP-FES) system.

Three different frequency conditions (35, 70 and 120 Hz) were used for stimulation. The intensity of the electrical stimulation was kept constant across all frequencies. The order of the stimulation parameters was determined using a computerized random number generator. The study was conducted according to the L2 (8) orthogonal array design. Subjects were blinded to the stimulus parameters. The wrist extension exercise involved extending the wrist in three repetitions per set, performed in four sets. This was done for each of the three frequency conditions (35, 70 and 120 Hz). The intensity of the electrical stimulation was constant. The maximum value of three consecutive repetitions of wrist extension in each set was used for analysis. The action potentials of the non-paralyzed side hand were used to switch the electrical stimulation on and off. Specifically, the muscle potential threshold of the brachioradialis muscle in the non-paralyzed side hand was used to control the electrical stimulation. An appropriate stimulation frequency condition was defined operational as the condition that maximizes the extension angle of the wrist joint, while minimizing pain.

Therefore, the commonly used 35 Hz was used as the control condition in this study. Higher frequency bands of 70 Hz and 120 Hz were used as intervention conditions. These frequency conditions (35, 70 and 120 Hz) were evaluated to induce extension of the wrist joint to examine the effectiveness of different current conditions. A pulse width of 120 μs was used for all frequencies. The results were obtained from a single session, in which wrist extension was performed a total of twelve times for each condition.

Statistical analysis

Some of the statistical analysis includes:

Wrist extension angle and pain assessment: Normality of the data was assessed using the Shapiro-Wilk test. Nonparametric Friedman test was used to analyze significant differences between the three frequency conditions (35 Hz, 70 Hz and 120 Hz) for Maximum extension angle of the wrist joint and pain, as normality was not confirmed.

Association between awareness of paralyzed hand movements and frequency: The chi-square test was used to examine the association between awareness of paralyzed hand movements ("can move" or "cannot move") and the three frequency conditions (35 Hz, 70 Hz and 120 Hz).

Association with other factors: To examine the association between awareness of paralyzed hand movements and BMI, skeletal muscle mass, body fat percentage, months since onset, age, severity of hand paralysis, maximum frequency and maximum extension angle of the wrist joint, we divided the data by median values and conducted a chi-square test.

Complementary Bayesian estimation was also used to examine whether these factors were significant predictors for paralyzed hand movement awareness.

Product set of pain and variance: Using pain (<7 in the NRS as 1 and >7 as 0) and motor stability (variance <1 SD as 1 and >1 SD as 0), we examined the distribution of participants who met these two conditions by frequency condition. This identified the optimal frequency condition that satisfied both pain and motor stability.

In this study, we focused on awareness of movement for the paralyzed hand and expected a significant effect size (Cohen's d=0.9 to 1.2). Awareness of paralyzed hand movement refers to the state in which a chronic hemiplegic actively maintains self-practice in order to maintain the health of the paralyzed hand. It also includes an interest in restructuring the movement of the paralyzed hand and making a financial investment in treatment. We defined this outcome operationally with the awareness of "being able to move the joint spontaneously." For persons with hemiplegia who have relatively fixed levels of paralysis, the use of NP-FES, which can induce joint movement, was anticipated to result in substantial improvements in this awareness (Figure 2).

Therefore, we estimated a high effect size for this outcome. Based on this effect size, the sample size required to ensure 80% statistical power and a 5% alpha level was pre-calculated using SPSS. The calculations estimated that 10-16 participants per group would be required.

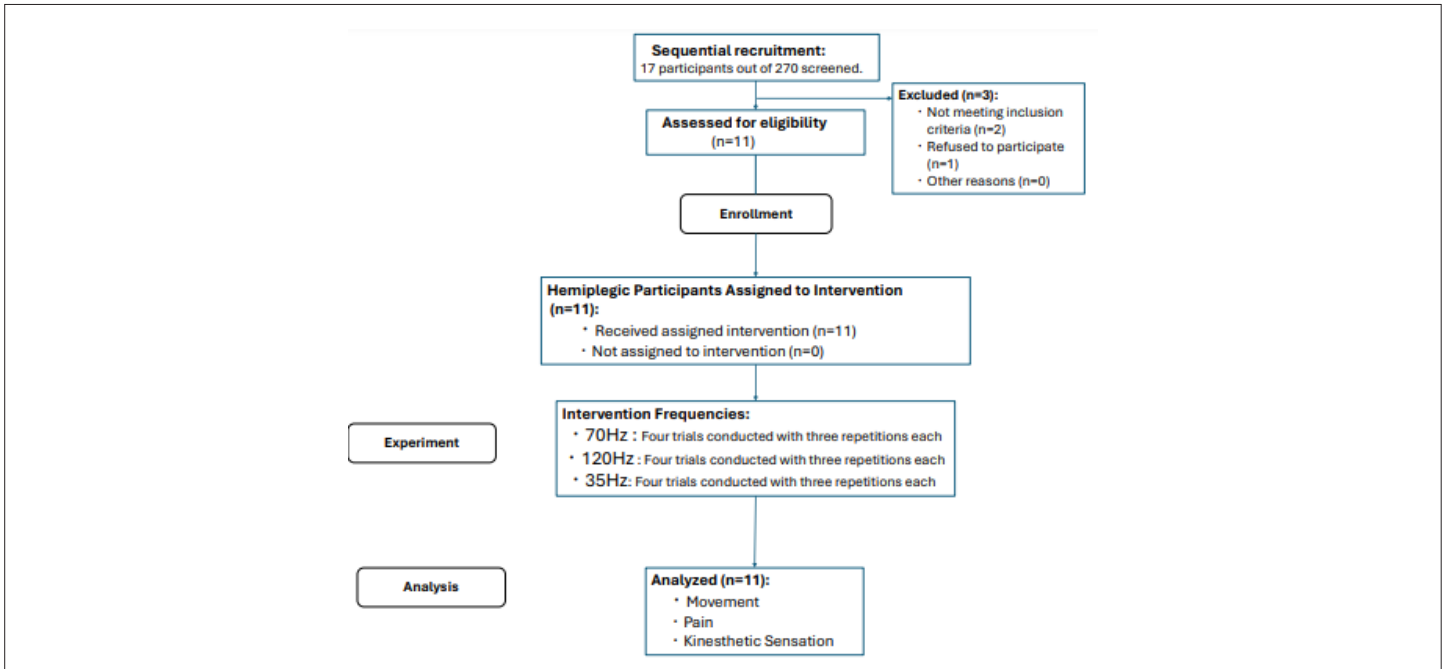

Figure 2: Flowchart of participant recruitment, enrollment and analysis for the neuroprosthetic intervention study.

RESULTS

Subject characteristics

There were eleven persons with hemiplegia. Of the total sample, 36.4% were male. The mean age was 68.8 (± 11.6) years, ranging from 50 to 84 years. The mean elapsed time from stroke onset to investigation for persons with hemiplegia was 75.7 (± 51.9) months, with a minimum of 12 months and a maximum of 160 months (Table 1).

Table 1: Characteristics of subjects.

	Hemiplegic	Subjects (n=11)
	Mean	SD
Age (years)	68.8	11.6
Gender (% male)	36.4	-
Height (cm)	148.5	13.3
Weight (kg)	53	7.6
BMI	24.3	3.9
Severity of paralysis	Br. stage hand 2-4	

Note: Br stage: Brunnstrom stage; SD: Standard Deviation.

Friedman test results for maximum extension angle of the wrist joint and pain

The results for the maximum extension angle of the wrist joint and pain for each frequency are shown (Figure 3).

The Friedman test was performed because of the lack of normality of the data. The Friedman test did not identify significant differences between the three frequency conditions (35 Hz, 70 Hz and 120 Hz) for maximum extension angle of the wrist joint and pain (Table 2).

Maximum extension angle of the wrist joint: The mean rank was 1.75 (35 Hz), 2.13 (70 Hz) and 2.13 (120 Hz), with a chi-square value of 1.500, p=0.472.

Pain: Mean rank was 1.69 (35 Hz), 2.06 (70 Hz) and 2.25 (120 Hz), with a chi-square value of 3.652, p=0.161.

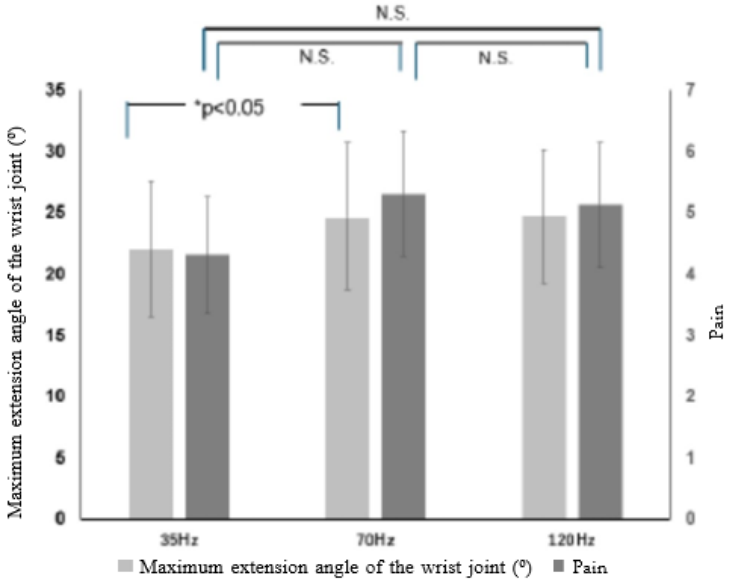

Figure 3: Mean frequency on the maximum extension angle of the wrist joint and pain during electrical stimulation.

Table 2: Friedman test results for maximum extension angle of the wrist joint and pain during electrical stimulation (n=11).

	Frequency	Median	Mean rank	Chi-square	p-value
Maximum extension angle of the wrist joint (°)	35 Hz	25.83	1.75	1.5	0.472
	70 Hz	28.31	2.13	-	-
	120 Hz	27.9	2.13	-	-
Pain	35 Hz	3.5	1.69	3.652	0.161
	70 Hz	5	2.06	-	-
	120 Hz	5	2.25	-	-

Note: p-value statistically significant at the p<0.05.

Chi-square test results for awareness of paralyzed hand movements by frequency

A chi-square test was conducted on the association between awareness of paralyzed hand movements ("can move" and "cannot move") and frequency (35 Hz, 70 Hz and 120 Hz). The results confirmed a significant association between the frequency condition and the perception of paralyzed hand movements. The results of the chi-square test showed a chi-square value of 11.727, p=0.003, indicating a significant difference in the perception of paralyzed hand movements among the three frequency conditions. In particular, more participants reported "moved" in the 70 Hz and 120 Hz frequency conditions (Table 3).

Chi-square test results and Bayesian chi-square test results

BMI, skeletal muscle mass, body fat percentage, months since onset, age, severity of hand paralysis, maximum frequency and maximum extension angle of the wrist joint were divided into two median values and their association with the perception of paralyzed hand movements was examined by chi-square test and Bayesian estimation. The results of the chi-square test showed no significant differences in the following factors, but the maximum extension angle of the wrist joint had a p-value of 0.087 (Table 4).

Pain and variance as a product set

The results were examined as a product set, where pain was less than 7 on the NRS and the variance of the extension angle was less than 1 SD. As a result, zero participants were identified in the 35 Hz condition, five participants in the 70 Hz condition and three participants in the 120 Hz condition, with more participants meeting the criteria in the 70 Hz condition compared to the other frequencies (Table 5).

Table 3: The outcome of whether participants answered that they might be able to move their paralyzed hand, in relation to the frequency during electrical stimulation and other frequencies (Chi-square test results).

Frequency	Movement (Yes)	Movement (No)	Chi-Square	p-value
35 Hz	3	8	11.727	0.003
70 Hz	9	2	-	-
120 Hz	10	1	-	-

Note: Movement (Yes) indicates the number of respondents who answered 'can move' and 'cannot move'; Movement (No) is the number of respondents who answered cannot move.

Table 4: The association between the binary conditions for whether or not the participants answered that they might be able to move their paralyzed hand, with the variables dichotomized using the median and the outcome presented using Chi-square test results and Bayesian factor.

Factor (Median)	Chi-Square value	(χ^2) Chi-Square p-value	Bayesian BF_{10}	Posterior mean (95% CI)
BMI (23.5)	0.02	0.887	0.733	0.196 (-2.34, 2.74)
Skeletal muscle mass (22.1)	0.02	0.887	0.733	0.205 (-2.37, 2.77)
Body fat percentage (33.0)	2.037	0.154	1.467	-1.698 (-4.766, 1.37)
Months since onset (69.0)	0.02	0.887	0.733	0.013 (0.00, 0.02)
Age (67.0)	0.02	0.887	0.733	0.187 (-2.36, 2.73)
Severity of hand paralysis (4)	0.196	0.658	0.786	0.621 (-1.93, 3.18)
Maximum frequency (3.0)	2.037	0.154	1.467	-1.708 (-4.79, 1.38)
Maximum extension angle of the wrist joint (38.8)	2.933	0.087	2.2	2.142 (-0.99, 5.27)

Note: The values in parentheses represent the 95% Confidence Interval (95% CI).

Table 5: Intersection of stable movement and tolerable pain by frequency in each case.

ID	Severity of hand paralysis	35 Hz pain	70 Hz pain	120 Hz pain	35 Hz movement	70 Hz movement	120 Hz	Intersection (pain+movement)
1	4		X	X		X	X	70 Hz, 120 Hz
2	4	X	X				X	
3	3	X						
4	4	X				X	X	
5	4	X	X			X		70 Hz
6	3	X				X	X	
7	4						X	
8	3	X	X			X		70 Hz

9	2	X	X	X	X		70 Hz
10	4	X	X	X	X	X	70 Hz,120 Hz
11	4	X	X	X		X	120 Hz

Note: X for pain means the mean value is less than NRS 7; X for Movement means the variance of the extension angle is less than 1 standard deviation; The intersection is represented by "X" frequencies for both pain and movement. Severity of hand paralysis means Brunnstrom stage of hand.

DISCUSSION

Results of the Friedman test for extension angle and pain

The Friedman test for extension angle and pain showed no significant differences among the three frequency conditions. This was a nonparametric test and was analyzed by median in the sample obtained in this study. This suggests that neither the extension angle nor the degree of pain changed significantly at any of the frequencies.

Awareness of paralyzed hand movements and differences by frequency

A significant association between frequency conditions and awareness of paralyzed hand movements was observed. More participants reported that they could move in the 70 Hz and 120 Hz conditions, suggesting that these conditions were more effective than the 35 Hz condition. These results indicate that frequencies of 70 Hz and 120 Hz may improve motion perception in the paralyzed hand.

The hemiplegics in this study had been paralyzed for more than one year and the degree of paralysis was fixed to some extent. It has been suggested that microcirculatory function in the skin of the paretic upper limb may be impaired after stroke [15]. In chronic hemiplegic persons, prolonged peripheral vascular dysfunction and poor circulation may exacerbate muscle atrophy and delay recovery. It has been reported that physical function, including participation in ADLs, correlates with self-efficacy and that persons with low self-efficacy are more likely to become depressed than those with high self-efficacy [16]. Owing to paralysis, hemiplegics are thought to have been in a state of resignation. However, after performing NP-FES, the persons were able to feel that their paralyzed limbs could move again and the high affirmation rate of being aware of the movement of the paralyzed hand again suggested that it may lead to the creation of new motivation for rehabilitation. The impaired circulation in these patients could also contribute to increased pain sensitivity during stimulation, making the careful selection of frequency even more important for balancing pain and motor function outcomes. The significantly higher rate of positive reaffirmation of awareness of paralyzed hand movement observed in this study suggests that NP-FES can be an effective intervention to increase awareness of the ability to move the paralyzed limb, which may improve overall rehabilitation outcomes. In the acute phase, 35 Hz may correspond to more severe symptoms. With the same current intensity, higher frequencies tend to reduce pain but are more likely to cause fatigue and result in weak. In this trend, for cases of mild paralysis, 120 Hz may cause increased pain as current intensity rises, potentially reducing adaptability.

The superiority of 70 Hz and 120 Hz over 35 Hz may be attributed to the fact that higher frequencies are more likely to penetrate thicker subcutaneous fat and activate deeper muscle tissue. This is supported by previous research on the effects of fat thickness and electrode configuration during NMES [16].

The results of the chi-square test for individual factors also showed no significant differences, but the maximum extension angle may be a potential factor with p=0.087 and BF=2.200.

What is the optimal frequency as an initial stimulation parameter?

The results, investigated as a product set with pain less than NRS 7 and variance less than 1 SD, suggest that the 70 Hz condition may be superior to other frequencies. When pain is severe, subjects may refuse to continue electrical stimulation due to pain, even when extension movements are emerging. In fact, reactions focused on pain were obtained in subjects who responded with NRS 8 or higher and were negative. Therefore, the analysis was conducted assuming that pain up to NRS 7 was acceptable pain.

The subject's reactions were positive when the extension movement obtained by electrical stimulation appeared stable. Therefore, one index was defined as stable movement generation of less than 1 SD. The results suggested that 70 Hz was the optimal frequency, which elicited stable movement with less pain.

It is believed that increasing the frequency and intensity of muscle contraction is thought to result in more powerful contractions [17]. The 35 Hz reported in the acute phase suggests less pain in chronic hemiplegic persons. However, higher frequencies may be effective in generating stable extension movements.

From this, if stimulation parameters are determined by intersection, the conditions with less pain are 35 Hz and 70 Hz and those with greater movement are 70 Hz and 120 Hz. Therefore, selecting 70 Hz as the initial stimulation parameter seems reasonable.

CONCLUSION

The present study shows that 70 Hz may be the optimal frequency to increase the affirmation rate of re-awakening awareness of paralyzed hand movements in the disused hand of persons with chronic hemiplegia during NP-FES adaptation. Electrical stimulation at this frequency significantly increased the affirmation rate of re-awakening awareness of the paralyzed hand movement before and after NP-FES in the product set condition of pain and movement, while at the same time minimizing pain compared to higher frequencies.

LIMITATIONS

Future studies should be cautious in interpreting these results, as larger samples and diverse patient groups cannot be included. Therefore, a comprehensive Bayesian estimation was also performed. The results may provide complementary information to the analytical results.

A further limitation of the present study is that the affirmation rate of reaffirming awareness of the movement of the paralyzed hand needs to be examined in more detail.

All frequencies successfully induced movement in each participant. However, the effectiveness was influenced by age-related muscle denervation or degeneration in participants aged 50-90 years. The extension induced by the stimulation was often brief and difficult to maintain as a functional movement. Consequently, the responses to electrical stimulation may differ from those typically observed in the acute phase.

Future studies should further investigate the interaction of body composition, frequency and NP-FES efficacy as similar trials are conducted in different facilities and regions to further accumulate data to increase the positivity of re-awakening awareness of paralyzed hand movements.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

All prospective participants received both a written and oral explanation of the study's purpose, procedures and ethical considerations, in accordance with the Declaration of Helsinki. They were informed that participation was voluntary and they had the right to withdraw from the study at any time without penalty. Only those who provided written informed consent were included in the study. This study was approved by the Gunma PAZ University Ethical Review Committee (PAZ21-17) and registered in the UMIN Clinical Trials Registry (UMIN000051267).

CONSENT FOR PUBLICATION

Participants were fully informed, both in writing and verbally, about the study's objectives, ethical considerations and the possibility of publication. Written consent was obtained for the publication of any anonymized data.

AVAILABILITY OF DATA AND MATERIALS

The datasets generated and/or analyzed during the current study are not publicly available due to (insert reason, if applicable), but are available from the corresponding author upon reasonable request.

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AUTHORS CONTRIBUTIONS

All authors contributed equally to the conception, design and writing of the manuscript. No specific individual contributions are to be highlighted.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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