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RESEARCH ARTICLE

Selective Drive and Control of Index Finger Joint Using Multipoint Functional Electrical Stimulation

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ABSTRACT Functional electrical stimulations (FES) drive human joints by stimulating peripheral nerves electrically. FES is applied to the rehabilitation of paralyzed patients or force feedback applications. However, exerting a large force to a specified finger using FES is difficult, because high-intensity stimulation can cause low selectivity. This problem is remarkable for the index finger because its fascicles are distributed deep in the forearm with a small area close to the skin. This paper describes a method for simultaneously stimulating multiple points to solve the problem. We conducted experiments focusing on selectivity and exerting torque to the index finger. The phase difference between stimulation waveforms and electrode isolation states were varied in the experiments. The proposed method was confirmed to induce a larger force than one-point stimulation and did not deteriorate selectivity if appropriate parameters were selected. Moreover, a finger angle control experiment considering selectivity was conducted. The selectivity problem makes selective control difficult. The proposed method was advantageous for finger controlling.

INDEX TERMS Finger control, functional electrical stimulation, haptic interfaces, motion control, selective stimulation.

I. INTRODUCTION

Functional electrical stimulation (FES) is used to drive human joints by electrically stimulating their peripheral nerves [1]. FES has mainly been studied for patient rehabilitation for spinal cord injuries. For instance, there are studies on grasping, standing, and walking movements using FES [2], [3], [4]. Moreover, in recent years, FES has been applied to force feedback systems. Tamaki et al. used FES to drive fingers and proposed its use for helping people play musical instruments [5]. Lopes et al. combined FES with a virtual reality system to allow users to experience the reaction force from virtual objects [6]. In addition, FES was shown to applicable to bilateral control systems between two humans [7] or between a human and a robot [8]. To make FES control suitable for use by healthy people, which requires high controlling performance, a high-precision controlling method using FES has been studied [9].

There are numerous activities that require hand movements in our daily life. Owing to this, several FES devices have been developed for hand movements. Devices such as the Handmaster [10], Bionic Glove [11], and MecFes [12] are well known. However, it is still challenging to realize fine finger movements with FES. This failure is because electrical stimulations activate nerves of muscles that should not be activated, harming selectivity [13]. Hence, driving the desired

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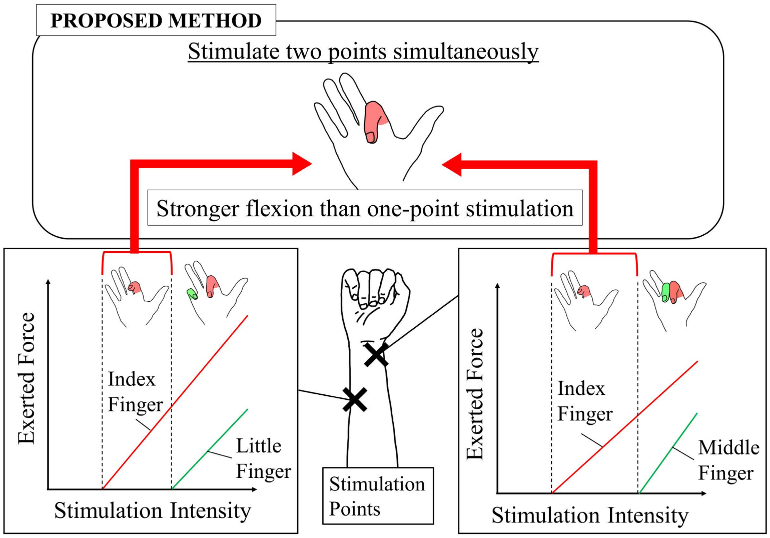


FIGURE 1. Concept of the proposed method. Note that this figure shows an example, and the fingers flexed simultaneously depends on the distribution of finger muscles. In this example, the target finger is the index finger. Each stimulation point (×) has a range of stimulation intensities, retaining selectivity. By stimulating these points with the intensities within the range, the index finger will independently bend by a large degree.

fingers using FES is difficult. This is because muscles that generate finger movements are distributed densely on the forearm [14]. Invasive electrodes have better selectivity than non-invasive electrodes. However, invasive electrodes require surgical operations and have infection risks [15], [16]. Therefore, muscles must be selectively activated via non-invasive electrodes.

Electrode arrays have been proposed for detecting the appropriate stimulation points on the forearm [17], [18], [19]. An electrode array consists of multiple small electrode pads. With an electrode array, we can change stimulation points without physically moving electrode pads. Electrode arrays are effective in searching for appropriate stimulation points because they can scan many stimulation points in a short time. However, in FES for fingers, the selectivity also depends on the stimulation intensity. Namely, when the stimulation intensity increased, the selectivity can worsen [20], [21]. The two graphs at the lower half of Fig. 1 illustrate the examples when increased stimulation intensity moves undesired fingers (little and middle fingers), although an independent flexion of the index finger was desired. This is likely to occur when the motor points of the fingers are close. We focused on the index finger because selective activation is more difficult for it than others. In a previous study on an electrode array [19], the index finger was flexed independently in 2 out of 8 participants, which was the most difficult among four fingers (index, middle, ring, and little fingers). This low success rate is likely because the fascicles of the index finger are distributed relatively deep in the forearm with a small area close to the skin [14].

To solve this problem, we propose the stimulation of the nerves of finger muscles via multiple stimulation points that drive the same fingers. This scheme can make the exerted force larger than that of conventional one-point stimulations, and selectivity can be ensured by limiting the stimulation intensities at each point. Therefore, this method could selectively exert a large force, which cannot be realized with one-point stimulation. Note that even though the conventional methods [17], [18], [19] use multiple electrodes, they drive one joint with one pair of electrodes. The concept of the proposed method is illustrated in Fig. 1.

Surface-distributed low-frequency asynchronous stimulation (sDLFAS) has been proposed for simultaneously stimulating multiple points [22], [23], [24]. It can reduce muscle fatigue because multiple points are stimulated sequentially, which results in decreased stimulation frequency on each point. However, these studies did not focus on the selectivity of finger muscles, and there was no detailed investigation of the phases of the stimulation waveforms. Moreover, most of them realized multi-point stimulation by distributing only one stimulator output with fast switching, which was unable to simultaneously stimulate multiple points completely. They hypothesized that if the intervals between stimulation pulses to each electrode were shorter than the refractory period of the cells: 5 ms or less, the effect of the stimulation is the same as when stimulating all the points synchronously [25].

The main objective of this study is to examine the capacity of multi-point stimulation to induce a larger force than one-point stimulation while maintaining high selectivity.

FIGURE 2. Example of electrode placement.

TABLE 1. Physical information of the participants.

	Participant			
	P	Q	R	S
Length from the elbow joint to the tip of the hand	0.42	0.42	0.40	0.45
Length of the forearm's arm circumference	0.28	0.25	0.21	0.23

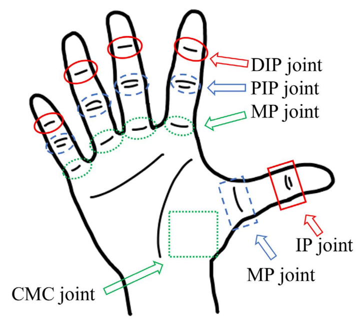


FIGURE 3. Name and position of hand joint.

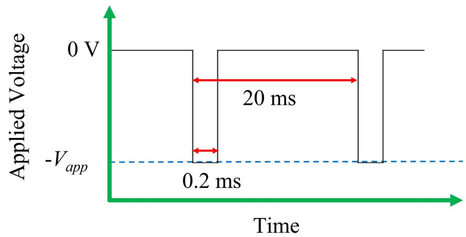


FIGURE 4. Stimulation voltage waveform used in the experiment.

Moreover, we investigated the effect of the phase difference between stimulation waveforms applied to each electrode and the effect of isolation. Additionally, we conducted finger joint angle control using multi-point stimulation.

The remainder of this paper is organized as follows: Section II describes the environment of the experiments we conducted. Section III describes the processes and results of the experiments and analyses. Section IV provides a discussion of the results, and section V concludes this paper.

II. EXPERIMENTAL ENVIRONMENT

We employed two-point stimulation for multi-point stimulation. Experiments 1 and 2 were conducted to examine selectivity and exerted torque, respectively. The relationship between the stimulating intensity and finger angle was investigated in experiment 3. Furthermore, we conducted finger joint angle control using two-point stimulation in experiment 4. To avoid muscle fatigue, we took breaks for each experiment. The target finger was the index finger of the right hand, and we searched for two stimulation points that caused index finger flexion for each participant. We obtained permission from the system information research ethics committee of the University of Tsukuba for the experiments. The participants were three right-handed healthy men and one healthy woman. All the participants were in their twenties, and were labelled as P, Q, R, and S. The participants previously participated in FES experiments but did not use FES daily. The lengths from the elbow joint to the hand tip and the lengths of the forearm's arm circumference are listed in Table 1. To protect their personal information, their age and gender are not listed. Informed consent was taken from the participants before the experiments.

A. STIMULATOR

A voltage-controlled stimulator developed following Japanese Industrial Standards (JIS) was used. For safety, the stimulator had a current limiter that limited the current output to 20 mA or more.

B. ELECTRODE PAD

Adhesive electrodes were used to apply electrical stimulation. Round electrodes (with a diameter of 2.5 cm) or small rectangular electrodes (2.0 cm $\times$ 1.5 cm) were used as cathodes, and large rectangular electrodes (4.0 cm $\times$ 9.0 cm) were used as ground electrodes. To reduce electric resistance, conductive gel was applied between the skin and electrodes. Two stimulation points to flex the index fingerwere selected for each participant, and cathodes were placed on them. When selective stimulation points could not be found with the round electrodes, we used small rectangular electrodes instead, because smaller electrodes are better for selective stimulation [19]. The two stimulation points and electrodes were defined as A and B, and the point closer to the thumb was A. An example of electrode placement is shown in Fig. 2.

C. MEASURING JOINT ANGLE

We employed a data glove (Prime X Haptic; Manus, Netherlands) to measure finger joint angles (Fig. 2). The sampling rate was 90 Hz. The finger proximal interphalangeal (PIP) joint and thumb carpometacarpal (CMC) joint angles were measured. The direction in which the fingers bent was defined as the positive direction. The measurable ranges of the angles were 0° to 100° for the PIP joints and −40° to 5° for the CMC joint. Fig. 3 shows the names and positions

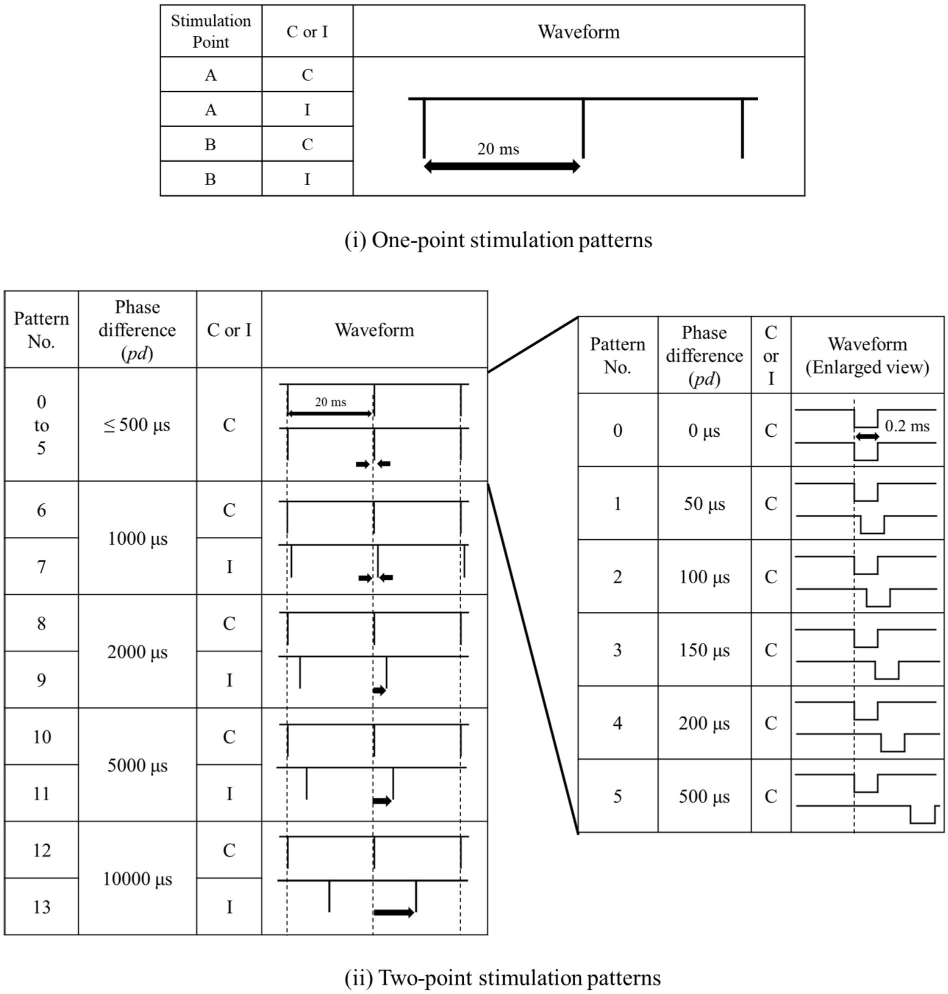


FIGURE 5. **Stimulation patterns used in the experiment. The patterns of one-point stimulation are listed in (i), and those of two-point stimulation are listed in (ii). The letters "C" and "I" represent conducted and isolated patterns, respectively.**

of finger joints. Before each experiment, the data glove was calibrated.

D. STIMULATION VOLTAGE WAVEFORM

The stimulation voltage waveform was a square wave of 50 Hz with negative voltage pulses. The pulse width was 0.2 ms (Fig. 4). Fig. 5 shows the stimulation patterns used in experiments 1 and 2. The stimulation patterns are roughly divided into two: one is the group of one-point stimulation (Fig. 5 (i)), and another is the group of two-point stimulation (Fig. 5 (ii)).

1) ONE-POINT STIMULATION

In a one-point stimulation, stimulation was applied to either point A or B. Moreover, there were two variations in the isolation state. One was the "conducted pattern" and the other was "isolated pattern". Within conducted patterns, the nonstimulating cathode was connected to the ground. On the other hand, in isolated patterns, the nonstimulating cathode was isolated from the stimulation generator using photocouplers. The letters "C" and "I" in Fig. 5 represent the conducted and isolated patterns, respectively. The examples are shown on the left side of Fig. 6. Within the blue shaded zones of Fig. 6, the electrodes are connected to the ground and isolated from the stimulation generator within the orange shaded zones.

2) TWO-POINT STIMULATION

In two-point stimulation, stimulation was applied to both points A and B. Note that the stimulation voltage waveform applied to each electrode was the same as that shown in Fig. 4. The parameters of the two-point stimulation were phase difference and isolation state.

a: PHASE DIFFERENCE

We defined the phase difference between the waveforms to points A and B as *pd*. The maximum value of *pd* was 10000 μs, which was the waveform's half period.

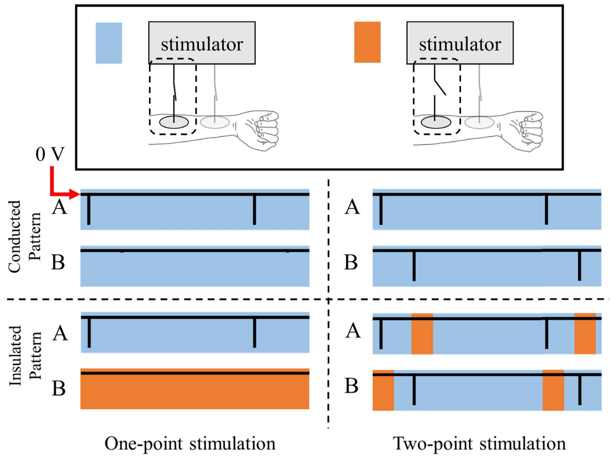


FIGURE 6. Examples of conducted and isolated patterns. A and B can be swapped, and the phase difference is only an example. Electrodes are conducted to the stimulator in the blue shaded zones, and isolated from the stimulator in the orange shaded zones.

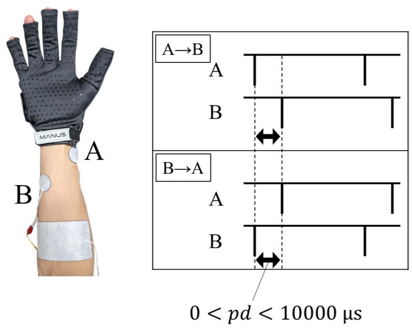


FIGURE 7. Two stimulation patterns with the same phase difference.

When 0 µs $< pd <$ 10000 µs, there were two cases: one in which the phase of A was advanced compared to that of B and that in which the phase of A was delayed compared to that of B (Fig. 7). The former is represented by A→B and latter by B→A. Considering those two variations, the number of two-point stimulation patterns was 25. However, for general discussions, we distinguished the stimulation patterns using the absolute phase differences in the analyses. Specifically, one averaged result was calculated for each pair of A→B and B→A patterns with the same pd.

b: STATE OF ISOLATION

The second parameter, the state of isolation, was a "conducted pattern" or "isolated pattern". Within the conducted pattern, no isolation was applied. On the other hand, within the isolated pattern, while an electrical pulse was applied to one electrode, the other electrode was isolated from the stimulation generator. For the patterns with small pd (the right side of Fig. 5), the experiments were performed only with conducted patterns because isolation was impossible. "C" and "I" in Fig. 5 represent conducted and isolated patterns, respectively. Examples are shown on the right side of Fig. 6.

TABLE 2. V_{Aapp} and V_{Bapp} for each participant in experiment 1.

Participant	V_{Aapp} [V]	V_{Bapp} [V]
P	28	32
Q	20	26
R	32	32
S	18	24

III. EXPERIMENTAL PROCEDURE AND RESULT

A. EXPERIMENT 1

The objective of experiment 1 was to examine the selectivity of two-point stimulation. Moreover, we focused on the effects of phase difference and state of isolation on selectivity. Participants P, Q, R, and S participated in the experiment.

1) QUANTIFYING SELECTIVITY

To quantify and evaluate selectivity, we defined the individuation index (II) of the index finger with reference to [26] as follows:

$$II = 1 - \frac{\frac{1}{4}(|\theta_t^{norm}| + |\theta_m^{norm}| + |\theta_r^{norm}| + |\theta_l^{norm}|)}{|\theta_i^{norm}|} \quad (1)$$

where θ_k^{norm} represents the normalized joint angle of finger k, and t, i, m, r, and l represent the thumb, index finger, middle finger, ring finger, and little finger, respectively. In this experiment, the angles of the fingers' PIP joints and thumb's MCP joint were measured. We measured PIP joints because the selectivity of a voluntary flexion was higher than that of metacarpophalangeal (MP) joints [26]. Thus, the effect of skeletal structures on selectivity could be suppressed. The normalized angle of finger k was calculated as follows:

$$\theta_k^{norm} = \frac{\theta_k^{flex} - \theta_k^{init}}{\theta_k^{limit} - \theta_k^{init}}. \quad (2)$$

where θ_k^{flex} is the joint angle of finger k when flexed by electrical stimulation, and θ_k^{init} is the joint angle of finger k just before stimulation. Moreover, θ_k^{limit} is the maximum measurable angle of finger k. When the index finger was fully flexed independently, II became 1. When the other fingers were flexed simultaneously, II became small. The range of II is $0 \leq II \leq 1$ and selectivity is better for larger II. Due to slight changes in the arm's posture, the index finger was sometimes not flexed even when stimulated. In such cases, (1) became a negative value or not calculable; thus, we considered them exceptions and eliminated them from the results.

2) DETERMINING STIMULATION POINTS AND STIMULATION VOLTAGE

The PIP joint of the index finger is flexed when flexor digitorum superficialis is stimulated. Points A and B were stimulated with an increasing voltage, and II was calculated for each voltage. Fig. 8 shows the variation of the normalized finger joint angles and II with a stimulation voltage in participant P. II decreases when the other fingers are flexed.

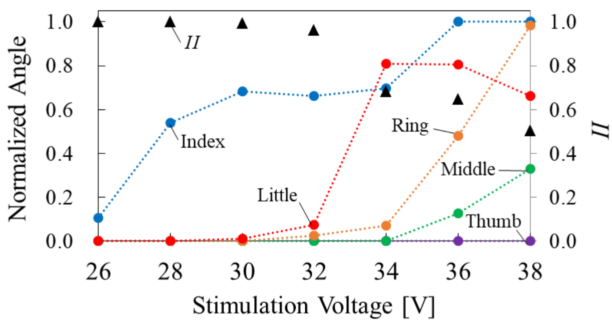


FIGURE 8. Variation of the normalized angles and *II* with stimulation voltage in participant P. II decreased when fingers other than the index finger were flexed.

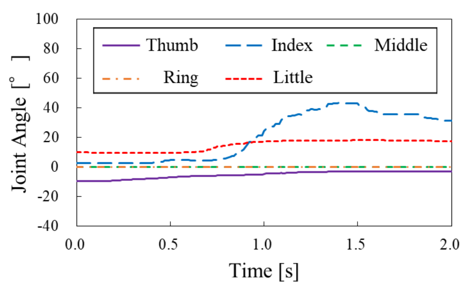


FIGURE 9. Participant S's finger joint angles for one-point stimulation on point B. The stimulation started at 0.0 *s*, and the voltage was 24 V. Note that the green line indicating the middle finger's angle almost overlaps with the line indicating the ring finger's angle.

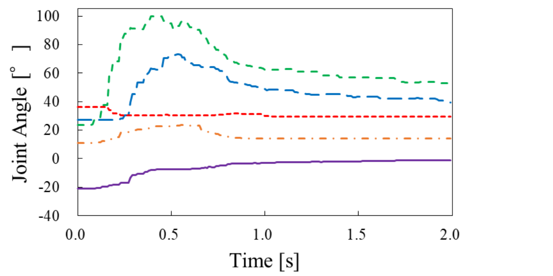


FIGURE 10. Participant S's finger joint angles at two-point stimulation when $pd = 0$ µs (Pattern 0). The stimulation started at 0.0 *s*. The voltages applied to points A and B were 18 and 24 V, respectively. The legend is the same as in Fig. 9.

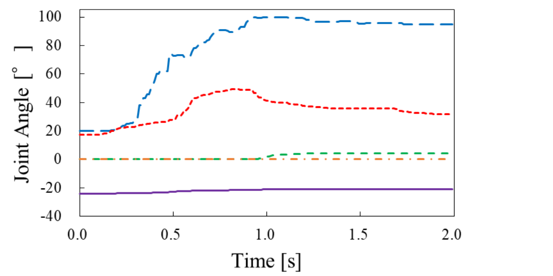


FIGURE 11. Participant S's finger joint angles at isolated two-point stimulation when $pd = 2000$ µs (Pattern 8). The stimulation started at 0.0 *s*. The voltages applied to points A and B were 18 and 24 V, respectively. The legend is the same as in Fig. 9.

The maximum voltages at which index finger flexion could be visually observed and values of II became greater than 0.8 were selected for each electrode as V_{Aapp} and V_{Bapp}. They were the voltage amplitudes in this experiment. The V_{Aapp} and V_{Bapp} for each participant in this experiment are shown in Table 2.

3) STIMULATION EXPERIMENT

In one trial, 25 patterns of electrical stimulations, consisting of the 14 patterns shown in Fig. 5 and their A→B and B→A variations were applied in random order. The duration of each stimulation pattern was 2 s and an interval of 2 s was set between patterns. During the interval, participants let their hands relax and returned their fingers to neutral positions. Five trials were conducted for each participant.

4) RESULT

Figs. 9 to 11 show the examples of the angles of fingers for Participant S. In those graphs, stimulation starts at 0.0 s. The index finger was flexed slightly at one-point stimulation (Fig. 9). At two-point stimulation, the behaviors of fingers varied by the phase difference. When $pd = 0$ µs, fingers other than the index finger were also flexed remarkably (Fig. 10). On the other hand, when $pd = 2000$ µs, the index finger was flexed strongly, and the other fingers were not significantly flexed (Fig. 11). Note that these graphs include the initial angles: angles at 0.0 s, and we applied a normalization when we calculated II to suppress its effect. Figs. 12 and 13 illustrate the averages of II within each participant and inter-participant averages, respectively. Patterns with relatively long phase differences tended to maintain high selectivity. Moreover, the inter-participant averages of II at pattern 5 and after were more than 0.8. The following sections describe the relationships between selectivity and phase difference or state of isolation.

a: EFFECT OF PHASE DIFFERENCE ON SELECTIVITY

Fig. 14 shows the relationship between pd and II in conducted patterns. The horizontal axis is a logarithmic scale. The patterns with large pd tended to have high selectivity. To check whether the changes in pd creates significant differences in II, we conducted a Friedman test. As a result, a significant difference was observed ($n = 3, df = 9, \chi^2 = 19.0, p = 0.0253$).

b: EFFECT OF THE STATE OF ISOLATION ON SELECTIVITY

We examined the selectivity difference between conducted and isolated patterns. A paired two-tailed t-test was conducted on the inter-participant averages of stimulation patterns with $pd \geq 1000$ µs (patterns 6 to 13). As a result, no significant difference in selectivity between conducted and isolated patterns was observed ($t(3) = 0.358, p = 0.743$). Fig. 15 shows the averages of II analyzed here. The result at 1000 µs was different from others. However, all results shown

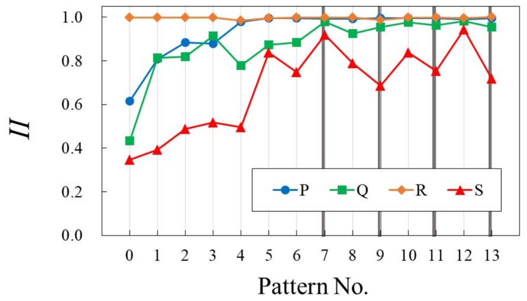


FIGURE 12. Average of *II* for each participant. The black vertical lines indicate isolated patterns.

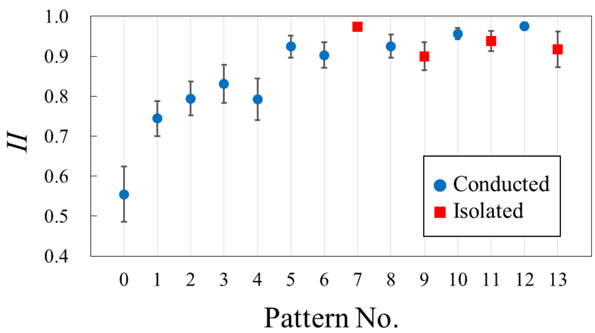


FIGURE 13. Inter-participant averages of *II*.

in Fig. 15 have large values, which indicate that they have no practical differences as shown by the t-test.

B. EXPERIMENT 2

The objective of experiment 2 was to compare the exerted torque by one-point and two-point stimulations. Furthermore, we considered the relationships between torque and phase difference or the state of isolation. The stimulation points and voltages were determined through the process of III-A2. The V_{Aapp} and V_{Bapp} of each participant in experiment 2 are shown in Table 3. All the participants P, Q, R, and S took part in this experiment.

1) MEASURING EXERTED TORQUE

We measured the exerted torque using a force sensor (PFS055YA251U6, "Leptrino", Japan). For the experimental conditions of experiment 2 to match those of experiment 1, participants wore a data glove. To measure the torque around the index finger's PIP joint, the whole hand including the index finger's MP joint was fixed. The fingertip and force sensor were connected with a string, and the exerted force was measured as the tensile force on the string. The measuring scene is shown in Fig. 16. In one trial, 29 stimulation patterns consisting of the 25 patterns in experiment 1 and 4 one-point stimulation patterns were applied in random order. The duration of each stimulation pattern was 2 s and an interval of 2 s was set between patterns. During the interval time, participants relaxed their hands. Five trials were conducted for each participant.

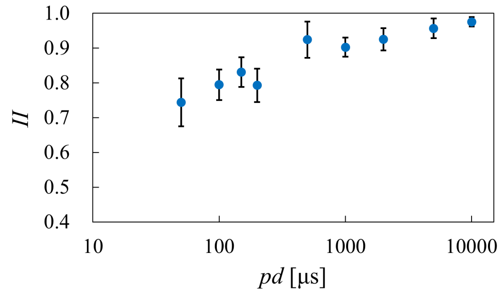


FIGURE 14. Relationship between *pd* and inter-participant average of *II* in conducted patterns.

TABLE 3. V_{Aapp} and V_{Bapp} for each participant in experiment 2.

Participant	V_{Aapp} [V]	V_{Bapp} [V]
P	26	30
Q	34	24
R	40	36
S	18	24

2) RESULT

The averages of five trials for each pattern were calculated for each participant. Moreover, the average values were normalized by the values at the patterns that recorded the largest torque. Fig. 17 shows the normalized torques for each participant. The rightmost plot in Fig. 17 is the average normalized torque for the conducted pattern of one-point stimulation. This value was calculated using the larger of the values obtained when stimulating A and B. Additionally, inter-participant averages were calculated and are shown in Fig. 18.

a: COMPARISON OF EXERTED TORQUE FOR TWO-POINT AND ONE-POINT STIMULATIONS

We compared the exerted torque of each two-point stimulation pattern with that of the one-point stimulation. Table 4 shows the normalized torque at one-point stimulation in each participant. Here, "C" and "I" represent the conducted and isolated patterns, respectively. For example, "A-C" represents the conducted pattern when point A was stimulated. The larger torque values of A and B were used to calculate the average values of the conducted and isolated patterns. Consequently, the average values of the normalized torque of conducted and isolated patterns were 0.28 and 0.27, respectively, where the value of the conducted patterns was slightly larger. Thus, taking the conducted pattern as a representative of one-point stimulation, we compared it with each two-point stimulation pattern. The blue horizontal line in Fig. 18 is the average normalized torque for the one-point stimulation conducted pattern. Further, the blue shaded zone overlapping the line represents the error range. Here, paired two-tailed t-tests were conducted to compare each two-point stimulation pattern and conducted one-point stimulation pattern. The results are shown in Table 5. The conducted patterns of two-point stimulation except for patterns 5 (pd = 500 μs)

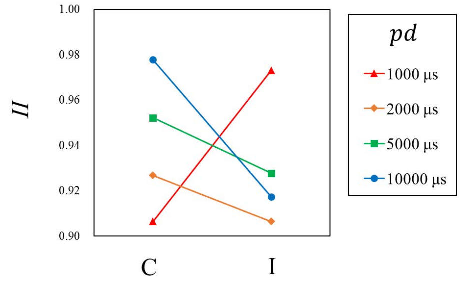


FIGURE 15. Inter-participant averages of *II* in conducted (C) and isolated patterns (I).

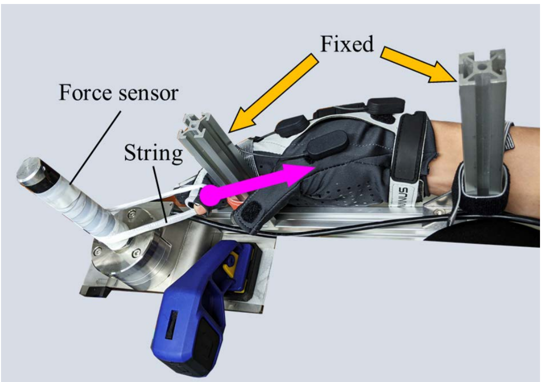


FIGURE 16. Scene of measuring torque.

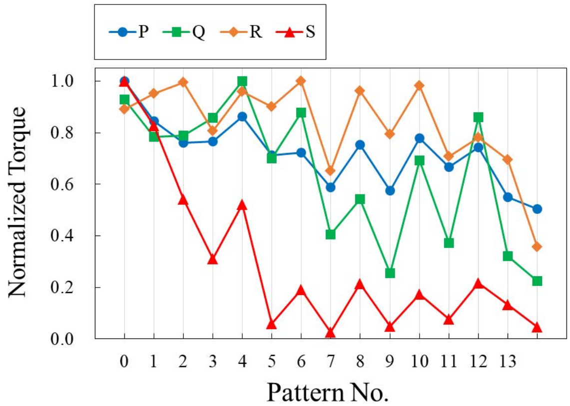


FIGURE 17. Normalized torque in each participant. The black vertical lines indicate isolated patterns.

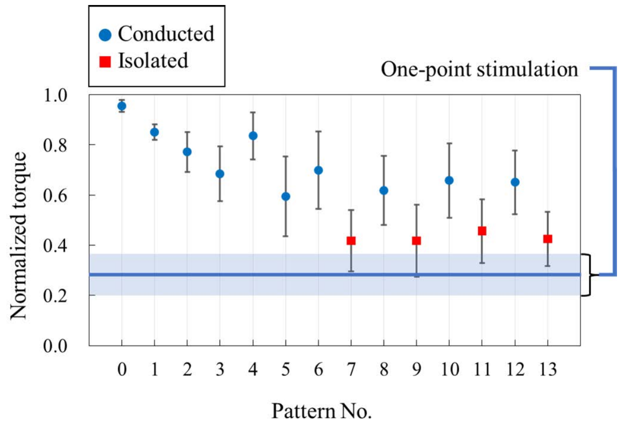


FIGURE 18. Average normalized torque for each stimulation pattern. The blue line and blue shaded zone represent the average and range of the standard error for the conducted pattern of one-point stimulation, respectively.

and 6 ($pd = 1000$ μs) had significant differences between one-point stimulation. On the other hand, all isolated patterns of two-point stimulation did not have significant differences from one-point stimulation.

b: EFFECT OF PHASE DIFFERENCE ON EXERTED TORQUE

Fig. 19 shows the relationship between the average value of normalized torque and *pd* for conducted patterns. The horizontal axis is a logarithmic scale. To check whether the changes in *pd* caused significant changes in exerted torque, we conducted a Friedman test for ten conducted patterns. As a result, no significant change in exerted torque was observed ($n = 3$, $df = 9$, $\chi^2 = 13.5$, $p = 0.140$).

c: EFFECT OF THE ISOLATION STATE ON THE EXERTED TORQUE

According to the results of the t-tests shown in Table 5, all isolated patterns did not have significant differences with one-point stimulation. Here, we compared the exerted torques for the conducted and isolated patterns of two-point stimulation. Paired two-tailed t-test was conducted on the inter-participant averages of stimulation patterns with $pd \geq 1000$ μs (patterns 6 to 13). As a result, there was a significant difference in exerted torque between the two isolation states ($t(3) = 12.1$, $p = 0.00122$). Therefore, conducted patterns are suitable to induce large force. Fig. 20 shows the normalized torques analyzed here.

C. EXPERIMENT 3

We measured the maximum angles of fingers during stimulation. Participant P participated in this experiment. Two electrode pads were pasted on the positions described in II-B. Stimulation was applied with some combinations of intensity.

1) EXPERIMENTAL PROCESS

The process of stimulation was the same as in experiment 1. The patterns of the stimulation intensity are listed in Table 6. In this experiment, the isolated pattern was used for the one-point stimulation, and a conducted pattern of $pd = 2000$ μs (A→B) was used for two-point stimulations. The details of the variables in Table 6 are as follows:

$V_{\square max}$: Maximum voltage

The maximum voltages that maintain selectivity $V_{\square max}$ were selected through the process of III-A2. The subscript □ is replaced by *A* (=stimulation point A), *B* (=stimulation point B), or *E* (=extensor). The maximum voltage to the extensor V_{Emax} was determined as the largest

TABLE 4. Measured torque for one-point stimulation patterns. "C" and "I" represent the conducted and isolated patterns, respectively.

Participant	Normalized torque			
	A-C	B-C	A-I	B-I
P	0.31	**0.50**	0.16	**0.34**
Q	**0.21**	0.11	**0.21**	0.13
R	0.26	**0.28**	**0.39**	0.28
S	0.021	**0.048**	0.019	**0.023**

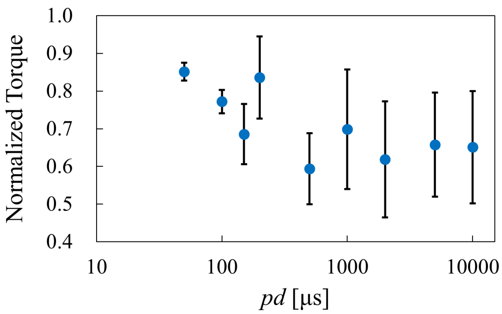


FIGURE 19. Relationship between *pd* and the inter-participant average of normalized torque.

voltage at which the wrist extension was barely induced. V_{Emax} was used in experiment 4.

$V_{\square over}$: Over voltage

Over voltages were voltages larger than $V_{\square max}$. The subscript $\square$ is replaced by A or B. They were defined by the following equation.

$$V_{\square over} = V_{\square max} + 4 \text{ V} \tag{3}$$

$V_{\square th}$: Threshold voltage

Threshold voltages $V_{\square th}$ were the minimum stimulation voltages at which fingers were driven. The subscript $\square$ is replaced by A, B, or E. Stimulation was applied while the voltage was increasing in 2 V increments, and the minimum voltage at which flexion or extension of the finger was visually observed was set to $V_{\square th}$. V_{Emax} was used in experiment 4.

r_{th}: Threshold coefficient

The following process decided the minimum stimulation intensity of two-point stimulation. A variable r satisfies $0 \leq r \leq 1$, and the voltages to A and B were defined as rV_{Amax} and rV_{Bmax}, respectively. Starting with $r = 0.1$, r increased in increments of 0.1 while applying stimulations. The minimum value of r at which index finger flexion was visually observed was defined as r_{th}. Thus, the threshold voltages of A and B at two-point stimulation were $r_{th}V_{Amax}$ and $r_{th}V_{Bmax}$, respectively.

2) RESULT

The results are shown in Fig 21. The upper left graph shows the conditions described in Table 6 using a diagram. Nine bar graphs illustrate the fingers' maximum angles. The values were the averages of five trials, normalized by equation (2). At (a) to (f), fingers other than the index finger were not

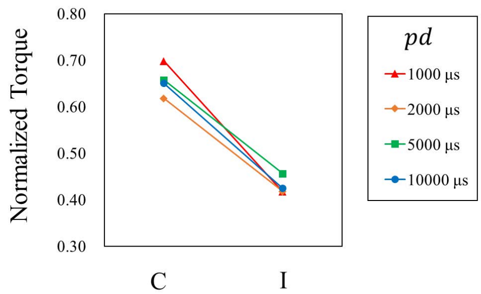


FIGURE 20. Inter-participant averages of normalized torque in conducted (C) and isolated patterns (I).

flexed much. This limited flexion implied that if intensities that maintain selectivity are used, two-point stimulation does not deteriorate selectivity. On the other hand, when voltages exceeding $V_{\square max}$ were used, the other fingers bent. The thumb and little finger were remarkably flexed at (g) and (h), respectively. When the two over voltages were used simultaneously ((i)), the thumb and little finger were driven simultaneously. Note that joint angles are easily saturated, which was why (d) and (e) flexed the index finger fully, although they were one-point stimulation. However, as confirmed in experiment 2, two-point stimulation could exert a larger force than one-point stimulation.

D. EXPERIMENT 4

Experiments 1 and 2 indicated that two-point stimulation could induce larger torque than one-point stimulation with high selectivity if appropriate parameters were set. In experiment 4, joint angle control of the index finger was conducted. A dynamic target angle was set to see how adaptable each stimulating method was to the disturbances like finger angle changes. The index finger of participant R was hardly controllable, probably because the appropriate stimulating position was very vulnerable to slight changes in the electrode position. Therefore, participants P, Q, and S participated in this experiment.

1) STIMULATING POSITION

The index finger's PIP joint was controlled using FES. In addition to the flexor muscle described in the above experiments, the extensor indicis muscle was stimulated to extend the finger. One-point stimulation or two-point stimulation was applied to the flexor muscle. For two-point stimulation, a conducted pattern of $pd = 2000$ μs (A→B) was used based on the results of experiments 1 and 2. The stimulation point of the extensor was searched from the dorsal side of the forearm and a round electrode was pasted. Fig. 22 illustrates an example of the electrode position for the extensor.

2) MAXIMUM AND MINIMUM VOLTAGES

To maintain selectivity, we defined the maximum voltages during control as V_{Amax}, V_{Bmax}, and V_{Emax}. Moreover, the minimum voltages to apply ($V_{\square th}$) were determined because

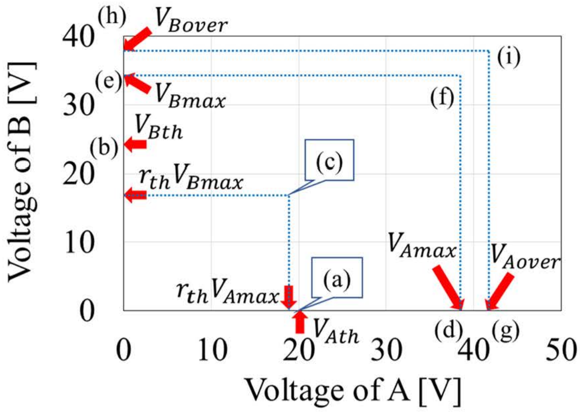
TABLE 5. Result of t-test between one-point stimulation and each two-point stimulation (*: $p < 0.05$, **: $p < 0.01$).

Patten No.	0**	1**	2**	3*	4**	5	6
Result	$t(3) = 6.47$ $p = 0.00740$	$t(3) = 6.34$ $p = 0.00793$	$t(3) = 5.93$ $p = 0.00958$	$t(3) = 4.54$ $p = 0.0200$	$t(3) = 6.18$ $p = 0.00854$	$t(3) = 2.53$ $p = 0.0851$	$t(3) = 3.07$ $p = 0.0547$

7	8*	9	10*	11	12*	13
$t(3) = 2.00$ $p = 0.139$	$t(3) = 3.53$ $p = 0.0386$	$t(3) = 1.32$ $p = 0.277$	$t(3) = 3.43$ $p = 0.0417$	$t(3) = 2.60$ $p = 0.0805$	$t(3) = 3.53$ $p = 0.0387$	$t(3) = 2.15$ $p = 0.121$

TABLE 6. Combinations of stimulation intensity in experiment 3.

(a)	A: V_{Ath}	B; none
(b)	A: none	B: V_{Bth}
(c)	A: $r_{th}V_{Amax}$	B: $r_{th}V_{Bmax}$
(d)	A: V_{Amax}	B: none
(e)	A: none	B: V_{Bmax}
(f)	A: V_{Amax}	B: V_{Bmax}
(g)	A: V_{Aover}	B: none
(h)	A: none	B: V_{Bover}
(i)	A: V_{Aover}	B: V_{Bover}



human muscles do not contract unless the stimulation intensity is higher than certain threshold values. Furthermore, the threshold stimulation intensity of two-point stimulation was defined by the process of III-C1. The threshold and maximum voltages and r_{th} used for this experiment are listed in Table 7.

3) CONTROLLING METHOD

a: HIGH-ORDER SLIDING MODE CONTROLLER

We employed the high-order sliding mode controller with the super-twisting algorithm. The super-twisting algorithm is written as

$$\begin{cases} u = -\lambda|S|^{\rho}\mathrm{sgn}(S) + u_a \\ \dot{u}_a = -W\mathrm{sgn}(S) \end{cases} \tag{4}$$

where λ, ρ, and W are positive constants, and ρ is preferably 0.5 when there are two input variables [27]: here, angle and velocity command. The values of λ and W were determined by trial and error ($\lambda = 10$, $W = 1.0$). The sliding manifold was set as follows:

$$S = \dot{\theta}^{cmd} - \dot{\theta}^{res} + \lambda(\theta^{cmd} - \theta^{res}) \tag{5}$$

where θ^{cmd} and θ^{res} are the angle command and angle response, respectively. The angular velocities were calculated by pseudo-differentiation whose cutoff frequency was $g = 3$ Hz.

b: FINGER CONTROL USING ONE-POINT STIMULATION

Here, the ramp function $R(x)$ is defined as follows:

$$R(x) = \begin{cases} x & (x > 0) \\ 0 & (x \leq 0). \end{cases} \tag{6}$$

The flexor was stimulated when $u > 0$ and the extensor was stimulated when $u < 0$. The voltages to the flexor and extensor minus threshold voltages, V'_F and V'_E, were

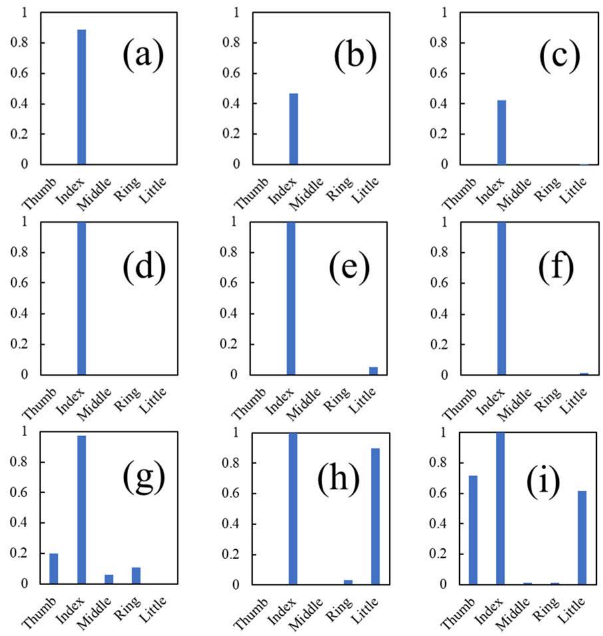


FIGURE 21. Maximum angles of participant P's five fingers during stimulation in experiment 3 (T = Thumb, I = Index, M = Middle, R = Ring, L = Little).

calculated by the following equations using $R(x)$.

$$V'_F = R(u), \tag{7}$$

$$V'_E = R(-u). \tag{8}$$

Finally, the applied voltages V_F and V_E were determined by adding the threshold voltages as follows:

$$V_F = V'_F + V_{Ath}, \tag{9}$$

$$V_E = V'_E + V_{Bth}. \tag{10}$$

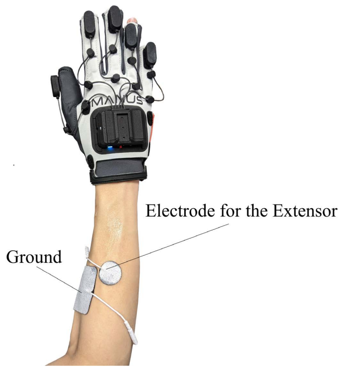


FIGURE 22. Example of the placement of an electrode for the extensor.

To increase the joint stiffness, we stimulated the antagonist muscle with its threshold voltage for the entire control period [28]. In other words, even when the joint was bending, the extensor muscle was stimulated with minimum voltage and vice versa. Moreover, V_F and V_E were limited not to exceed the defined maximum voltages. Note that V_F represents the stimulation voltage to point A (V_{FA}) or that to point B (V_{FB}). The block diagram of the finger control using one-point stimulation is shown in Fig. 23.

c: FINGER CONTROL USING TWO-POINT STIMULATION

The voltages to the flexor and extensor minus threshold voltages, V'_F and V'_E, were calculated by (7) and (8), respectively. Moreover, the voltages applied to A and B were determined as follows:

$$V_{FA} = R(u) + r_{th} V_{Amax}, \tag{11}$$

$$V_{FB} = R(u) + r_{th} V_{Bmax}. \tag{12}$$

The voltage applied to the extensor was determined by (10). In addition, V_{FA}, V_{FB}, and V_E were limited not to exceed V_{Amax}, V_{Bmax}, and V_{Emax}, respectively. The block diagram of the finger control using two-point stimulation is shown in Fig. 24.

4) CONTROL EXPERIMENT

The target value was a sinusoidal wave with an amplitude of 40° and a frequency of 0.2 Hz. The following three stimulating methods were used for control:

- One-point stimulation with the point A.
- One-point stimulation with the point B.
- Two-point stimulation.

Each method was tested five times, and the duration of one trial was 30 s.

5) RESULT

The control performances of one-point and two-point stimulation were compared based on the root mean square errors (RMSEs). The RMSEs were calculated using the response values of 10–30 s to avoid the effects of transient responses. We selected the better result from the cases of A and B for each participant and used the selected result as the representative result of one-point stimulation. The RMSE for each condition is listed in Table 8. The variation within subgroups was large. Considering that, we conducted a two-way variance analysis (two-way ANOVA) with replication, because it considers variations within subgroups. The sources of variance were the number of stimulation points and individual factors. The result showed a significant difference in the number of stimulation points ($p = 0.0489$). We did not find any significant differences in an individual factor ($p = 0.193$) and interaction effects ($p = 0.332$). Therefore, one-point and two-point stimulation significantly differed in the control performance. Table 9 shows the ANOVA table. Figs. 25 and 26 show participant P's best and worst results, respectively, for one-point stimulation. Moreover, Figs. 27 and 28 show participant P's best and worst results, respectively, for two-point stimulation. The direction in which the finger bends is the positive direction. The blue-shaded zones were not involved in computing RMSEs considering transient responses. In the best results, one-point and two-point stimulations were not significantly different. However, during the experiments under both conditions, the cases where the finger was not flexed enough were sometimes observed, and such cases were fewer for two-point stimulation. This discrepancy was probably because two-point stimulation could induce larger torque than one-point stimulation. Furthermore, muscle force induced by electrical stimulation depends on the muscle length (joint angle), which can increase the actual threshold voltages [29]. This relationship caused the lack of torque and might have affected the control performance, particularly in one-point stimulation. The minimum voltages of both A and B for two-point stimulation ($r_{th}V_{Amax}$, $r_{th}V_{Bmax}$) were smaller than those at one-point stimulation (V_{Ath}, V_{Bth}) in all participants. Thereby, two-point stimulation could flex the finger more easily than one-point stimulation. In Table 8, the controlling performance decreased with one-point stimulation in the latter trials, although we set interval times to avoid muscle fatigue. We consider that this was caused by the slight forearm's pronation or supination. This pronation or supination could happen because fixing the arm completely was difficult. We conducted an additional experiment to compare the two stimulating methods in terms of robustness against posture changes. The details of the additional experiment are described in the next section.

In a past study, the index finger was controlled better even though they did not use two-point stimulation [30]. This better control was because they ignored the selectivity and did not limit the stimulating voltage, which made it possible to more strongly drive the finger. Moreover, the finger joint oscillated because the parameters of the control system were not appropriate. However, we do not discuss the suppression of the oscillation, because it was not the main purpose of this study.

6) ADDITIONAL EXPERIMENT

a: ROBUSTNESS AGAINST POSTURE CHANGES

We conducted an additional experiment to compare one-point and two-point stimulations in terms of their robustness

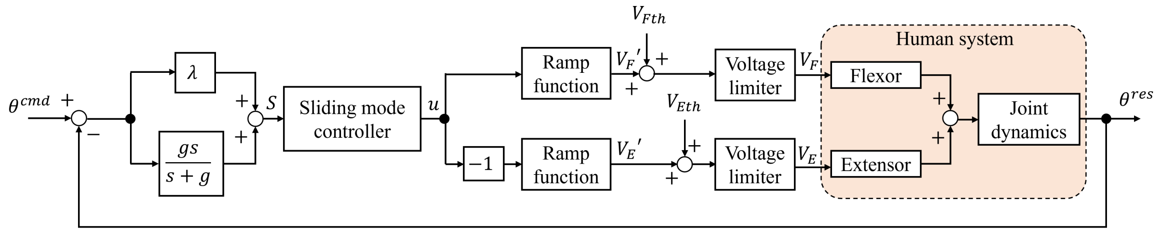


FIGURE 23. Block diagram of finger angle control with one-point stimulation.

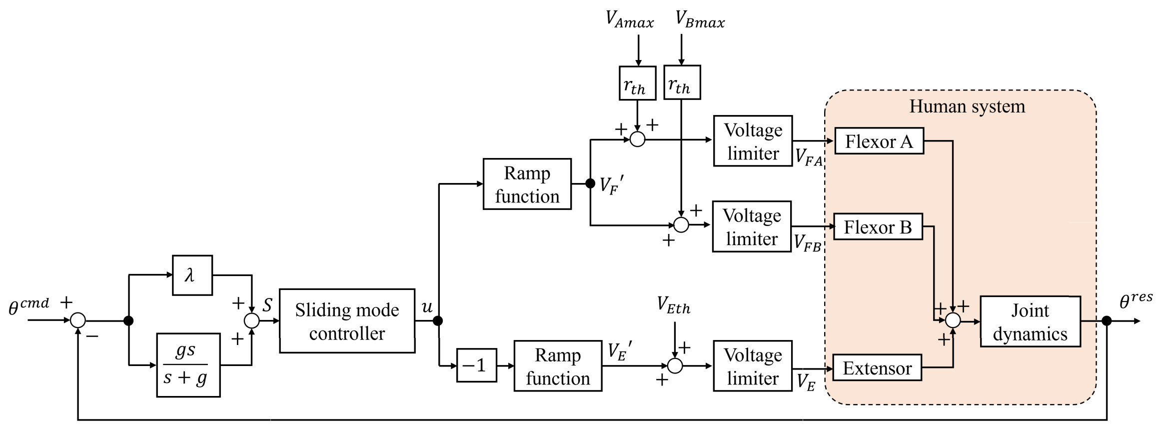


FIGURE 24. Block diagram of finger angle control with two-point stimulation.

TABLE 7. Threshold and maximum voltages and r_{th} for each participant.

Participant	V_{Ath} [V]	V_{Amax} [V]	V_{Bth} [V]	V_{Bmax} [V]	V_{Eth} [V]	V_{Emax} [V]	r_{th}	$r_{th}V_{Amax}$ [V]	$r_{th}V_{Bmax}$ [V]
P	24	28	28	36	14	26	0.7	20	25
Q	24	32	24	32	16	24	0.7	22	22
S	26	32	18	24	18	26	0.7	22	17

TABLE 8. RMSE at one-point and two-point stimulation for each participant.

Participant	RMSE [°]	
	One-point	Two-point
P	8.40 19.0 20.5 13.5 26.6	9.00 11.0 12.6 10.6 10.2
	Average = 17.6	Average = 10.7
Q	9.38 22.8 23.6 24.2 16.9	17.9 17.5 12.0 22.8 9.48
	Average = 19.4	Average = 16.0
S	12.1 14.4 12.4 12.1 21.5	12.1 15.5 14.5 12.6 15.4
	Average = 14.5	Average = 14.0

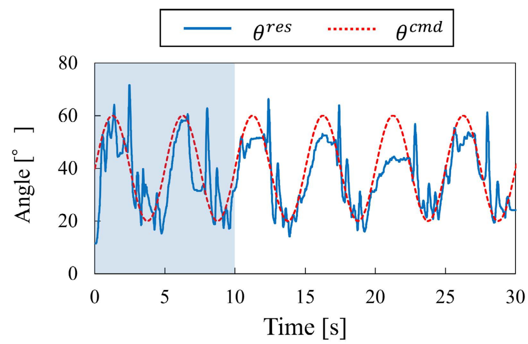


FIGURE 25. Participant P's result of angle control with one-point stimulation when the smallest RMSE was calculated (RMSE = 8.40°).

against changes in the forearm's posture, such as pronation or supination. Participants P, Q, and S took part in this experiment. Like the other experiments, two stimulation points were selected to flex the index finger. Stimulating voltages were selected using the process from III-A2. Using these voltages, one-point and two-point stimulation were each applied for 10 seconds, and the angle of the index finger's PIP joint was recorded with a data glove. The participants were instructed to assume three arm postures during this experiment. The arm postures of 0° pronation, 45° pronation, and 90° pronation are illustrated in Fig. 29. The stimulation method is not robust if the posture change deteriorates the flexion. We conducted three trials for each posture and stimulating method. Therefore, the number of trials was $3 \times 2 \times 3 = 18$ for each participant. Fig. 30 shows participant Q's index finger PIP joint angle as an example. At 45° or 90° pronation, one-point stimulation could not flex the index finger at the same level as for 0° pronation. On the other hand, two-point

TABLE 9. Two-way ANOVA table.

Source of variation	Sum of square	Degree of freedom	Mean square	F	p
The number of stimulation point (one or two)	97.2	1	97.2	4.30	0.0489
Individual factor	79.6	2	39.8	1.76	0.193
Interaction	52.2	2	26.1	1.16	0.332
Error	542	24	22.6		
Total	771	29	26.6		

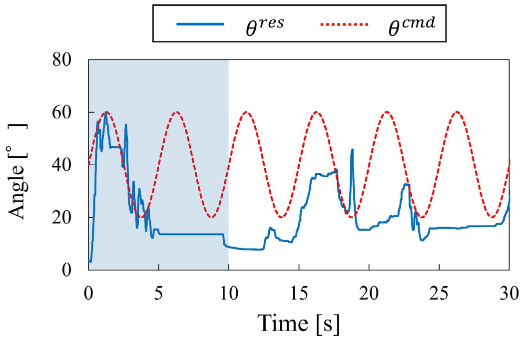


FIGURE 26. Participant P's result of angle control with one-point stimulation when the largest RMSE was calculated (RMSE = 26.6°).

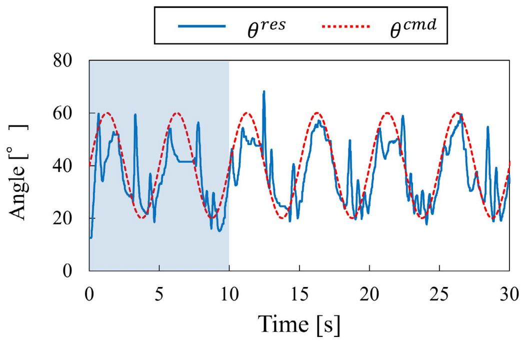


FIGURE 27. Participant P's result of angle control with two-point stimulation when the smallest RMSE was calculated (RMSE = 9.00°).

stimulation flexed the index finger fully, even at pronated postures. Fig. 30 illustrates the maximum angles during the stimulation process. At one-point stimulation, the maximum angle was the largest for the 0° pronation, and it decreased for pronated postures for all participants. With participants P and Q, the maximum angles were almost saturated (100°) by two-point stimulation. At participant S, the maximum angle was degraded by pronation even with two-point stimulation. However, the maximum angle was at least 50° with two-point stimulation, whereas it was almost 0° with one-point stimulation for 45 ° pronation. From the above results, two-point stimulation proved robust against posture changes such as pronation or supination. This robustness made the results of the controlling experiment better with two-point stimulation than with one-point stimulation.

b: STABILITY OF FORCE DURING STIMULATION

We also discuss the stability of force using the results of this experiment. Fig. 32 shows the changes in the index finger's angle during stimulation with no pronation or supination.

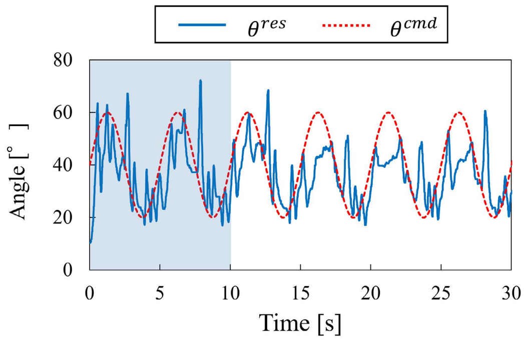


FIGURE 28. Participant P's result of angle control with two-point stimulation when the largest RMSE was calculated (RMSE = 12.6°).

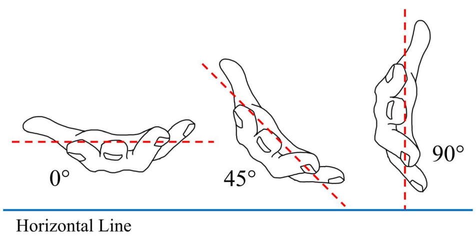


FIGURE 29. Three postures of the arm used in an additional experiment. Views from the direction of fingertips.

The difference between the maximum angle and the angle at 10 s was as follows:

P : One-point 21.9°, Two-point 0.0°
Q: One-point 44.8°, Two-point 0.0°
S : One-point 29.0°, Two-point 13.6°

Thus, two-point stimulation was more stable than one-point stimulation. If the force by stimulation decreased, the finger angle decreased spontaneously because the data glove was elastic. This elasticity was why the angle decreased in time, particularly in the results of one-point stimulation. Therefore, the force was more stable when two-point stimulation was applied.

IV. DISCUSSION

We propose the application of simultaneous electrical stimulation from multiple points to exert large finger torque with high selectivity. The result of experiment 1 indicates that selectivity changes significantly with the phase difference. In Fig. 14, the average of II exceeded 0.9 when pd was larger than 500 µs. Therefore, we suggest to set phase differences at least 500 µs in our experimental condition for ensuring selectivity with two-point stimulation. This result is related to

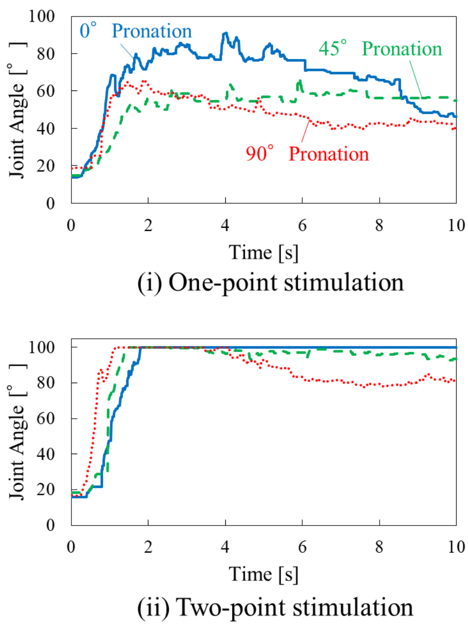


FIGURE 30. Angle of the index finger's PIP joint during one trial of the additional experiment (Participant Q).

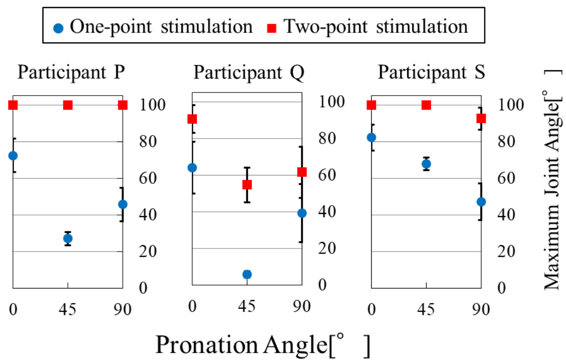


FIGURE 31. Maximum angles of the index finger's PIP joint in the additional experiment. Each plot is the average of three trial results.

the pulse width of waveform. If the phase difference was less than 500 μs (=pulse width), the pulses to the two stimulation points overlapped in time. This overlap probably affected the current path, and untargeted muscles were activated. However, more detailed studies are necessary to properly understand this phenomenon. Moreover, no significant difference in selectivity was observed between conducted and isolated patterns.

The result of experiment 2 showed that regarding the exerted torque, the conducted patterns, except for the ones at $pd = 500$ μs and $pd = 1000$ μs, had significant differences between one-point stimulation, whereas the isolated patterns did not. At conducted patterns, when an electrical pulse was applied to electrode A, the current flowed into electrode B and vice versa. This flow was because the non-activated electrode behaved as a ground electrode. Therefore, two parts were stimulated simultaneously, which increased the exerted force. On the other hand, for the isolated patterns, two parts were stimulated alternately because the non-activated electrode

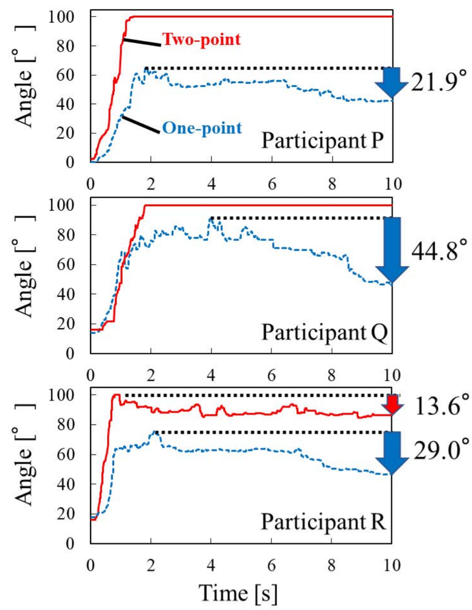


FIGURE 32. Angle of the index finger joint during the additional experiment. The rightmost values are the differences between the maximum angle and the angle at 10 s.

was isolated. Thus, one-point stimulation and isolated two-point stimulation had little difference. Further, no significant change in exerted torque was observed with phase difference changes. From the above discussion, two-point stimulation is considered effective when there is some phase difference and no isolation is applied.

Experiment 3 implied that if intensities that maintain selectivity are used, two-point stimulation does not deteriorate selectivity. Furthermore, in two-point stimulation, fingers bent in one-point stimulation tended to bend as well.

Experiment 4 demonstrated that two-point stimulation was effective for finger angle control because it induced a larger force than one-point stimulation. Moreover, the robustness against disturbances was improved by two-point stimulation. In particular, the additional experiment confirmed that two-point stimulation was more robust against posture changes, such as pronation or supination. This robustness is likely because even when one electrode missed a stimulation point because of posture changes, the other electrode could compensate for it. Moreover, the stability of the exerted force was higher in two-point stimulation than in one-point stimulation.

Note that we only used the waveform type shown in Fig. 4; thus, the discussions about phase difference can depend on applied waveforms. Our method is effective for selective finger movements with FES, because it has the capacity to induce a large force that cannot be obtained with conventional one-point stimulation.

V. CONCLUSION

In this paper, we proposed multi-point stimulation in FES to exert a large force on fingers with high selectivity.

This method stimulates multiple points within intensity ranges that ensure selectivity. In the experiments, two stimulation points that drove the index finger were stimulated simultaneously, while the phase difference between the two stimulation waveforms and isolation state were changed. Hence, we found that two-point stimulation was effective when some phase difference was set and a conducted pattern was used. Furthermore, two-point stimulation was also effective in controlling finger angles, likely because it improved the robustness of FES against disturbances. However, detailed research on the phenomenon under multi-point stimulation is required to apply our method more generally. In the future, we will apply the proposed method to other fingers than the index finger, and combine it with solutions for detecting the appropriate stimulation points, such as electrode arrays. Moreover, we will apply the mixed method to controlling multiple fingers.

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